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Effect of Slot Height on Efficiency of Gas-Solid Multivortex Separator with Coaxial Tubes

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Abstract. A multivortex separator with coaxial tubes has been developed to separate fine particles from dusty gas. The design and operation principle of the device is given. The paper numerically studied the influence of the design parameters of the separator on the capture efficiency and pressure drop. The height of the rectangular slots of the multivortex separator of 45 mm was found to provide the separation efficiency of 68% and a moderate pressure drop. Higher centrifugal forces in the separation zone are achieved with the smaller height of the rectangular slots, so the efficiency of the device can be enhanced by increasing the inlet gas velocity. The pressure drop of the developed separator with the slot height of less than 45 mm should not exceed 160 Pa at the gas velocity at the device inlet up to 10 m/s).

INTRODUCTION

Air separation is based on the fact that large particles (coarse fraction) of the feed material suspended in the air flow are deposited under the influence of forces (gravity, centrifugal, inertia, and friction), and small particles (fine fraction) are drawn off by the air flow. Air separators are used in a variety of industries: ferrous, and non-ferrous metallurgy, chemical, industrial, building material's industry, energy, etc. [1, 2]. The final properties of the products depend on the quality of the separation process. Air separators can operate in a closed air cycle and meet environmental requirements. The separation is influenced by many factors, such as the two-phase nature of the flow, polydispersity, uniformity of the continuous phase velocity field and field of local particle concentrations, particle rotation, etc.; so this is a complex multiparameter process. Therefore, the best method for evaluating the efficiency of the air separator is a numerical study using CFD [3–5].

CFD is used in work [6] to study the particle distribution law and the flow field for various matching schemes, and the influence of classification for different laws of particle distribution. The classification size ratio is utilized to evaluate separation efficiency. The larger this ratio, the higher the efficiency. The authors [7] performed numerical calculations of the separator influence of the design parameters (rotor body shape, number of blades, and blade profile) on the internal flow field, as well as the efficiency of classification. Guizani et al. [8] investigated optimization of the flow profile and reduction of pressure drop. During CFD studies, the fine material output of the classifier was changed, which significantly reduced the pressure losses. The work [9] described the change in the spatial distribution of the dispersity of a gas suspension in a low-velocity flow of a z-shaped classifier. The authors [10] presented the results of simulating the operation of a classifier with a change in blade length and opening angles.

Previously, a gas-solid separator with coaxial tubes was proposed, whose design provides the formation of multiple vortices [11, 12]. The simple design of the separator makes it possible to manufacture it directly at the

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enterprise. The separation of fine particles from the dusty gas in the developed separator occurs primarily due to the formation of centrifugal fields in which the centrifugal forces have high values. As a rule, they are sufficient to change the fine particle trajectory of the movement inside the multivortex separator.

In order to improve the operation of the multivortex separator with coaxial tubes, it is necessary to determine the influence of structural, technological, and thermophysical parameters on the efficiency and pressure drop of the device. Thus, the aim of this work is to study the influence of the rectangular slot height on the efficiency of the gas-solid multivortex separator.

MATERIALS AND METHODS

The main components of the multivortex separator are two tubes forming tube-in-tube design and a plate with holes 2 (fig. 1). The plate shuts off the space of the upper part of the outer pipe, providing gas flow to be discharged through the holes. There are rectangular slots 3 in the bottom part of the inner tube. The number of rectangular slots is half the number of circular outlet holes in the plate 2. There is an open-end at the bottom part of the inner tube.

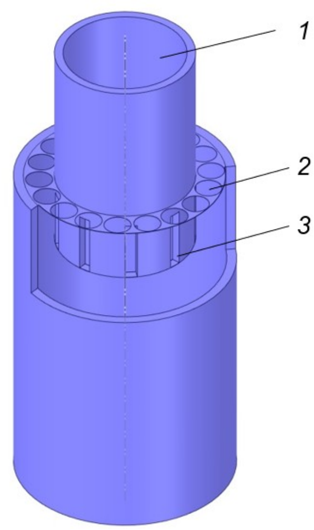

FIGURE 1. 3D model of the multivortex separator with coaxial tubes: 1 – gas inlet; 2 – plate with outlet holes for purified gas; 3 – rectangular slots.

The working principle of the separator is as follows. The dusty gas enters the device through the inlet 1 and flows down. When the gas flow reaches the rectangular slots, made in an axisymmetric direction with constant pitch, it is distributed on them in equal parts. When each part of a stream leaves the rectangular slot 3, it is divided into two streams. Each of which, by inertia, rushes to the opposite side; i.e. one to the right, the other to the left. Due to the design of the rectangular slots, the separating streams that exit from the slots form a multiple of vortices in the intertube space. In this case, the rotation of each vortex does not destroy the neighboring one. At the borders of adjacent vortices, the velocity vectors are co-directed, which allows the vortices to support each other. Thus, a vortex system is supported in the intertube space. Moreover, the diameter of such vortices usually reaches 20–30 mm. Accordingly, the centrifugal forces of rotating vortices in the intertube space of the multivortex separator reach high values. As a result, fine particles are successfully separated from the dust gas.

When fine particles are separated from the gas, they hit the walls of the device and stick to them. The large particles or particles that have been agglomerated fall to the bottom of the multivortex separator. In turn, the vortices gradually move into the upper part of the separator, moving towards the outlet holes 2. Each hole is located in a rotation area of the single vortex. In this way, the perforated plate makes it possible to additionally support a multi-vortex system in the intertube space of the separator. It should be noted that when the dust flow moves along the inner tube, part of the flow passes through the hole in the lower part. This flow changes direction by 180º and rises to the upper part of the multivortex separator. Medium and large particles are separated from the gas flow by an inertial action. Then, they settle at the bottom of the separator. Depending on the initial concentration in the gas, the operating period of the multivortex separator is determined. The device must be cleaned.

The study is performed using numerical simulation in the complex Ansys Fluent. For the research, a solid-state model of the multivortex separator (fig. 1) was modeled for the research. A flow area of the model is divided into many polyhedral elements. The k-ω SST turbulence model is used in the numerical simulation. The basic geometric dimensions of the multivortex separator with coaxial tubes are the following: the outer diameter of the inlet tube is 57 mm with wall thickness of 3.5 mm, the diameter of the outer tube is 90 mm with wall thickness of 4 mm, height of the outer tube is 140 mm and diameter of the holes is 11 mm. The width of the rectangular slots was determined by the angle of their opening. It was obtained earlier [12] that the maximum efficiency of the separator is achieved at the angle of opening of rectangular slots $\alpha = 20^{\circ}$.

In the course of simulation, the height of the rectangular slots varies from 15 to 60 mm. As the slot height increased, the length of the inner tube increased by a similar value. The diameter a changes from 1 to 15 μm. The gas velocity W at the inlet to the multivortex separator varies from 3 to 10 m/s. The particle density is 1000 kg/m^3. The atmospheric pressure is 10^5 Pa and is set at the outlet circular holes. The condition of particle adhesion is specified on the walls. The influence of fine particles on the carrier phase is not taken into account.

During the results processing the results, the efficiency of the multivortex separator with coaxial tubes is calculated as:

$$E = 1 - \frac{n}{n_0}, \tag{1}$$

Where n is the number of fine particles remaining in the gas flow after separation; n_0 is the total number of fine particles at the separator inlet.

The pressure drop of the multivortex separator can be determined by the following equation:

$$\Delta p = p_1 - p_2, \tag{2}$$

Where p_1 and p_2 are the inlet and outlet pressure of the separator, respectively.

RESULTS AND DISCUSSION

The results showed that the device with coaxial tubes is able to separate fine particles up to 10 μm from the gas with high efficiency if a particle agglomeration process occurs. At a certain time, an enlarged particle falls into the device bunker under the action of gravity. Studies show that the efficiency of the separator with coaxial tubes is influenced by the height of the rectangular slots and the gas velocity at the device inlet. By increasing the height of the rectangular slots, separation efficiency for fine particles is reduced. This is due to the fact that the height of the separation zone (vortex height) also increases; correspondingly, low centrifugal forces are created under condition that the inlet gas velocity remains constant and the height of the slot rises. In addition, proximity of the slots to the exit of the device can lead to particle slippage. In other words, some of the particles dispersed in the gas that pass through the upper part of the rectangular slots are immediately removed from the intertube space of the separator with a high probability. At the same time, increasing the inlet gas velocity to the device (W) leads to an increase in the efficiency of particle capture by the separator. Clearly, this is caused by an enhancing of the centrifugal force that appears in the intertube space during the rotation of vortices. In addition, the separation efficiency for particles less than 3 μm is less than 25%. When the particle size varies from 3 to 6–10 μm, the efficiency improvement increases by up to 90 to 100%.

The efficiency of the multivortex separator with coaxial tubes averages 60, 43, 21, and 16% with the height of the rectangular slots (h_{sl}) of 15, 30, 45, and 60 mm, respectively. Note that when $h_{sl} > 45$ mm, 4 μm particles are not captured (fig. 2). According to fig. 3, the separation efficiency is averaged 60, 81, and 84% at the gas inlet velocity of 3, 7, and 10 m/s, respectively. It was found that fine particle capture efficiency close to 100% is achieved when the particle size is greater than 5 μm (at $W = 10$ m/s), 6 μm (at $W = 7$ m/s) and 9 μm (at $W = 3$ m/s).

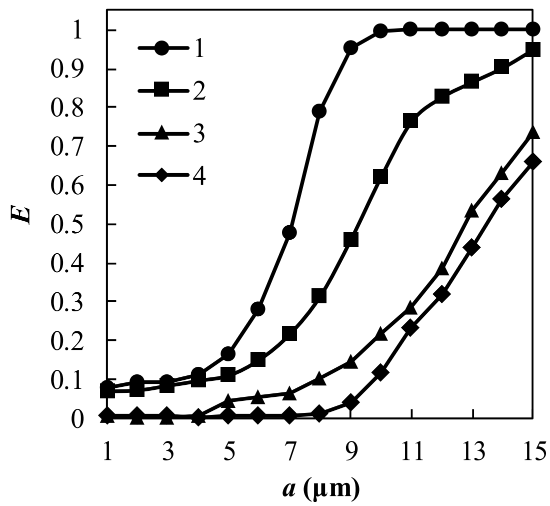

FIGURE 2. Separation efficiency versus particle diameter for various slot height h_{sl}, mm: 1 – 15; 2 – 30; 3 – 45; 4 – 60 (at inlet gas velocity W = 3 m/s).

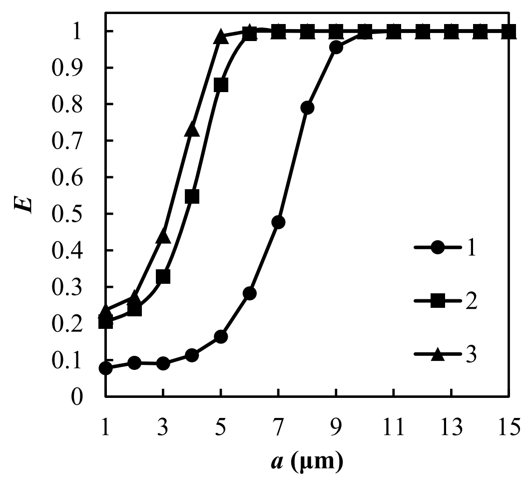

FIGURE 3. Separation efficiency versus particle diameter for various gas inlet velocity W, m/s: 1 – 3; 2 – 7; 3 – 10 (at slot height h_{sl} = 15 mm).

In particular, at the rectangular slot height of 30 mm, the efficiency of the multivortex separator with coaxial tubes averages 43, 66, and 62% at the gas velocity of 3, 7, and 10 m/s at the device inlet, respectively. The separation efficiency for fine particles close to 100% is achieved at a > 10 µm (at W = 10 m/s), 10 µm (at W = 7 m/s), and 15 µm (at W = 3 m/s) (fig. 4). Similarly, at h_{sl} = 30 mm, the separation efficiency of the device averages 54, 73, and 78% at a gas velocity of 3, 7, and 10 m/s at the inlet of the device, respectively. Maximum capture efficiency for fine particles close to 100% is achieved at a > 6 µm (at W = 10 m/s), 7 µm (at W = 7 m/s) and 12 µm (at W = 3 m/s). Note that efficiency of about 100% is attained more rapidly than at h_{sl} = 30 mm (fig. 5).

The pressure drop of the separator is not exceed 420, 160, 140, and 115 Pa at the height of the rectangular slots of 60, 45, 30, and 15 mm, respectively. Note that as the height of the rectangular slots increases, the pressure losses of the multivortex separator decreases (fig. 6).

Thus, the results obtained have shown that it is necessary to reduce the size of rectangular slots of the multivortex separator with coaxial tubes, because it provides high centrifugal forces in the intertube separation zone, increasing the separation efficiency for fine particles from the dusty gas. On the other hand, reducing the height of rectangular slots results in an increase in the pressure drop. Therefore, to develop gas-solid multivortex separator, it is necessary to combine high separation efficiency and reasonable pressure drop.

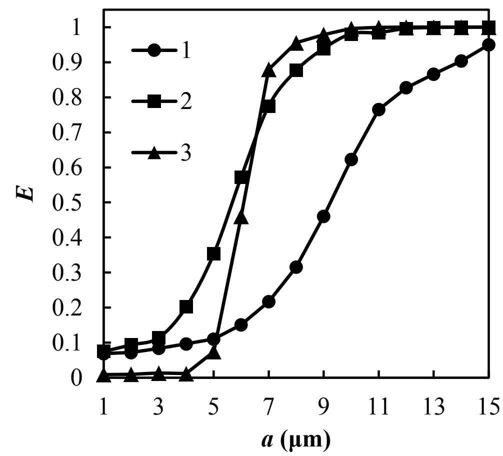

FIGURE 4. Separation efficiency versus particle diameter for various gas inlet velocity W, m/s: 1 – 3; 2 – 7; 3 – 10 (at slot height h_{sl} = 30 mm).

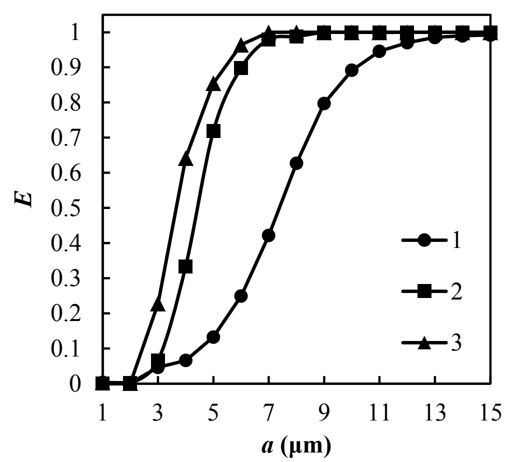

FIGURE 5. Separation efficiency versus particle diameter for various gas inlet velocity W, m/s: 1 – 3; 2 – 7; 3 – 10 (at slot height h_{sl} = 45 mm).

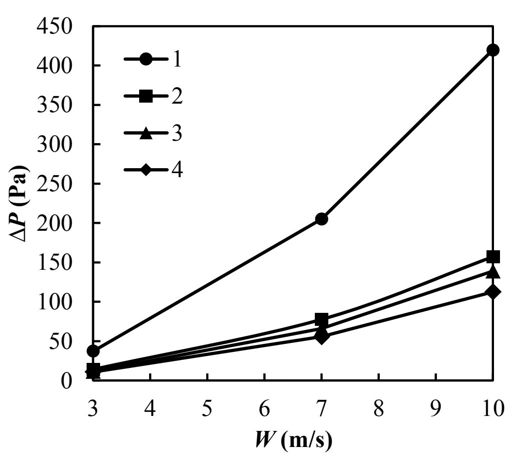

FIGURE 6. Relationship curves between pressure drop and gas inlet velocity for various slot height h_{sl}, mm: 1 – 15; 2 – 30; 3 – 45; 4 – 60 (at inlet gas velocity W = 10 m/s).

CONCLUSION

The following conclusions can be drawn from this work:

- The maximum height of the rectangular slots of the multivortex separator is 45 mm. It provides the separation efficiency of 68% and moderate pressure drop;
- The pressure drop of the developed separator with the slot height of less than 45 mm should not exceed 160 Pa at the gas velocity at the device inlet up to 10 m/s;
- Higher centrifugal forces are achieved with the small height of the rectangular slots, correspondingly, the efficiency of the device is enhanced by increasing the gas velocity;
- Improved efficiency of the multivortex separator with coaxial tubes can be achieved by using several devices connected in-series.

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