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Research on flow field and kinematic characteristics of fly ash particles in rotary triboelectrostatic separator

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ABSTRACT

Rotary triboelectrostatic separator is employed to remove and recycle unburned carbon from fly ash which are main solid wastes of coal-fired power plants. The products after decarburization can be used for building materials, road construction material and other function materials. In previous works, effects of structural parameters and operating parameters on recovery process of fly ash were studied. The present work shows the inlet airflow velocity, rotating angular airflow velocity and co-flow velocity directly affect the airflow filed and motion characteristics of fly ash particles from the analysis of separation process using numerical simulation methods. The average airflow velocity in rotary triboelectrostatic chamber have a trend of first increase, then decline and increase again with the increase of inlet airflow velocity, and it increases with the rotating angular airflow velocity in the selected range. Vortexes appeared on both sides of the inlet and grew bigger with the increase of inlet airflow velocity and rotating angular airflow velocity. Co-flow velocity only affected the airflow in the electrostatic chamber. Moving in the airflow and colliding with friction walls were main motion characteristics of ash particles and carbon particles. The collision numbers were closely related to the net charge from the comparison of simulation and experiment results, it suggested that the net charge of ash particle would increase with the collision numbers.

1. Introduction

Fly ash is an industrial by-product which generated during the combustion of coal for energy production [1]. In China, the amount of about fly ash had increased to 600 million in 2017, only 70% of them were recycled and reutilized. They still occupied large amount area and caused severe dust pollution [2]. The fly ash with low LOI were excellent building materials, road construction material and other function materials [3]. The unburned carbon was the main valuable resources of fly ash and could be recycled, though it had low content [4]. Flotation was an effective technology which was used to separate the unburned carbon and ash products [5], and it could remove 61.2% of the unburned carbon from MSW fly ash having 5.24% unburned carbon content [4]. However, the high costs and agent pollution could not be ignored. To avoid these problems, researchers paid attention to the dry beneficiation process such as electrostatic separation [6,7] and triboelectrostatic separation [8,9]. Ban et al. recovered 50% of the carbon with a carbon content >50 wt% using a laboratory-scale triboelectrostatic separation system, which demonstrated the potential of dry separation technology for removing unburnt carbon from coal ash [10]. Tao et al. used the innovative rotary triboelectrostatic separator to reduce the LOI of fly ash to less 2% [11].

Triboelectrification process can be used in the separation of mineral, PVC plastics, coal et al. [12–17]. Fly ash consist of single particle and particle group usually can be charged by rubbing on friction media and separated using different triboelectrification device such as rotary triboelectrostatic separator (RTS for short) [18]. RTS with innovative triboelectrostatic structure is widely applied in the separation of coal, fly ash and phosphate [18–21]. The previous study of dry triboelectrostatic process mostly focused on the process optimization and industrial application. Structural parameters and operating parameters were studied to illustrate the basic separation characteristic of RTS in the previous literatures [22]. Feed rate, roller rotating speed, injection airflow velocity and co-flow velocity were main factors for the separation of fly ash. Especially injection airflow velocity and co-flow velocity, which strongly affected the separation [11]. Negative potential of the rotary charger and hot dry air could enhance the net charge of phosphate, quartz, and dolomite [19,20,23]. High potential between electrode plates would improve the segregation of pure coal and clay which have different polarity and net charge [18]. Meanwhile, two-stage separation had better separation than single-stage separation [19].

However, the particle and particle group which as the separation objects should be concerned in the separation process. Particles with

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similar physical or physicochemical properties migrating, gathering together and constituting the final products under specific separating condition. Usually, high speed dynamic picturing [24] and numerical simulation are used to track their trajectories and analyze kinetic characteristics. In the present study, the friction material of RTS are made of copper or stainless steel, it is inappropriate to observe the airflow and particles' trajectories in rotatory triboelectrostatic chamber using high speed dynamic picturing method. Numerical simulation using Fluent software has the advantage of describing flow field and tracking particles with appropriate parameters intuitively.

In our preceding work, electrical properties of fly ash and operating parameters optimization of RTS based on decarbonization had been studied [25–28]. The present investigation focuses on illustrating flow field and describing fly ash particles' motion characteristics in RTS using Fluent 14.5.

2. Materials and methods

2.1. Physical properties calibration of fly ash particles

Fly ash samples were collected from coal-fired power plant in Shandong Province. Made the samples dried at 105 °C for 2 h in drying oven and cooled to room temperature in vacuum chamber, meanwhile assumed ash particles and carbon particles constituted the fly ash. Ash particles were obtained by heating the fly ash particles in muffle furnace at 1050 °C for 30 min and cooled to room temperature. The size fraction of fly ash was measured by laser particle analyzer (Microtrac S3500) which showed in Fig. 1. The density of fly ash particles and ash particles were measured with pycnometric method. The loss on ignition (LOI), density and yield of carbon particles were calculated from the known properties of fly ash particles and ash particles. All the parameters of fly ash particles relating to simulation were showed in Table 1.

2.2. Simulation methods

The RTS consist of inlet airflow chamber, rotating triboelectrostatic chamber and electric separation chamber (see Fig. 2-①, ②). Fly ash were released from the inlet, and moved in the airflow, collided and charged with the rotating triboelectrostatic chamber wall and rotating friction roller. Then they fell into the electric separation chamber and separated under high potential difference between electrode plates, and became ash products, middle products and carbon products.

A computational grid consisting of 3,546,360 structured meshes were generated by ICEM software (Fig. 2-③). Standard k-epsilon model and standard wall functions were adopted in simulation. SIMPLEC solution method was used to solve the governing equation. Discrete particles was added after the governing equation reached convergence. The interaction between particles and continuous air phase were took into consideration. The inlet airflow, rotating airflow and co-flow which had a great influence on particles' movement were described with contour graph and vector graph.

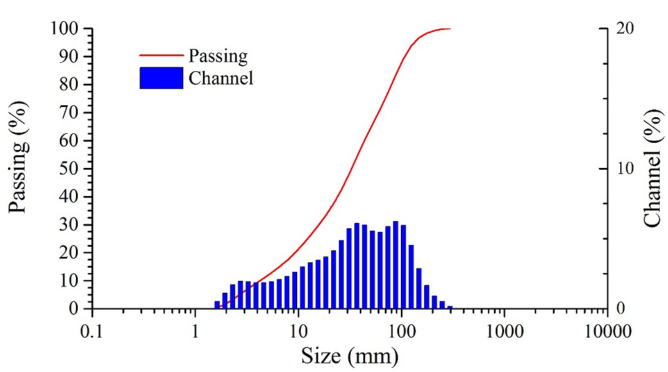

Fig. 1. Size fraction of fly ash.

Table 1
Parameters of fly ash particles.

	LOI/%	Density/kg·m^{-3}	Yield/%
Fly ash particles	11.32	2542	100
Ash particles	–	2653	88.68
Carbon particles	–	1670	11.32

All the values of these factors were measured from experiments, and assigned in gradient. The generation and development of vortexes which resulted from inlet airflow and rotating airflow were also studied. Two ideal inert particle models including carbon particle and ash particle were built in discrete phase model (DPM) [29]. Single particle and particle group (in the form of surface particle) were released from the inlet, their trajectories were recorded and analyzed. The numbers of collision (hereafter short for collision numbers) with friction material were calculated and discussed from the exported data. Meanwhile, the kinetic parameters of particles at some key positions were also obtained. The correlative parameters of simulation were listed in Table 2.

2.3. Governing equations

The standard k-epsilon model (k-ε) is a model based on model transport equations for the turbulence kinetic energy (k) and its dissipation rate (ε) [30]. It has moderate calculation and is applicable to most turbulence flows. Standard wall functions were adopted in the simulation. The major governing equations can be described as (1)–(6):

Mass conservation:

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho u_i}{\partial x_i}=0 \tag{1}$$

Momentum conversation:

$$\frac{\partial}{\partial t}(\rho u_i)+\frac{\partial}{\partial X_j}(\rho u_i u_j)=-\frac{\partial \rho}{\partial X_i}+\frac{\partial}{\partial X_j}\left[\mu\left(\frac{\partial u_i}{\partial X_j}+\frac{\partial u_j}{\partial X_i}-\frac{2}{3}\delta_{ij}\frac{\rho u_l}{\rho X_l}\right)\right]+\frac{\partial}{\partial X_j}\left(-\rho \bar{u_i'}u_j'\right) \tag{2}$$

Energy conservation:

$$\frac{\partial \rho h}{\partial t}+\frac{\partial}{\partial X_j}\left(\rho u_j \mathrm{h}-\frac{\mu_e}{\sigma_h}\frac{\partial h}{\partial X_j}\right)=\frac{dP}{dt}+S_h \tag{3}$$

The k-ε turbulence model:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial X_i}(\rho k u_i)=\frac{\partial}{\partial X_i}\left[\left(\mu+\frac{\mu_t}{\delta_k}\right)\frac{\partial k}{\partial X_j}\right]+G_k+G_b-\rho\varepsilon-Y_M \tag{4}$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial X_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial X_j}\left[\left(\mu+\frac{\mu_t}{\delta_\varepsilon}\right)\frac{\partial \varepsilon}{\partial X_j}\right]+C_{l\varepsilon}\frac{\varepsilon}{k}(G_k+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{5}$$

$$\mu_t=\rho C_\mu\frac{k^2}{\varepsilon} \tag{6}$$

where k is the turbulence kinetic energy, ε is dissipation rate of turbulence kinetic energy, μ_t is the turbulent viscosity.

The instantaneous volume fraction of fly ash particles in the RTS is <5%, therefore, the DPM is chose to simulate the solid fly ash particles. The DPM model assumes that the particle–particle interactions and the effect of the volume fraction of particles on the continuous phase