Separation and Purification Technology 158 (2016) 357–366

Contents lists available at ScienceDirect

Separation and Purification Technology

journal homepage: www.elsevier.com/locate/seppur

Fine particle sorting and classification in the cyclonic centrifugal field

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ARTICLE INFO

Article history:
Received 6 November 2015
Received in revised form 4 December 2015
Accepted 23 December 2015
Available online 23 December 2015

Keywords:
Multi-product classification
Particle sorting
Particle separation
Cyclonic centrifugal field
Monodispersion

ABSTRACT

Fine particle sorting and classification are not only important processes during the powder preparation, but also vital to the sequential separation of discrete fine particles with different sizes. The moving fine particles with different sizes have different trajectories in the cyclonic centrifugal field under the actions of radial and axial forces, which inspire us to develop a novel cyclonic multi-product sorting classifier. Both particle size and mass distribution gradually increase axially from the inlet side to the outlet side and radially from the inside to the outside at the rectangular outlet of the sorting classifier. When the mean particle size of the inlet is 15.7 μm and the coefficient of variance is 90.1%, 12 different particle sizes (the minimum and maximum particle sizes are 8.41 and 26.16 μm, respectively) with better monodispersion are obtained, all products achieve a particle coefficient of variance below 40%. An effective calculation method was used to represent the overall sorting and classification performance of sorting classifiers with different height. The results show that the best height is 5 times as high as the rectangular inlet, and the optimum gas flow is 30–60 m^3/h with the pressure drop not exceed of 80 Pa. The present study could also serve as a useful guide in the industrial sequential separation and capture of fine particles of different sizes. Notably, it may exhibit a high potential for the control of $PM_{2.5}$ throughout studies in future.

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1. Introduction

Fine particle sorting and classification is a vital step in powder preparation. Efficient classification and sieving technologies can obtain various sizes of products with better monodispersion, and then increase the powder utility value and production level [1,2]. The fine powder classification technologies are generally based on the inherent physical and chemical properties of fine particles [3–7]. The representative technologies are sifting [8], cyclone classification [9], electromagnetic classification [10], flotation [11] and so forth. However, these technologies are either low classification accuracy, or high energy consumption, even some of them need additional step, for example, wet sifting requires additional drying step. Fine particle classification in the industrial field is mainly based on the centrifugal field [12], such as impeller classifier [13] and cyclone classifier [14,15]. The most major problem is that most of the classifiers can only obtain two kinds of products, namely large and fine particles [15–17], whereas the common method to obtain multiple products is to connect several devices in a series [1], resulting in a large-scale setup and high energy consumption. Therefore, an accuracy and efficiency classifier which can obtain multi-products with different sizes is a great demand.

What is more, the separation of fine particles and control of particle emission into the atmosphere is another technical challenge in environmental protection field. Fine particles, especially PM_{10} and $PM_{2.5}$ are a major medium that often cause atmospheric pollution and induce harm to human [18–21]. The existing methods to separate suspended particulate matter in aerosols mainly include electrostatic separation [22], settling separation [23], bag-type dust removal [1,24], and rotating centrifugal separation [25–27]. However, aerosols often contain particles with different sizes [15,28]. Usually, a single device or method can only separate particles of or larger than a certain particle size; therefore, effective separation of smaller particles, especially those smaller than $PM_{2.5}$, is difficult to achieve, resulting that the overall particle separation efficiency is hard to improve. If particles were classified into different sizes first, then those of different sizes can be precisely separated using devices with different separation accuracies, There is no doubt that the overall separation efficiency can be increased effectively.

Studies have shown that fine particles entering separation devices by a certain sorting method can also improve the separation

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http://dx.doi.org/10.1016/j.seppur.2015.12.044
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performances of a single device. Taking the centrifugal separation for example, Wang et al. [29] found that the initial position of particles fed into the inlet section of the hydrocyclone affects separation performance. They also pointed out that the pre-sorting inlet is conducive to particle separation. Liu et al. [30] introduced a spiral case structure at the inlet to regulate the position of the fed particles, effectively improving the separation of small particle. Yang et al. [31] studied the influences of the installation of a pre-arrangement device before the inlet of the hydrocyclone on the trajectories of dispersed-phase particles and on the continuous-phase flow field by CFD simulations, improved the flow field structure and separation efficiency.

All in all, if a high-efficiency sorting and classification method can be successfully developed, it will not only benefit the development of powder technology, but also can enhance the separation of fine particles and reduce particle emission into the atmosphere.

The density of solid particles is approximately equal in a system composed of the same material. Particle sorting and classification in this system basically depends on field force. Particles of different sizes are exposed to different field forces, thereby producing different transport velocities and trajectories. Currently, solid particle classification and sorting in the flow process are largely based on the electric field, magnetic field, and centrifugal field. For example, Kobayashi et al. [32] introduced a method for sorting micron particles in suspension under the action of electrostatic force. However, a simple and feasible way to arrange fine particles in a fast-flowing system is to use rotation centrifugal force field. Chu et al. [33] found that centrifugal sedimentation inside the column of hydrocyclone enables particle sorting from the center to the side wall according to an ascending order of particle sizes.

In the present study, for the purposes of multi-products classification and separation enhancement of fine particles, a novel sorting classifier was designed. Compared with these existing approaches, this new type of design has the advantages of high efficiency, low energy consumption, simple structure and easy operation, more important, it can obtain multi-products and achieve orderly sorting of different sized particles at the outlet, which is conducive to the sequential separation of fine particles. The sorting classifier proposed in this study can also connected with other separating devices to improve the separation performance, such as cyclone. It is important for researchers to promote the knowledge level to the particle sorting and classification, and also serves as a valuable reference for the separation enhancement of particle matter, especially $PM_{2.5}$.

2. Theoretical section

In the revolving centrifugal force field, the discrete fine particles of the same kind are equal in density but have different sizes. The different sized particles are exposed to different radial/axial forces, forming different kinematic velocity and trajectories, leading to the orderly sorting and classification of particles.

In a high-speed 3D cyclonic flow field, the discrete particles are mainly affected by gravity, centrifugal force, fluid resistance, and additional force originating from continuous-phase velocity/pressure gradients. The radial forces mainly include the centrifugal force F_C produced by the high-speed rotation around the axis; a centripetal buoyant force F_B resulting from unequal radial pressure because of the radial pressure gradients; and a radial fluid resistance F_D resulting from the relative motions of the particles and continuous-phase medium. These radial forces are calculated as follows:

$$F_C = \frac{\pi d^3}{6}\rho_s \frac{u_t^2}{r} \tag{1}$$

$$F_B = \frac{\pi d^3}{6}\rho \frac{u_t^2}{r} \tag{2}$$

$$F_D = \zeta \frac{A\rho \upsilon^2}{2} = \zeta \frac{\pi d^2 \rho \upsilon^2}{8} \tag{3}$$

When particles are in a balanced rotary motion relative to the continuous-phase fluid with a radial velocity of u_r, they are under a balanced radial force:

$$\frac{\pi d^3}{6}\rho_s \frac{u_t^2}{r} - \frac{\pi d^3}{6}\rho \frac{u_t^2}{r} - \zeta \frac{\pi d^2 \rho u_r^2}{8} = 0 \tag{4}$$

Through simplifying Eq. (4), the relationship between the balanced turning radius r of particle and the particle size d is expressed by Eq. (5):

$$r = \frac{4(\rho_s - \rho)}{3\zeta\rho}\left(\frac{u_t}{u_r}\right)^2 d \tag{5}$$

Eq. (5) indicates that, whatever the value of the resistance coefficient ζ, the balanced turning radius r increases with the particle size d. Thus, particles can be orderly sorted and classified from the axle center to the side wall according to particle size.

The main axial forces on fine particles in the cyclonic field include gravity F_g, axial buoyant force F_b, axial fluid resistance F_d. These main axial forces are calculated as Eqs. (6)–(8), respectively.

$$F_g = \frac{\pi d^3}{6}\rho_s g \tag{6}$$

$$F_b = \frac{\pi d^3}{6}\rho g \tag{7}$$

$$F_d = \zeta \frac{A\rho \upsilon^2}{2} = \zeta \frac{\pi d^2 \rho u_z^2}{8} \tag{8}$$

When particles are in a balanced motion relative to the continuous-phase fluid at the axial velocity u_z, they are under a balanced axial force:

$$\frac{\pi d^3}{6}\rho_s g - \frac{\pi d^3}{6}\rho g - \zeta \frac{\pi d^2 \rho u_z^2}{8} = 0 \tag{9}$$

It can be obtained by Eq. (9) that the relationship between the axial relative velocity u_z and the powder particle size d is as follows:

$$u_z = \sqrt{\frac{4d(\rho_s - \rho)g}{3\zeta\rho}} \tag{10}$$

Eq. (10) indicates that, in the cyclonic centrifugal field, the axial velocity u_z relative to the continuous-phase flow field increases with the powder particle size d. Because of the residence time of particle in a cyclonic sorting classifier is very short, the bigger particles with faster axial velocity u_z can move longer axial distance before exported from the sorting classifier, which is conducive to the orderly axial sorting of fine particles.

In combination of Eqs. (5) and (10), it show that both particle size and mass distribution gradually increase axially from the inlet side to the outlet side and radially from the inside to the outside, respectively. The theoretical regular of sorting and classification of fine particles after passing through the sorting classifier is shown in Fig. 1. On the basis of these theories, we designed a novel sorting classifier, studied the influence of related factors on sorting and classification effect, and deeply researched the rules of particles sorting at the outlet of sorting classifier for the purpose of further study on separation enhancement of fine particles in future.

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