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Impact of entrance angle of rectangular openings of centrifugal multivortex device on its classification efficiency

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Abstract. Air classification is a common process in many industries. The paper presents an analysis of the operation of a centrifugal multivortex classifier designed to separate solid particles. The classification process of gas-solid system is observed between the outer pipe and the inner pipe, which has rectangular openings that provide the formation of the stable vortex system. The purpose of this work is to study the influence of the entrance angle of rectangular openings on the classification effectiveness of the device. The results show that the maximum effectiveness in the classification of particles larger than 40 μm is achieved at an angle of 0.8 and a gas flow speed of 16 m/s, providing an effectiveness of 69.6%. Increasing the speed at the inlet to the device improves the effectiveness, since the vortex structure in the interpipe space becomes more stable. It is recommended to select the classifier with the largest entrance angle of rectangular openings, since the lowest pressure loss is achieved. Changing the entrance angle of rectangular openings of the device has practically no effect on the effectiveness of particle classification.

1 Introduction

Air classification of solid particles is an important process in enterprises of various industries, both directly for the fractionation of materials and for improving product quality, as well as for optimising production processes. Therefore, the design and research of devices necessary for effective air classification of solid particles is relevant [1–3].

Different industrial plants use different types of air classifiers, depending on specific production requirements and particle requirements [4,5]. Cyclonic classifiers are often used in the food industry to separate crushed materials and powders according to their density and size. Vortex classifiers are widely used in the mining industry and can effectively separate materials of varying densities. The chemical industry often uses multistage classifiers to provide more precise separation of particles by size and shape.

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Due to their high efficiency, the most common air separators are centrifugal type devices, which use a swirling flow to separate multicomponent systems [6–8]. Since there are several ways to create a swirling flow, there are quite a lot of designs and their research. Moreover, assessing the effectiveness of such devices is quite difficult due to many factors that influence the separation process [9–11].

The authors [12–14] developed a separator with coaxial pipes to classify particles with a cut size of 30–40 μm. On the basis of experiments and numerical study, the parameters affecting the effectiveness and pressure drop of the device were evaluated.

Esmaeilpour et al. [15] presented the centrifugal air device for classification of cement. The effect of rotor rotation rate, pressure drop, and gar temperature on the effectiveness was assessed using CFD simulation and working condition analysis.

In the work [16], a new separator with square settlers was presented to classify fine particles. It was calculated that the separation effectiveness can reach almost 100% for particles larger than 5 μm. Huang et al. [17] presented a centrifugal air separator with special toothed rotating blades. They studied the influence of different types of tooth structure on the pressure field and classification effectiveness. Zinurov et al. [18] investigated the pressure drop and effectiveness of a rectangular separator in which the separation elements had different shapes. Further, in the works of Salakhova et al. [19,20], it was proven that the proposed separator with arc shape of the separation elements can be used as the substitution of the cyclone to separate particles in fluidized bed reactors.

2 Device description

This work proposes a centrifugal multivortex classifier (CMVC) designed for the classification of solid particles, as presented in Fig. 1. Structurally, the device consists of two coaxially located pipes 1 and 2, an outlet branch pipe 5, and a perforated plate 4. The bottom plane of the inner pipe is located at a distance of 69 mm from the bottom 6. Rectangular openings 3 have different entrance angle, a height of 60 mm, and are located at a distance of 93 mm from the top plane of the CMVC. The plate with holes 4 is located at a distance of 85 mm from the top plane of the CMVC and has a thickness of 5 mm. The outer diameter of the inner pipe 1 is 66 mm, and its wall thickness is 3 mm. The inner diameter of the outer pipe 2 is 90 mm, and the wall thickness is 2.5 mm. Outlet branch pipe 5 has an internal diameter of 60 mm, the thickness of its walls is 2.5 mm, and its axis is located at a distance of 49 mm from the top plane of the CMVC. The cross-sectional area of the space between pipes 1 and 2 is 0.0029 m^2. The height of the device is 239 mm.

The mechanism of the particle classification process in CMVC is as follows. The gas containing solid dust particles of various sizes enters inner pipe 1. Passing through rectangular openings 3, the gas flow forms vortices in the interpipe space. Due to the structural arrangement of the holes 3 relative to each other and the geometric dimensions of the inner and outer pipes, a stable multivortex system occurs. In other words, many vortices rotate simultaneously in the interpipe space, the number of which is twice the number of rectangular openings 3. The gas-solid flow after passing through each opening is divided into two jets, each of which forms a separated vortex. During their rotation, the vortices do not intersect, which maintains their integrity along the height of the interpipe space. The formed vortices have a high centrifugal force, which makes it possible to separate particles of the required size, which are subsequently discharged into the bottom of the CMVC. The remaining particles leave the device with the exhaust gas flow.

For example, if it is necessary to classify a silica gel with a cut size of 40 μm, particles larger than 40 μm will be separated by the CMVC and directed back for re-grinding, while particles less than 40 μm will leave the device through outlet pipe 5. The cut size depends on the centrifugal force, which can be varied by changing the diameter of the vortices by increasing or decreasing the size of the pipes, and on the height of the separation zone, characterised by the height of the annular space from the angle of rectangular openings 3 to the perforated plate 4. To support the structure of the vortices along the height of the annular space, plate 4 is installed in the CMVC, in which the axis of each hole coincides with the calculated centre of each vortex. After the particle classification process, the gas with the particles of the given cut size leaves the CMVC through the outlet pipe 5. To prevent clogging of the inner pipe 1 with large particles, a hole was made in its lower part.

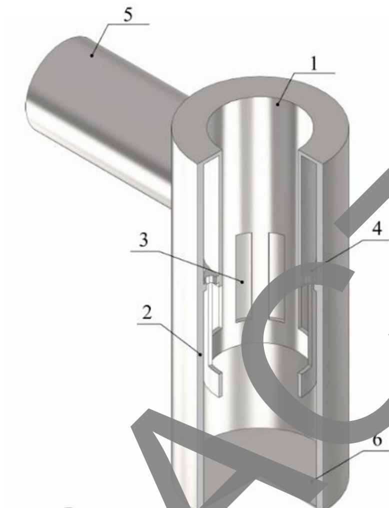

Fig. 1. CMVC**:** (1) inner pipe; (2) outer pipe; (3) rectangular openings; (4) plate with holes; (5) outlet branch pipe; (6) bottom.

To improve the effectiveness of the CMVC, it is necessary to establish the influence of most geometric dimensions of its structural elements. The purpose of this work is to study the influence of the entrance angle of rectangular openings on the effectiveness of the CMVC.

3 Numerical method

Numerical simulation of gas-dynamic processes that occurred in the CMVC during its operation was performed using the Ansys Fluent programme. For modelling, four 3D models of CMVC were created, in which the entrance angle of rectangular openings α was changed from 0.6 to 0.9 with a step of 0.1. Changing the entrance angle led to a change in the diameter and number of holes in plate 4. The diameter of the holes at α equal to 0.6, 0.7, 0.8, and 0.9 was 2.4 mm, 4.8 mm, 5.6 mm and 7.2 mm, respectively, and the number of holes was 34, 28, 26, and 22, respectively. During modelling, air was chosen as gas and silica gel with a density of 1075 kg/m³ was chosen as particle material. The speed at the inlet to device *W* was set to 8 m/s, 12 m/s, and 16 m/s. The particle size ranged from 5 to 100 μm with a 5 μm step. At bottom 6, the "Trap" condition was set, according to which all particles that reached a given plane stuck to it.

When modelling, the Navier-Stokes equation was used, which was supplemented by the continuity equation to describe the movement and distribution of the gas phase in the CMVC. These equations allow fluid dynamics to be accurately modeled, taking into account viscosity and flow speed. One of the key assumptions in this study was that the discrete phase does not have a significant effect on the continuous phase. This means that the interaction of particles with a gas does not change its parameters, such as density and speed. In addition, the particles were considered to be spherical. Such assumptions ensure the reliability of the results obtained under the given conditions.

The effectiveness of CMVC was evaluated as the ratio of the number of particles entering and leaving the device:

$$E = 1 - \frac{n_f}{n_i}, \quad (1)$$

where n_f is the final number of particles at the outlet of the CMVC; n_i is the initial number of particles at the inlet of the CMVC.

The pressure loss of the CMVC can be calculated using the following equation:

$$\Delta p = p_{in} - p_{out}. \quad (2)$$

where p_{in} is the static pressure at the inlet of the inner pipe of the CMVC, Pa; p_{out} is the static pressure at the outlet of the CMVC branch pipe, Pa.

4 Results and discussion

During the mathematical modelling of four classifier designs with different entrance angles of rectangular openings, the dependences of particle classification effectiveness on their size at different values of the gas speed at the inlet to the CMVC (Fig.2–4), the pressure loss in the CMVC on the gas speed at the inlet was obtained. From the results, it is clear that the effectiveness of the CMVC practically does not change when the opening entrance angle α of the holes is varied. It was also found that the greatest effectiveness of the CMVC is achieved at an inlet gas speed of 12 m/s. It was found that at a low inlet speed, a jump in particle classification effectiveness can be clearly observed in two stages (Fig. 2).

The greatest effectiveness in the classification of particles larger than 40 μm was shown by a design with an entrance angle of rectangular openings α = 0.8, which averaged 64.5%. The lowest effectiveness in the classification of particles larger than 40 μm was shown by a design with α = 0.7, which averaged 60.7%.

The maximum effectiveness (E = 69.7%) of the classification particles of larger than 40 μm in size was recorded at a gas flow speed at the inlet to the CMVC W = 16 m/s with α = 0.8. The minimum effectiveness (E = 57.3%) of classification particles larger than 40 μm was observed at a gas flow speed at the inlet to the CMVC W = 8 m/s with α = 0.7.

The pressure losses in the CMVC at gas speeds of 8–16 m/s are in the intervals of 2133–8463 Pa, 1907–7550 Pa, 1205–4786 Pa, and 671–2604 Pa at α values equal to 0.6, 0.7, 0.8, and 0.9, respectively. These values are due to the fact that when the entrance angle of rectangular openings decreases, the pressure drop to the gas flow increases, since the size of the flow area of the hole decreases.

When the gas flow speed at the inlet W = 8 m/s, changing the entrance angle of rectangular openings did not lead to a significant change in the effectiveness of particle classification. At this speed, there is a sharp increase in particle classification effectiveness in two stages: from 55 to 65 μm and from 75 to 90 μm (Fig. 2).

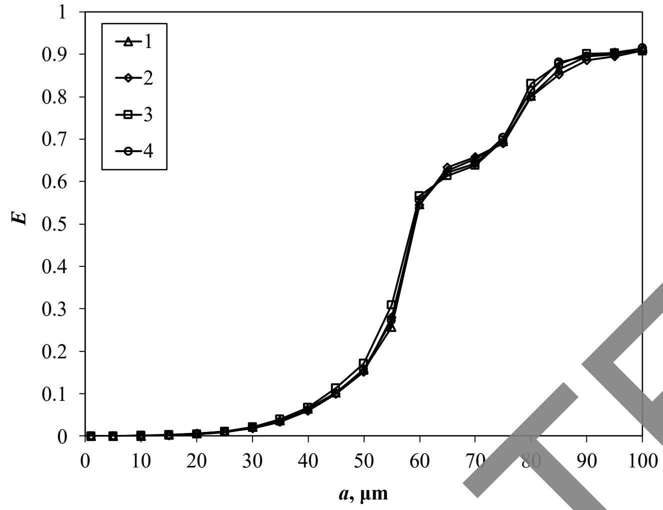

Fig. 2. Effectiveness (*E)* against particle size (*a*) at different entrance angles of rectangular openings: (1) α = 0.6; (2) α = 0.7; (3) α = 0.8; (4) α = 0.9. The inlet gas flow speed *W* = 8 m/s.

At the gas flow speed at the inlet W = 12 m/s, the change in the entrance angle of rectangular openings also leads to a significant difference in the effectiveness of particle classification. However, at a given speed, the *E* value changes more smoothly without sharp jumps, which may indicate more stable gas-dynamic conditions inside the CMVC (Fig. 3).

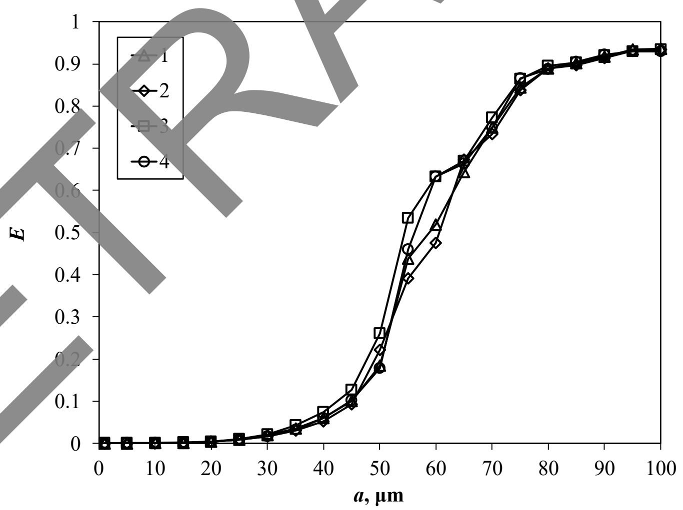

Fig. 3. Effectiveness (*E)* against particle size (*a*) at different entrance angles of rectangular openings: (1) α = 0.6; (2) α = 0.7; (3) α = 0.8; (4) α = 0.9. The inlet gas flow speed *W* = 12 m/s.

At a speed of *W* = 16 m/s, the effectiveness of particle classification increases significantly, indicating more favourable conditions for centrifugal separation of particles from the gas. The design with an entrance angle α = 0.8 demonstrates the best results, which may be due to the optimal relationship between the size of the holes and the stability of the vortices formed in the CMVC (Fig. 4).

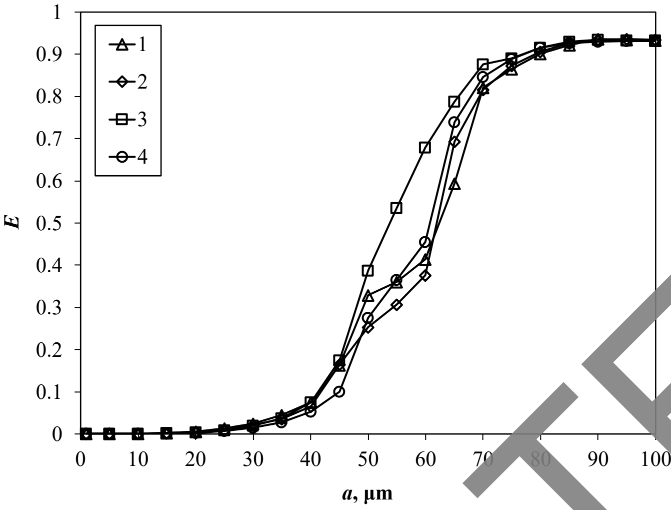

Fig. 4. Effectiveness (*E)* against particle size (*a*) at different entrance angles of rectangular openings: (1) α = 0.6; (2) α = 0.7; (3) α = 0.8; (4) α = 0.9. The inlet gas flow speed *W* = 16 m/s.

The pressure loss increases as the entrance angle of rectangular openings α decreases, as shown in Fig. 5. This trend is saved by increasing the gas speed at the CMVC inlet from 8 to 16 m/s.

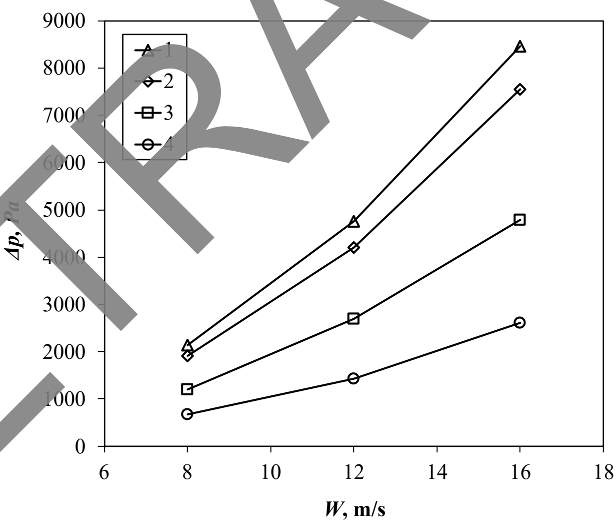

Fig. 5. Pressure loss (*Δp)* against inlet gas speed (*W)* at different entrance angles of rectangular openings: (1) α = 0.6; (2) α = 0.7; (3) α = 0.8; (4) α = 0.9.

5 Conclusion

The simulation results can be summarised as follows:

• The design of the CMVC should be selected with the maximum angle of rectangular openings, as it provides the lowest pressure loss;

• Changing the entrance angle of rectangular openings of the CMVC has no significant effect on the effectiveness of particle classification;

• As speed increases, the effectiveness of classification increases, since the vortex structure in the interpipe space becomes more stable and intense.

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