Numerical study of particles removal from dusty gas in separation device with straight arc-shaped elements

Elmira Salakhova[1*], *Vadim* Zinurov[2], *Vitaly* Kharkov[1], *Azalia* Abdullina[2] and *The Vu* Pham[3]

[1]Kazan National Research Technological University, 420015, Karl Marx str., 68, Kazan, Russia
[2]Kazan State Power Engineering University, 420066, Krasnoselskaya str., 51, Kazan, Russia
[3]Hanoi University of Industry, Cau Dien Street, Bac Tu Liem District, 298, Hanoi, Vietnam

Abstract. The paper presents an original design of the separator with straight rows of arc-shaped elements, which allows efficient separation of solid particles without significant abrasive wear of the device's surfaces. A three-dimensional model of the device is developed, and the principle of its operation is described. In this paper, a numerical study of the capture of solid particles from a gas flow in the separation device is performed. It is found that at a relatively low inlet gas velocity (1 m/s), the separation efficiency of particles with a diameter of 20 to 100 μm is on average 78.9%. An increase in the inlet velocity of the dusty gas flow results in a decrease in the efficiency of the device for particles ranging in size from 25 to 80 μm. The pressure drop of the separator at a velocity of 1 m/s ranges from 45.5 to 95.4 Pa, and at a gas velocity of 4 and 7 m/s – from 740.8 to 4652.1 Pa. An increase in the number of straight arc-shaped elements from 4 to 12 and an increase in particle density from 3400 to 10000 kg/m^3 leads to improved separation efficiency.

1 Introduction

In industrial conditions, abrasive wear of the surface of design elements of technological equipment is a serious problem. Solid particles dispersed in the gas create attrition, which, over time, leads to the inevitable wear of the material in the contact area and the consequent loss of the operational properties of the equipment [1,2]. Dispersion systems containing particulate matter are the most susceptible to abrasion, such as air separators used for gas-solid separation, powder classification, etc.

Many works are devoted to air separation, and several air devices of different designs have been developed. However, while significant results have been achieved in many aspects of the process, there are several important issues to consider in relation to efficiency evaluation and the flow dynamics in the air separation process. The study is devoted to the evaluation of technological parameters for the separation efficiency of fine solid particles from the gas system in a rectangular separator [3]. The paper presents a new mathematical

* Corresponding author: vadd_93@mail.ru

model for the separation of a solid-gas flow in a z-shaped inertial separator [4]. The authors developed an original design of a classifier with coaxially arranged pipes, carried out a numerical study of the vortex flow patterns inside the device [5] and the pressure drop [6]. The most common industrial air separators are cyclones. Cyclone separators are often prone to holes in the body when separating abrasive particles. In [7], a simulation of the local surface erosion wear and flow dynamics was performed at the different thicknesses of the wall erosion inside the Stairmand cyclone. The authors of [8] developed a model that combines both separation and abrasive attrition processes to calculate a cyclone loss factor in fluidized bed systems.

To solve this problem, a new device with arc-shaped elements (Figure 1) has been developed for separating the dusty gas flow [9]. The operating principle is as follows. The dusty gas enters the device through inlet 1, after which it encounters a number of rows of arc-shaped elements 2 arranged in chess order. When the gas flows around these elements, its direction constantly changes from side to side, forming a wavelike flow pattern [10]. But, since a rotation radius is rather small, the resulting centrifugal forces acting on the particles are significantly greater than those in cyclonic separators [11]. Thus, due to the action of gravitational, inertial, and centrifugal forces, solid particles of different dispersity are separated from the gas flow using the separation device. The particles bounce off the walls of the arc-shaped elements and gradually settle in bunker 4. The largest particles larger than 60–80 μm are separated from the dusty gas mainly due to gravitational and inertial forces, that is, under the action of gravity and in direct contact with arc-shaped elements. Centrifugal forces are more important to separate medium and small particles from the gas flow. The gas is discharged from the outlet of the separation device 5.

The distance between adjacent rows of arc-shaped elements is determined by the formula:

$$l = \sqrt{0.75} d_{\mathrm{ml}}, \tag{1}$$

where d_{ml} is the diameter of the centerline of the arc-shaped element, m.

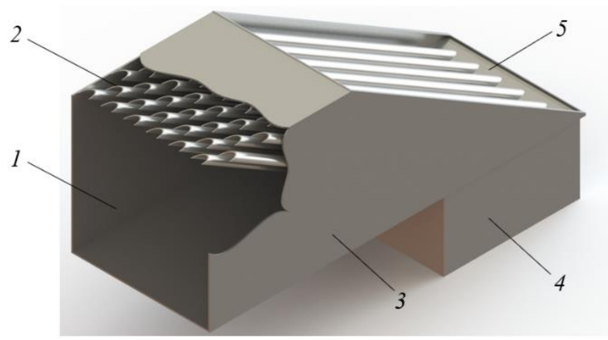

Fig. 1. 3D model of the separation device with arc-shaped elements: 1 – dusty gas inlet; 2 – arc-shaped element rows; 3 – body; 4 – bunker; 5 – gas outlet.

One of the main advantages of the developed separation device is the low wear capability of the walls of arc-shaped elements for abrasive particle separation compared with the cyclones. In particular, the particles, when ejected from the flow, move in different directions and come into contact with arc-shaped elements throughout their area. In this case, the contact force of the particle with the element wall is significantly reduced compared to a straight-line contact.

The aim of this work is to perform a numerical study of the separation process of particles from the dusty gas flow in the developed device with straight arc-shaped elements. Such elements are easier and more reliable to install, allowing a reduction of the height of the separator cross-section, which increases the efficiency of particle separation from the gas.

In order to avoid slacking and unnecessary vibration of arc-shaped elements 1 during the operation, it is proposed to fix them in the lower part of the device by means of a screen 2 that is partially immersed in the receiving bunker. The separation screen consists of longitudinal 3 and transverse plates 4 in relation to the direction of the gas flow motion. As can be seen in Figure 2, the arc-shaped elements 1 are inserted into the slots of longitudinal plates, and the transverse plates fix arc-shaped elements from the rear side.

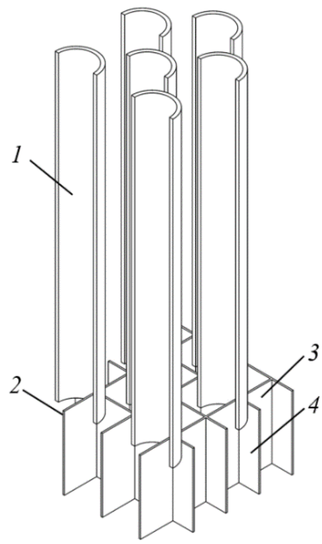

Fig. 2. Diagram of the main unit of the separation device: 1 – arc-shaped elements; 2 – screen; 3 – longitudinal plates; 4 – transverse plates.

2 Methodology

In the numerical simulation, the following geometry of straight arc-shaped elements is set: diameter of the centerline of element d_{ml} = 52.5 mm, thickness of the 4.5 mm, height of elements 250 mm, height of separation screen h of 100 mm, the depth of immersion of arc-shaped elements into the slots of longitudinal plates of 10 mm. The particle diameter changes from 10 to 170 μm, the rate of particles averages 5.728 g/s. The number of straight rows of arc-shaped elements N varies from 4 to 12 pcs, the inlet gas velocity W changes from 1 to 7 m/s, and the particle density in the dusty flow ρ_a changes from 3400 to 10000 kg/m^3. Given that the rows of arc-shaped elements are naturally arranged relative to the central plane, the symmetry condition is used to simplify numerical calculations. The bouncing condition is set near the walls for the particles. The no-slip condition of the particles is set at the bottom of the bunker. The simulation was performed using the k-ω SST turbulence model. The grid is about 2 million elements.

The efficiency of particle separation from the dusty gas flow E is estimated by the formula:

$$E = 1 - \frac{n}{n_0}, \tag{2}$$

where n is the number of particles in the gas flow, which remained in it after separation in the developed device; n_0 is the initial number of particles in the gas flow.

The pressure drop of the separation device with straight rows of arc-shaped elements Δp (Pa) can be determined by the equation:

$$\Delta p = p_{\text{in}} - p_{\text{out}}, \tag{3}$$

where p_{in} is the pressure at the device inlet, Pa; p_{out} is the pressure at the device outlet, Pa.

3 Results and Discussion

The results show a decrease in the efficiency of the separation device with an increase in the inlet gas velocity for certain fractions of particles (Figure 3). This is due to the fact that the particles are carried away by the gas flow without having time to settle into the receiving bunker. In particular, particles larger than 20 µm are captured from the dusty gas flow with an efficiency higher than 60.5% at the inlet gas velocity W of 1 m/s. The efficiency E for particles from 20 to 100 µm at $W = 1$ m/s averages 78.9%. At a particle size of more than 120 µm, the efficiency is close to 100%. At $W = 4$ m/s, the efficiency of the separation device for different particle fractions: less than 20 µm, from 20 to 80 µm, more than 80 µm is 74.3, 67.7, and 64.1%, respectively. When the gas velocity at the inlet to the separation device is increased to 7 m/s, the efficiency for particle fractions smaller than 20 µm, from 20 to 80 µm and more than 80 µm is on average 74.1, 60.7, and 46.5%, respectively.

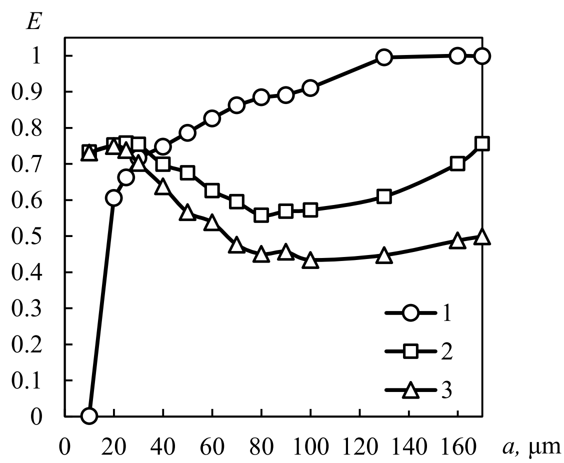

Fig. 3. Efficiency of the straight arc-shaped separation device E against particle diameter a at different inlet gas inlet velocities W, m/s: 1 – 1; 2 – 4; 3 – 7. Basic parameters: $h = 250$ mm, $N = 4$, $\rho_a = 3400$ kg/m^3.

Additionally, the efficiency of the device is calculated by increasing the number of straight rows of arc-shaped elements (Figure 4). It is shown that at the inlet velocity of the dusty gas flow of 1 m/s, the efficiency E when the number of rows of arc-shaped elements changes from 4 to 12 pcs for particles from 20 to 100 µm is on average 85.2, 85.3, 91.5, 91.8, and 93.1%, respectively. At a particle size of less than 20 µm, the separation efficiency is less than 40% for any number of rows N. At a particle size of more than 100 µm, the efficiency is close to 100%.

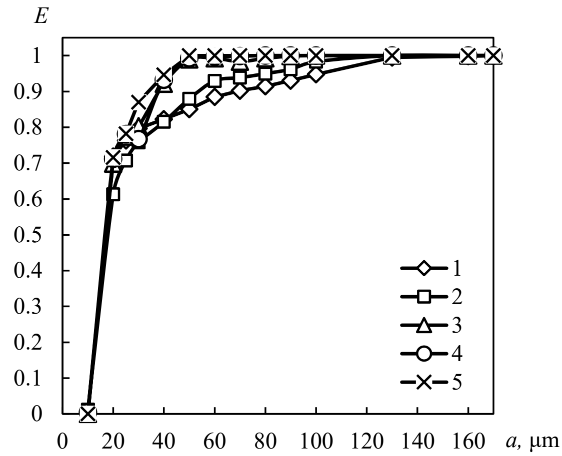

Fig. 4. Efficiency of straight arc-shaped separation device E against particle diameter a at different number of rows of arc-shaped elements N: 1 – 4; 2 – 6; 3 – 8; 4 – 10; 5 – 12. Basic parameters: h = 250 mm, W = 1 m/s, ρ_a = 3400 kg/m^3.

Figure 5 indicates the efficiency of the device when changing the density of particles at the number of rows N = 12 pcs, which corresponds to the maximum efficiency according to Figure 4. It is found that at W = 1 m / s, the efficiency of the separation device at a particle density of 3400, 7000, and 10000 kg/m^3 and a particle dispersion of less than 20 μm is 0.2, 37.4, and 71.7%, respectively. For particle densities under study, the separator efficiency averages 76.8% (particle size from 20 to 40 μm), 89.8% (particle size from 20 to 30 μm), and 93.6%, respectively. At greater particle size, the efficiency of the separation device is close to 100%.

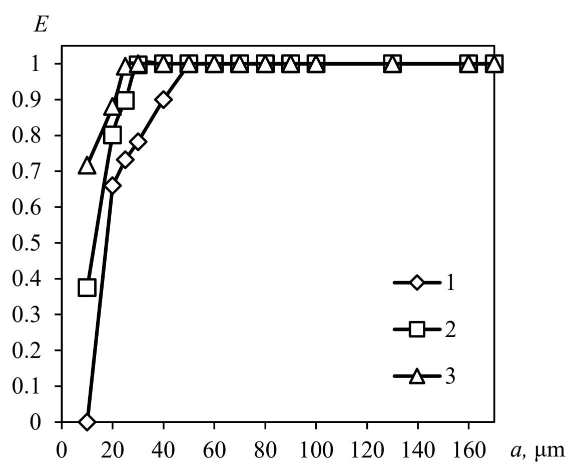

Fig. 5. Efficiency of straight arc-shaped separation device E against at different density ρ_a, kg/m^3: 1 – 3400; 2 – 7000; 3 – 10000. Basic parameters: h = 250 mm, W = 1 m/s, N = 12.

As presented in Figure 6, the pressure drop of the separation device grows with an increase in the inlet dusty gas velocity and an increase in the number of arc-shaped element rows is increased. At W of 1, 4, and 7 m/s, the pressure loss in the separation device with the number of rows of arc-shaped elements of 4–12 pcs changes from 45.5 to 95.4, 740.8 to 1514.4, and 2244.8 to 4652.1 Pa, respectively.

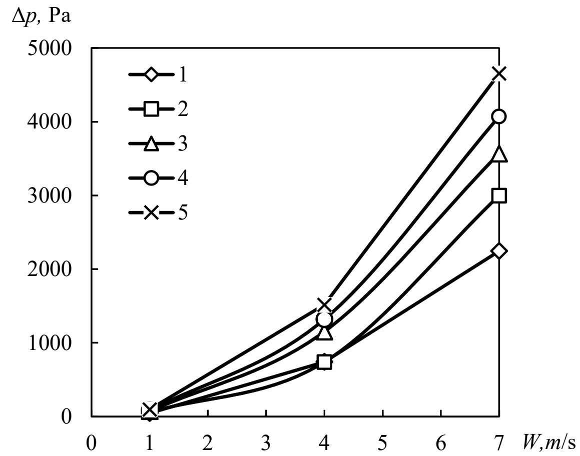

Fig. 6. Pressure drop of separation device Δp against gas inlet velocity W at different number of rows of arc-shaped elements N: 1 – 4; 2 – 6; 3 – 8; 4 – 10; 5 – 12.

Thus, using the separation device with straight arc-shaped elements is therefore feasible and promising under strict pressure loss control and high separation efficiency for particles larger than 20 μm. As can be seen, at the inlet gas velocity of less than 1 m/s, the pressure drop of the separation device is less than 100 Pa when the efficiency is more than 60.5%. Taking into account the low pressure losses of the developed device, the use of several series-connected devices allows capturing particles larger than 20 μm with an efficiency close to 100%.

4 Conclusion

On the basis of the conducted numerical study, it is found that the wavelike flow pattern of the dusty gas in the developed separation device makes it possible to achieve high efficiency of particle capture, low pressure loss, and reduce abrasive wear of the surfaces of arc-shaped elements. In particular, the following conclusions can be drawn:

• at the relatively low gas flow velocity of 1 m/s, the efficiency of the separation device for particles from 20 to 100 μm is on average 78.9% (particle density – 3400 kg/m^3, number of rows – 4);

• an increase in the inlet velocity of the dusty gas flow reduces the separation efficiency of the particles ranging from 25 to 80 μm, because the particles bounce off the walls of arc-shaped elements and return to the main flow;

•creates a higher centrifugal field by increasing the inlet gas velocity, and the efficiency increases by more than 73.1% for particles less than 20 μm;

• the pressure drop of the separator at a velocity of 1 m/s is between 45.5 and 95.4 Pa with the number of rows of arc-shaped elements from 4 to 12 pcs. At a gas velocity of 4 and 7 m/s, the pressure drop ranges from 740.8 to 4652.1 Pa;

• changing the number of straight arc-shaped element rows from 4 to 12 and the particle density from 3400 to 10000 kg/m^3 results in increased efficiency of the separation device.

In the future, it is planned to study the influence of the height of arc-shaped elements and the linear dimensions of the separation screen on the flow pattern of the dusty gas, efficiency, and pressure drop of the separation device.

Acknowledgements

The reported study was funded by the scholarship of the President of Russia (№ SP-3577.2022.1).

References

1. G. Tzordanidi, O. Pyatnitzkaya, E. Fisunova, T. Lavrenova, and O. Baryshnikova, E3S Web Conf. **210**, 08005 (2020)
2. B. A. Kotzur, R. J. Berry, S. Zigan, P. García-Triñanes, and M. S. A. Bradley, Powder Technol. **334**, 76 (2018)
3. V. Zinurov, A. Dmitriev, and V. Kharkov, in *2020 Int. Conf. Inf. Technol. Nanotechnol.* (IEEE, 2020), pp. 1–4
4. A. L. Tukmakov, V. V Khar'kov, and A. A. Akhunov, J. Eng. Phys. Thermophys. **95**, 902 (2022)
5. V. Zinurov, V. Kharkov, E. Pankratov, and A. Dmitriev, Int. J. Eng. Technol. Innov. **12**, 336 (2022)
6. V. E. Zinurov, V. V. Kharkov, and I. N. Madyshev, Min. Informational Anal. Bull. 173 (2022)
7. L. Zhang, J. Fan, P. Zhang, F. Gao, G. Chen, and J. Li, Powder Technol. **413**, 118007 (2023)
8. B. Freireich, M. Kodam, and K. Jacob, Powder Technol. **273**, 210 (2015)
9. E. I. Salakhova, V. E. Zinurov, A. V. Dmitriev, and I. I. Salakhov, Processes **11**, 156 (2023)
10. V. E. Zinurov, V. V Kharkov, E. I. Salakhova, M. R. Vakhitov, and M. G. Kuznetsov, IOP Conf. Ser. Earth Environ. Sci. **981**, 042024 (2022)
11. E. I. Salakhova, A. V. Dmitriev, V. E. Zinurov, I. R. Nabiullin, and I. I. Salakhov, Katal. v Promyshlennosti **22**, 57 (2022)