Study of eco-friendly static gas-solid centrifugal separator

Mariia Prets[1*], *Aidar* Ziangirov[1], *Pham* The Vu[2], and *Maxim* Kuznetsov[3]

[1] Kazan State Power Engineering University, 420066, Krasnoselskaya street 51, Kazan, Russia
[2] Hanoi University of Industry, Cau Dien street, Bac Tu Liem District 298, Hanoi, Vietnam
[3] Kazan State Agrarian University, 420015, Karl Marx street 65, Kazan, Russia

Abstract. Gas-solid separation is a common process in many industries, including transport and power engineering. A static centrifugal multivortex device has been developed for effective separating fine particles from gas streams. The work aims to numerically study the efficiency and pressure drop of the separator. It was found that a choice of the turbulence model does not affect the pressure drop. The efficiency of the static centrifugal separator is 64.3% at the input gas velocity of 7 m/s. The sloped blades located above the apertures made in the internal pipe results in the improvement of separation efficiency. Moreover, changing the slope of the blades does not affect the efficiency of the separator. The hydraulic resistance coefficient of the developed device is on average 20.6, with a Reynolds number from 11400 to 38000. The low pressure drop provides reduced energy cost, which promotes decarbonization efforts.

1 Introduction

Existing gas cleaning systems in the energy, transport, chemical and metallurgical industries are designed to provide proper quality of exhaust air. Effective separation system is characterized by lower energy costs, so the separator not only contributes to cleaner industrial emissions but also meets global decarbonization objectives, marking a significant step towards more sustainable development. The separation principle of different gas-solid devices is based on a certain physical mechanism. So, the following methods are used to separate suspended particles from the gas flow: deposition in a gravitational field, deposition under the influence of inertia [1], deposition in a centrifugal field [2,3], filtration [4], precipitation in an electric field [5], wet gas cleaning [6], etc. Among them, the most promising are devices that operate on the basis of the centrifugal forces [7–9]. Therefore, the expansion of the field of application and increasing the separation efficiency of centrifugal devices (centrifugal separators) is one of the actual problems of implementing energy and resource-saving technologies and protecting the environment from harmful industrial gas emissions.

* Corresponding author: precmari@gmail.com

One of the principles of centrifugal force formation is a using swirl vanes and an axial inlet or specific geometry of the separator. Pisarev and Hoffmann [10] performed numerical simulations of a gas-solid swirl pipe device to determine the detailed motion of a particle in the region of the «end of the vortex» and to assess the effect of this phenomenon on separation efficiency. Behrang et al. [11] developed a centrifugal dust separator with eight helical channels to clean gas-solid flow. Based on validated CFD results, they found that an increase in the gas input velocity results in a gradual growth of separation efficiency but significantly influences the pressure drop. The separator efficiency of 100% is achieved for particles larger than 13 μm at velocities of 8–13 m/s. Mohammadkhani et al. [12] presented simulation results of separation efficiency and pressure drop for a novel swirl pipe separator. They found that total separation efficiency of up to 88% could be obtained among various air inlet velocities by increasing the angle and length of the vane. The authors [13] performed the CFD-DEM numerical study to estimate the flow field and the separation performance of the annular pipe with a helical swirl generator. They concluded that the presence of the swirler improved both the turbulent disturbance and the gas vorticity. Another way to create a centrifugal force is to have a specific geometry of the separation zone. For example, Dmitriev et al. [14–17] developed and studied the efficiency of a rectangular separator in which a plurality of centrifugal force points occurs between different elements, affecting the flow pattern. Zinurov et al. [18–22] developed a multivortex device with coaxially arranged pipes. They established that this geometry provides numerous vortices with high centrifugal forces (compared with cyclones), which contributes to the separation of fine particles.

We propose a static centrifugal device with coaxial pipes, developed to separate fine particles from dust-laden gas of industrial enterprises. The purpose of the work is a numerical study of the separation of fine particles from dust-laden gas in a static centrifugal multivortex separator with coaxial pipes. By requiring lower energy costs, the separator not only contributes to cleaner industrial emissions but also aligns with global decarbonization objectives, marking a significant step towards more sustainable industrial practices.

2 Methods

The main parts of the proposed device are coaxially arranged pipes, sloped blades, a baffle plate, and a hopper, as shown in Figure 1. Cleaning of dust-laden gas from fine particles in the separator occurs because of the action of inertial and centrifugal forces. The gas stream enters the device through an upper opening made in the internal pipe 2. Then it descends into the lower part of pipe 2, in which apertures 5 are made with a certain circumferential pitch. Due to the uniform flow of the dust-laden gas over the section of the internal pipe 2, it is distributed in equal volume fractions along the apertures 5. Typically, when the dust-laden gas is rotated 90º sharply in aperture 5, most of the medium and coarse particles dispersed therein are knocked out of the flow by inertial forces, and they gradually settle to the bottom 11. Surely, over time, the internal pipe 2 is filled with bulk material. To prevent the plugging of pipe 2 by particles, the bottom 11 has a plurality of circular holes 12, through which the particles are discharged into the hopper 6. The gas stream passes through the apertures 5 from the internal pipe 2 to the annulus of the separator. Each jet formed from each aperture forms two vortices in the annulus.

Thus, a plurality of vortices are created in the annular space of the device. Also, the vortices do not intersect with each other during their rotation. So, a stable multivortex system, consisting of small-diameter vortices with high centrifugal forces provides effective separation of fine particles. As a result, they fly from the gas towards the sloped blades 8, when reflected from which, through the apertures, they are thrown into the space between the first external pipe 1 and the blades 8, where they gradually settle on the separator bottom 11. The presence of the sloped blades 8 increases the separation efficiency for fine particles.

Otherwise, fine particles are reflected from the cylindrical wall back into the structured gas stream in the absence of blades 8. In turn, the multivortex gas system moves along the annulus of the separator from bottom to top. When the gas passes through the holes 4 which are made in the baffle plate 3, the cleaned gas exits the device through the outlet 10. Holes 4 coincide with the location of vortices in the annulus, which allows additional support of the vortex system.

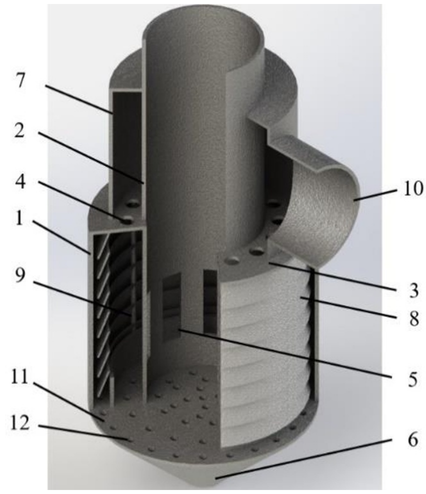

Fig. 1. Static centrifugal multi-vortex separator: (1) external pipe No 1; (2) internal pipe; (3) baffle plate; (4), and (12) holes; (5) apertures; (6) conical hopper; (7) external pipe No 2; (8) sloped blades; (9) studs; (10) outlet; (11) bottom.

The numerical study was performed using Ansys Fluent in a three-dimensional statement (Figure 1). The sizes of the model are as follows: the inlet opening diameter – 57 mm, the diameters of the external pipe No 2 and the external pipe – 57 and 120 mm, respectively, the diameter of the holes 4 of the plates 3 – 8 mm, the height of the apertures 5 – 40 mm, the diameter of the holes 12 of the separator bottom 11 – 4 mm, the height of the separator – 250 mm. During a numerical study, the design characteristics of the separator were changed: the number of sloped blades (k) – from 0 to 8 pcs and their angle of slope (α) – from 20 to 60°. The boundary conditions are as follows: the inlet velocity of the dust-laden gas (W) varied from 1 to 15 m/s, a pressure at the outlet of the device was 0 Pa, a no-slip condition was set at the bottom, and a particle reflection condition – on all other walls of the device. Fine particles have a diameter (a) of 1–15 μm, density (ρ_a) of 1075 kg/m^3 and an initial velocity of 0 m/s. The influence of particles on the flow was not taken into account, since their content in the flow is less than 5–10%. As the gas stream was set to air with a reference temperature of 20 °C, a density (ρ) of 1.2 kg/m^3 and a kinematic viscosity (ν) of $15.06\cdot10^{-6}$ m^2/s.

The efficiency of a static centrifugal multivortex separator was estimated by the equation:

$$E = 1 - \frac{n_k}{n}, \quad (1)$$

where n_k is the number of particles that have touched the bottom of the separator, pcs.; n is the number of particles entering the device, pcs.

The hydraulic resistance coefficient of the separator was calculated using the expression:

$$\xi = \frac{2\Delta p}{\rho W^2}, \quad (2)$$

where Δp – pressure losses in the separator, Pa.

The Reynolds number was determined by the following equation:

$$\mathrm{Re} = \frac{Wd}{\nu}. \tag{3}$$

In numerical modeling, a grid independence analysis was performed. Based on the 3D separator model (Figure 1), the size of the elements was changed from 2.0 to 0.8 mm with additional thickening in narrow areas, for example, in apertures 5. The results of the pressure drop study on different grids are presented in Table 1. It was determined that 2 mm elements were sufficient for our problem, so the difference between the results obtained with the grids consisting of elements from 2.0 to 0.8 mm was less than 1%.

Table 3. Grid independence.

Size of grid elements, mm	**Gas velocity at the inlet to the static centrifugal separator *W*, m/s**	**Pressure drop Δ*p*, Pa**
2.0	3	106.5
	7	567.1
	10	1165.6
1.0	3	108.2
	7	574.2
	10	1171.2
0.8	3	107.1
	7	570.2
	10	1168.3

3 Results and discussion

Figure 2 shows that there is no much difference in pressure drop for all turbulence models under study, so any model can be used to study gas dynamics of the static centrifugal multivortex separator. Using the k-ω SST turbulence model for simulation, the following efficiency dependencies are obtained: on particle size (Figure 3), on design parameters (Figures 4 and 5), on gas input velocity, and the hydraulic resistance coefficient on Reynolds number (Figure 6). The pressure loss Δ*p* in the separator changes from 11.2 to 2613 Pa with a gas input velocity of 1 to 15 m/s. The analysis of dependencies showed that the efficiency of the separator at the best selected design parameters is 64.3%.

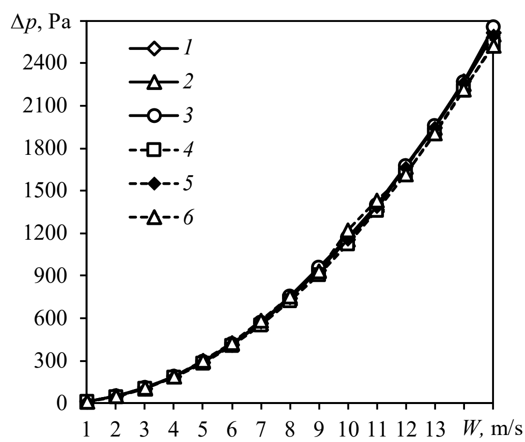

Fig. 2. Pressure drop vs. inlet gas velocity for various turbulence models: 1– Spalart–Allmaras; 2 – k-ε Standard; 3 – k-ω Standard; 4 – k-kl-ω; 5 – k-ω SST; 6 – RSM

As shown in Figure 3, the separator efficiency ranges from 0 to 74.8% for a particle size of 1 to 15 μm and a gas input velocity of 3–10 m/s. Zero values of E correspond to different fractions depending on the gas input velocity. At $W = 3$, 7, and 10 m/s this is associated with the particle size up to 7, 3, and 3 μm, respectively. The fractional efficiency of the separator for $a = 1$–15 μm is averaged 16.4, 38.3, and 39.3% at an inlet velocity of 3, 7, and 10 m/s, respectively. Thus, the use of a separator for fine particles ($a < 3$ μm) is not advisable, since centrifugal forces are insufficient to knock particles out of the gas flow. Furthermore, from Figures 2 and 3 it is clear that the gas flow input velocity, close to 7 m/s, is the best in terms of high efficiency and minimum pressure loss ($\Delta p = 562.3$ Pa at $W = 7$ m/s).

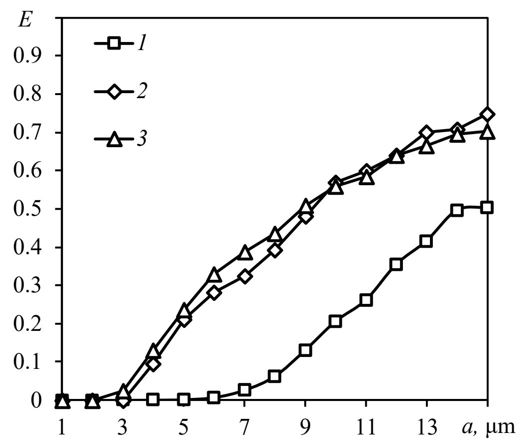

Fig. 3. Separation efficiency vs. particle size at different inlet gas velocity W, m/s: (1) 3; (2) 7; (3) 10 ($k = 8$)

With the number of sloped blades $k = 1$–3, the efficiency of the separator, as a rule, increases, but when $k > 3$ it decreases. At an inlet gas velocity of 3, 7, and 10 m/s, the efficiency of the separator varies from 23.3 to 26.3%, from 49.1 to 54.5%, and from 60.1 to 62.9%, respectively ($0 \leq k \leq 3$). At $k = 8$, the value $E = 16.4$, 38.3, and 39.3% with $W = 3$, 7, and 10 m/s, respectively (Figure 4).

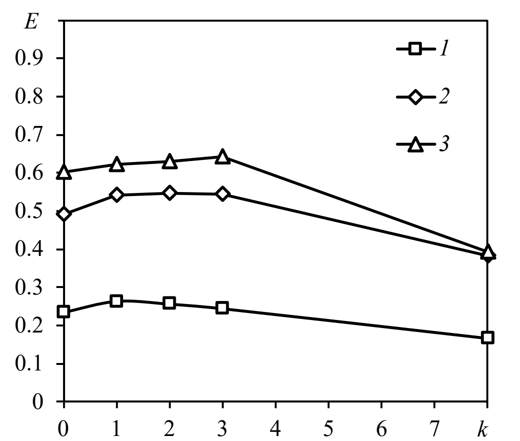

Fig. 4. Separation efficiency versus number of sloped blades k at different gas input velocity W, m/s: (1) 3; (2) 7; (3) 10

It is seen from Figure 5, that efficiency $E \neq f(\alpha^o)$ at any inlet gas flow velocity. Separator efficiency is 26.4, 55.4, and 63.2% at $W = 3$, 7, and 10 m/s. Note that the efficiency with an increase in velocity from 3 to 7 m/s varies by 2.10 times, and from 7 to 10 m/s, the value of E changes by 1.14 times. Thus, it is necessary to take into account the feasibility of increasing the velocity to a value equal to more than 7 m/s. The coefficient of hydraulic resistance of the static centrifugal separator is 20.7, 20.6, and 20.5 with the number of sloped blades 0, 1, and 8 pcs. ($11400 \leq Re \leq 38000$) (Figure 6).

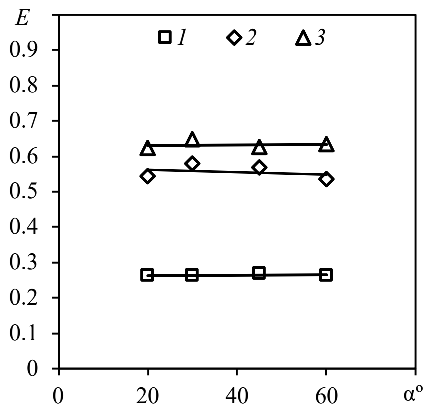

Fig. 5. Separation efficiency vs. angle of slope of the blades at different inlet gas velocity W, m/s: (1) 3; (2) 7; (3) 10

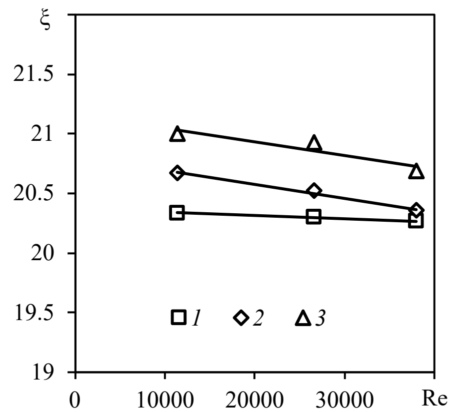

Fig. 6. Hydraulic resistance coefficient vs. Reynolds number for different numbers of sloped blades k, pcs.: (1) 0; (2) 1; (3) 8

Thus, the use of the static centrifugal multivortex separator with coaxial pipes for fine particles separation from dust-laden gas streams is an effective measure in the case of selecting the most efficient gas input velocity, which will, on the one hand, achieve high efficiency, and, on the other hand, minimize the energy costs of pumping the dust-laden gas through the proposed device.

Conclusion

The simulation results can be summarized as follows:

- The maximum separation efficiency of the static centrifugal separator is 64.3% with the best selected design parameters.
- The inlet velocity of the dust-laden gas of 7 m/s provides high efficiency and relatively low hydraulic resistance of the separator, resulting in low energy costs.
- The angle of slope of the blades does not affect the efficiency of the separator.
- The hydraulic resistance coefficient of the device is about 20.6 with the Reynolds number change from 11400 to 38000.

References

1. A. L. Tukmakov, V. V Khar'kov, and A. A. Akhunov, Journal of Engineering Physics and Thermophysics **95**, 902 (2022)
2. In *Coulson and Richardson's Chemical Engineering* (Elsevier, 2019), pp. 627–656
3. E. I. Salakhova, V. E. Zinurov, A. V. Dmitriev, and I. I. Salakhov, Processes **11**, 156 (2023)

4. X. Ji, J. Huang, L. Teng, S. Li, X. Li, W. Cai, Z. Chen, and Y. Lai, Green Energy & Environment **8**, 673 (2023)
5. Y. Mubula, M. Yu, D. Yang, B. Lin, Y. Guo, and T. Qiu, J Environ Chem Eng **11**, 111237 (2023)
6. Z. Jin, S. Hu, X. Zhu, G. Feng, and J. Sun, Advanced Powder Technology **33**, 103851 (2022)
7. E. I. Salakhova, A. V Dmitriev, V. E. Zinurov, I. R. Nabiullin, and I. I. Salakhov, Catal Ind **14**, 369 (2022)
8. V. E. Zinurov, R. Ya. Bikkulov, A. V. Dmitriev, and O. S. Dmitrieva, Chemical and Petroleum Engineering **58**, 550 (2022)
9. V. E. Zinurov, V. V Kharkov, I. N. Madyshev, O. S. Dmitrieva, and N. Z. Dubkova, J Phys Conf Ser **2388**, 012141 (2022)
10. G. I. Pisarev and A. C. Hoffmann, Powder Technol **222**, 101 (2012)
11. M. Behrang, M. Shirvani, and S. H. Hashemabadi, Chemical Engineering Research and Design **146**, 1 (2019)
12. A. Mohammadkhani, B. Ahmadi, and Q. Xiong, Advanced Powder Technology **33**, 103471 (2022)
13. Z. Wan, S. Yang, D. Tang, H. Yuan, J. Hu, and H. Wang, Powder Technol **419**, 118307 (2023)
14. A. V. Dmitriev, V. E. Zinurov, and O. S. Dmitrieva, IOP Conf Ser Mater Sci Eng **451**, 012211 (2018)
15. V. Zinurov, A. Dmitriev, and V. Kharkov, in *2020 International Conference on Information Technology and Nanotechnology (ITNT)* (IEEE, 2020), pp. 1–4
16. V. E. Zinurov, N. Z. Dubkova, O. S. Popkova, and O. S. Dmitrieva, J Phys Conf Ser **1745**, 012090 (2021)
17. 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)
18. V. Zinurov, V. Kharkov, E. Pankratov, and A. Dmitriev, International Journal of Engineering and Technology Innovation **12**, 336 (2022)
19. V. E. Zinurov, V. V. Kharkov, and I. N. Madyshev, Mining Informational and Analytical Bulletin 173 (2022)
20. V. E. Zinurov, A. V. Dmitriev, I. N. Madyshev, and O. S. Dmitrieva, Chemical and Petroleum Engineering **57**, 531 (2021)
21. V. E. Zinurov, A. V. Dmitriev, and O. S. Dmitrieva, Chemical and Petroleum Engineering **58**, 757 (2023)
22. E. Salakhova, V. Zinurov, A. Dmitriev, O. Dmitrieva and A. Abdullina, Ecology and Industry of Russia **28**, 12 (2024)