DOI 10.1007/s10556-023-01158-9

Chemical and Petroleum Engineering, Vol. 58, Nos. 9-10, January, 2023 (Russian Original Nos. 9-10, September–October, 2022)

INDUSTRIAL ECOLOGY

EFFECT OF THE DESIGN OF A MULTI-VORTEX CLASSIFIER–SEPARATOR ON THE SEPARATION EFFICIENCY OF POWDER BASED ON SILICA GEL

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UDC 66.074

This work proposes a design of a multi-vortex classifier–separator with coaxially arranged pipes for the fractionation of bulk materials based on silica gel with a boundary grain size equal to 30–40 microns. The article presents a three-dimensional model of the apparatus and its operation principle. The efficiency of a multi-vortex classifier–separator with coaxially arranged pipes at various design and technological parameters was determined. The *k–w* shear stress transport turbulence model was used in numerical simulations. The efficiency of one and three sequentially connected classifiers–separators was calculated. The use of an inner tube without a conical junction allows the fractionation of bulk materials based on silica gel with a near-mesh grain size equal to 30–40 microns. An engineering method for calculating a multi-vortex classifier–separator was obtained, which predicts the apparatus efficiency depending on the input velocity of the gas flow and the required size of the near-mesh grain.

Keywords: silica gel, adsorbent, classifier, efficiency, fractionation, loose powder, particle separation.

Silica gel (an amorphous form of silica with a porous structure) is widely used in the industry, for example, as a solid drying agent for cleaning and dehydrating various industrial gases and oils before transportation. The adsorption characteristics of silica gel depend on its surface area and the fractional composition of particles, so it is important to control its structure [1].

In the production of silica gel, after grinding, it is separated into several fractions (or a fraction with particles of certain sizes is separated). These industrial processes are performed in continuous grinding mills in combination with particle size classification equipment. After grinding, heterogeneous particles are separated in classifiers, where small particles are separated from large particles and large particles are returned to the mill for regrinding [2].

Different types of equipment are used to classify particles by size, depending on whether the powder is ground wet or dry [3] (due to the hydrophilicity of silica gel, "wet" classification methods are not applied).

Methods for separating loose media using vibrating sieves [4] are ineffective in the case of fine fractions (0.1–10 μm) in powder due to the resistance of the gaseous medium and adhesion. Accurate dry sieving results can be obtained with particle sizes greater than 40 μm. Despite the dielectric properties of silica gel, electrical classification methods are not used due to the high energy consumption and electrical safety requirements.

In many industries, for the dry separation of bulk materials, gravity and inertial aerodynamic separation units are used [5, 6]. Gravity classifiers based on a fluidized bed provide a stable separation of particles in the size range of 50–1000 microns. Centrifugal classifiers (cyclones) are effective for holding particles with a diameter

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Translated from Khimicheskoe i Neftegazovoe Mashinostroenie, Vol. 58, No. 9, pp. 23–27, September, 2022.

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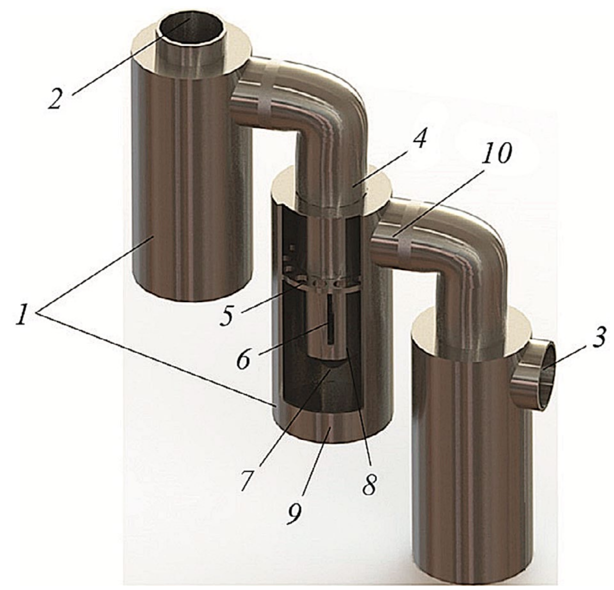

Fig. 1. 3D model of three series-connected classifier–separators with coaxial pipes: *1* — multi-vortex classifiers–separators; *2* — inlet pipe to the group of devices; *3* — outlet pipe from the group of devices; *4* — inlet part of the pipe to the apparatus 2; *5* — plate with round holes; *6* — rectangular slots; *7* — hole with a conical transition; *8* — inner pipe; *9* — outer pipe; *10* — outlet part of the pipe from the apparatus *2*.

of more than 10 μm [7]. However, due to the properties of silica gel particles (i.e., low selectivity, partial loss of the product during recycling, and additional energy costs), the use of cyclones for their classification is limited.

To improve the efficiency of grinding and separating powders in the industry, incorporated classifiers that can be installed directly after the mill (to minimize equipment and the duration of powder separation) must be developed, taking into account the effect on the classification efficiency of parameters, such as centrifugal force, aerodynamic drag force, particle concentration, and flow conditions [8].

For the classification of bulk materials based on silica gel with a near-mesh grain size of 30–40 μm, the authors of this work developed a multi-vortex classifier–separator of a simple design (Fig. 1) with coaxial pipes [9, 10], the manufacture of which is directly possible at enterprises, such as in a locksmiths or repair shops.

The design of the multi-vortex classifier–separator is based on two cylindrical pipes of different diameters *8*, *9* (Fig. 1), with one pipe placed inside the other and fixing the inner pipe at a certain immersion depth with a plate *5*. The annular space of the outer pipe *9* is limited above and below by partitions. To create a certain structure of the gas flow in the pipe *9*, rectangular slots *6* were made in the lower part of the wall of the pipe *8* at a certain height in the axisymmetric direction. To avoid clogging of the pipe *8* with large particles of silica gel, the open end hole of the pipe *8* was made with a conical transition *7*.

A previous study [11] revealed that a distinctive characteristic of the apparatus is low hydraulic resistance. In this regard, the use of several series-connected multi-vortex classifier–separators with coaxially arranged pipes is structurally possible to increase the selectivity of the separation of bulk materials into certain fractions.

The developed design of a multi-vortex classifier–separator was introduced at Salavat Catalyst Plant for the fractionation of bulk materials based on silica gel with a near-mesh grain of 30–40 μm.

The fine-powder fractionation process in the developed multi-vortex classifier–separator with coaxially arranged pipes is based on the formation of vortices with high values of centrifugal forces in the annular space (for separating fine particles from the gas flow) [12].

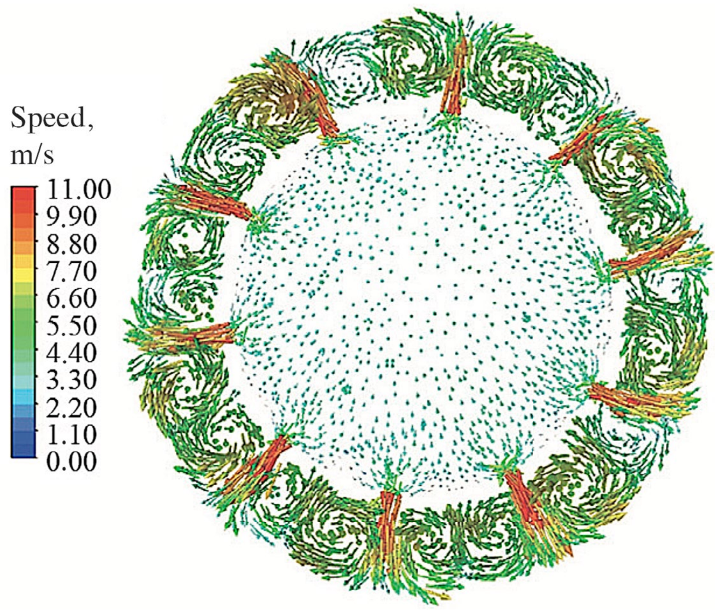

Fig. 2. Diagram of gas swirls in the annulus of a multi-vortex classifier–separator (top view), obtained by modeling in Ansys Fluent.

Operation Principle of the Classifier–Separator. The gas flow with silica gel particles dispersed in it enters the apparatus through a branch pipe. In the inner tube of the apparatus, one part of the gas flow enters the rectangular slots, whereas the other part is sent to the hole with a conical transition. Large particles of silica gel are removed from the flow (under the action of centrifugal and inertia forces arising during the gas rotation) and poured into the hopper through the hole (not shown in Fig. 1).

In the numerical simulation, to simulate the hopper, the condition of particle adhesion to the bottom of the apparatus (with direct contact) was set. When a dusty flow passes through rectangular slots, each gas jet was divided into two equal flows, one of which moves to the right side of the annulus and the other moves to the left. Due to the cylindrical shape of the outer body of the classifier–separator, all gas jets acquired rotational motion and moved as separate vortices into the upper part of the apparatus along the annulus. The dimensions of the cylindrical pipes and the location of the rectangular slots are selected by taking into account the formation of relatively stable vortices in the annulus. In this case, each vortex is in contact with neighboring vortices, and the velocity vectors in the vortices are co-directed, which helps to maintain the structure of the vortices in the apparatus (Fig. 2). Meanwhile, the structure of the vortices is corrected and ordered by round holes in the plate.

In particular, a part of the flow entering the annular space of the classifier–separator through the end hole with a conical transition negatively affects the vortex structure of gas flows, but such a hole is necessary to prevent the apparatus from clogging.

At Salavat Catalyst Plant, a classifier without a conical transition (with a completely open outlet section) was installed to simplify the design. However, due to the sufficient selectivity of the apparatus, the conical transition will not be installed in the future.

The output of the flow with a finely dispersed fraction from the apparatus was performed through a side-outlet pipe.

This Work Aimed to determine the efficiency of a multi-vortex classifier–separator with coaxially arranged pipes (taking into account the coarseness of the near-mesh grain) for various design and technological parameters of the apparatus.

The study was performed through a numerical simulation in the Ansys Fluent software product based on the finite element grid method.

The basis of the numerical simulation of the gas flow is the solution of the Navier–Stokes equation:

$$\frac{\partial \vec{v}}{\partial t} = -(\vec{v} \cdot \nabla)\vec{v} + \nu \Delta \vec{v} - \frac{1}{\rho}\nabla p + \vec{f}, \quad (1)$$

where ∇ is the nabla; Λ is the Laplace vector operator; t is the time, s; ν is the coefficient of kinematic viscosity, m^2/s; ρ is the gas density, kg/m^3; p is the pressure, Pa; $\bar{v}$ is the vector velocity field; and $\bar{f}$ is the vector field of body forces.

The Navier–Stokes equation is supplemented by the continuity equation:

$$\partial \rho / \partial t + \nabla \cdot (\rho \vec{v}) = 0. \quad (2)$$

In the numerical simulation, the k–w shear stress transport (SST) turbulence model was used, which combines the advantages of the k–w and k–ε models. The free turbulent flow was calculated as in the k–ε model, whereas the k–w SST model was directly resolved in the boundary layer, without the use of near-wall functions. The disadvantage of this model is the overestimation of the turbulence level in the dead areas, where the flow is practically stationary, and in areas with high accelerations.

For the research, a three-dimensional model of a multi-vortex classifier–separator was created with the following design dimensions: outer diameter of the inner tube = 65.6 mm; inner diameter of the outer pipe = 95.0 mm; wall thickness of the outer pipe = 5.0 mm; wall thickness of the inner pipe = 2.5 mm; height of the inner pipe = 190 mm; distance from the hole with a conical transition to the bottom of the classifier–separator = 50 mm; height of the outer pipe = 160 mm; hole diameter with a conical transition = 8 mm; diameter of the round holes in the plate = 8 mm; number of holes = 20; height of the conical transition of the inner tube = 22 mm; number of rectangular slots = 10; height of each rectangular slot = 60 mm; and width = 3.5 mm.

When studying the design aspects of the classifier–separator, variants of the lower part of the inner tube with a conical transition and without a conical transition (i.e., with a completely open outlet section of the inner pipe) were considered. The efficiency of the bulk material fractionation was studied during the operation of one classifier–separator and three series-connected classifier–separators. The silica gel particle size was varied from 5 to 100 μm, the particle density was set equal to 1075 kg/m^3, and the gas flow inlet velocity was varied from 2 to 16 m/s. In particular, in a real manufacturing line for the production of silica gel at Salavat Catalyst Plant, the gas flow velocity varies from 5 to 15–20 m/s. Research at other speeds is necessary to obtain more accurate relationships between the apparatus parameters.

Based on the numerical study results, a significant effect of design and technological parameters on the fractional efficiency of the separator–classifier has been established. When changing the geometric shape of the lower part of the inner pipe of the separator, the structure of the ascending gas flow changes, which affects the vortex structure in the annulus. The inlet velocity of the gas flow affects the frequency of rotation of the vortices and, accordingly, the interaction of the vortex structure with the upward flow entering the annulus through the hole *7* (Fig. 1).

Collectively, these factors affect the structure of flows and the speed of gas movement in transport channels, i.e., in areas with negative or close-to-zero axial gas flow velocities. It is assumed in the calculations that the axial velocity is positive when the velocity vector is directed upward and negative when the velocity vector is directed downward. When the particles enter such areas, they are removed from the stream and move gradually into the hopper. Such transport channels are formed between the vortices, in areas near the outer surface of

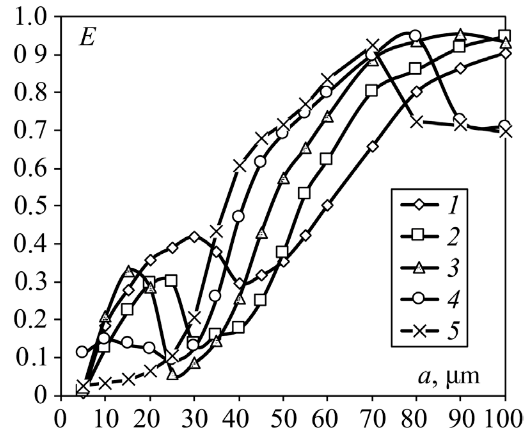

Fig. 3. Dependences of the efficiency of one multi-vortex classifier–separator with coaxially located pipes on the particle size of silica gel (inner pipe with a conical transition) at the inlet gas flow velocity *W*: *1* — 2 m/s; *2* — 4 m/s; *3* — 8 m/s; *4* — 12 m/s; *5* — 16 m/s.

the inner tube, and in the area near the inner surface of the outer tube. The occurrence of negative (or close-to-zero) velocities in the regions between the vortices can be caused by a high pressure gradient in the vortices. The formation of transport channels near the pipe walls can also be associated with a high pressure gradient and with the influence of the boundary layer (insignificant, because the boundary layer is partially destroyed by the whirling gas flow in the annulus).

The fractionation efficiency of the multi-vortex classifier was evaluated by the equation for calculating the particle trapping efficiency (this is due to the value of the near-mesh grain, where particles larger than the near-mesh grain must be captured in the apparatus and smaller ones should be passed):

$$E = 1 - n_k/n, \quad (3)$$

where n_k is the number of particles captured by the classifier–separator (i.e., reaching the apparatus bottom according to the adhesion condition upon contact) and n is the total number of particles in the gas flow at the classifier inlet (the values n_k, n were set by a group of monodisperse particles of a certain size a).

The research revealed that when using a pipe with a hole with a conical transition in the multi-vortex classifier–separator, the efficiency graphs E (Fig. 3) show peaks (maxima) of efficiency when trapping particles with sizes a from 5 to 40 μm, whereas as the inlet velocity of the gas flow increases, the peaks are shifted to the region with a smaller size of the near-mesh grain, which can degrade the fractionation efficiency.

In the apparatus without a conical transition, an almost ideal fractional efficiency is noted in the lower part of the inner tube. Up to a certain particle size of silica gel, the efficiency of the classifier–separator is close to 0%, and after reaching a certain particle size, the efficiency tends to 100% (Fig. 4).

With an increase in the inlet velocity of the gas flow from 2 to 16 m/s, the size of the near-mesh grain decreases. Consequently, this condition increases the frequency of rotation of the vortices in the annulus and increases the centrifugal forces, which separates smaller particles from the gas than at lower flow velocities.

At the inlet gas flow velocity W of 2 m/s, the maximum efficiency (at the peak) of the multi-vortex classifier–separator is 41.8% (with particle size a = 30 μm); at W of 4 m/s, it is 29.8% (a = 25 μm); at W of 8 m/s, it is 32.9% (a = 15 μm); and at W = 12 m/s, it is 14.7% (a = 10 μm; Fig. 3). At a gas flow velocity of 16 m/s, the peak was not recorded (taking into account the data for lower flow velocities, it can be assumed that at a velocity of 16 m/s, the peak occurs for a near-mesh grain of less than 5 μm). Parabolic peaks (Fig. 3)

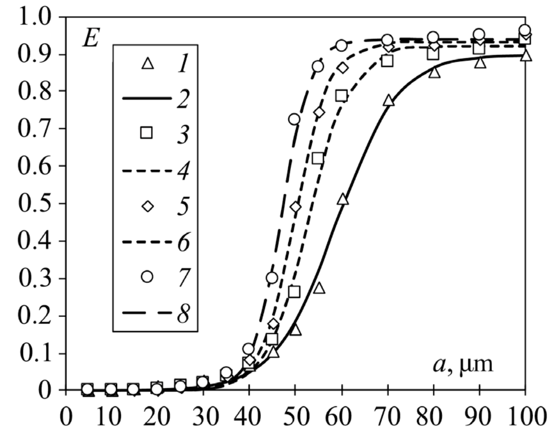

Fig. 4. Dependences of the efficiency of one multi-vortex classifier–separator with coaxially located pipes on the particle size of silica gel (inner pipe without a conical transition) at gas velocity W: *1, 2* — 4 m/s; *3, 4* — 8 m/s; *5, 6* — 12 m/s; *7, 8* — 16 m/s; icons — calculated values of E; lines are sigmoid functions indicating the change in efficiency at the corresponding flow rate.

are characterized by the dispersion of silica gel particles of 5–40 μm at inlet flow velocity $W = 2$ m/s, 5–30 μm at $W = 4$ m/s, 5–25 μm at $W = 8$ m/s, and 5–20 μm at $W = 12$ m/s. In the range of medium-dispersed particles larger than 80 μm, a decrease in the efficiency of particle trapping was noted at relatively high gas flow velocities (12 and 16 m/s), whereas the maximum efficiency of the classifier–separator is 94.7% (a = 80 μm) at a gas velocity of 12 m/s and 92.3% (a = 70 μm) at a gas velocity of 16 m/s. Consequently, as the gas velocity decreases, the maximum efficiency of the apparatus will probably be registered at particle sizes of more than 80 μm. In this study, particles larger than 100 microns were not considered because the apparatus under study is designed for the fractionation of bulk materials with a near-mesh grain size of 30–40 microns.

To increase the selectivity of the fractionation of the bulk material of the fraction, several (e.g., three) series-connected multi-vortex classifiers–separators can be used. The efficiency of three connected devices in series was calculated by the following equation:

$$E_3 = 1 - (1 - E)^3. \quad (4)$$

The use of three series-connected devices provides the possibility of obtaining narrow granulometric fractions of particles with a near-mesh grain of less than 40 microns with a significantly higher efficiency than that when using a single apparatus. At a gas flow velocity $W = 16$ m/s, the peak efficiency in the particle range less than 40 μm was not recorded (as well as for one apparatus; Fig. 3). However, the efficiency of the classifier–separator at a gas velocity of 16 m/s and a particle size of more than 40 μm is more than 93.1% (Fig. 5).

The gas flow structure closest to the ideal in the multi-vortex classifier–separator is ensured by the design of the apparatus without a conical transition on the inner pipe, where the separation selectivity is more than 90% when using one apparatus in the production line. The efficiency of the classifier–separator is no more than 2.6% for particles up to 30 μm in size and no more than 10.8% for particles up to 40 μm in size, whereas with an increase in the particle diameter, a rapid increase in the efficiency of particle trapping in the apparatus is noted.

Figure 5 reveals that the efficiency of trapping particles with sizes up to the near-mesh grain is close-to-zero, and then it sharply increases to a certain value, which practically does not change with a further increase in the particle size. Moreover, the angle of elevation of the lines on the graph depends on the inlet velocity of the gas flow. At gas velocities of 4, 8, 12, and 16 m/s, a practically constant efficiency value is 90% (a = 100 μm), 92% (a = 80 μm), 93% (a = 70 μm), and 94% (a = 65 μm) (Fig. 4).

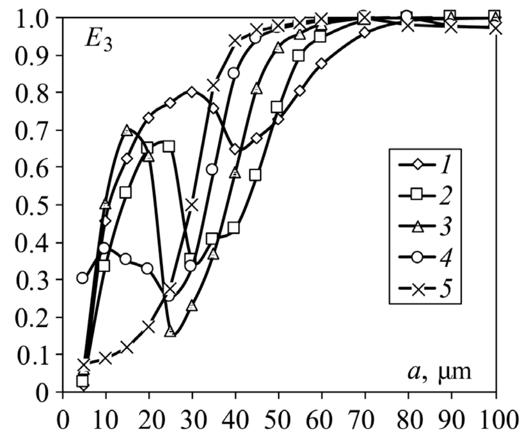

Fig. 5. Dependences of the efficiency of three multi-vortex classifiers–separators with coaxially located pipes on the particle size of silica gel (inner pipe with a conical transition) at the inlet gas flow velocity W: *1* — 2 m/s; *2* — 4 m/s; *3* — 8 m/s; *4* — 12 m/s; *5* — 16 m/s.

Based on the obtained dependences of the efficiency of a multi-vortex classifier–separator with an inner tube without a conical transition on the particle size, sigmoid functions of the following form were selected:

$$E = \frac{1}{1+e^{-c_1(a-c_2)}}A, \tag{5}$$

where c_1, c_2 are coefficients characterizing the angle of rotation of the curve; A is a correction factor for taking into account the value to which the function tends in the investigated range of particles; and a is the particle size, μm.

Thus, for the input gas flow velocities $W_1 = 4$ m/s, $W_2 = 8$ m/s, $W_3 = 12$ m/s, and $W_4 = 16$ m/s, the following system of equations (sigmoid functions) is obtained:

$$\begin{cases} E_{W_1} = \dfrac{1}{1+e^{-0.15(a-59)}}0.90, \\ E_{W_2} = \dfrac{1}{1+e^{-0.22(a-53)}}0.92, \\ E_{W_3} = \dfrac{1}{1+e^{-0.27(a-50)}}0.93, \\ E_{W_4} = \dfrac{1}{1+e^{-0.32(a-47)}}0.94. \end{cases} \tag{6}$$

The power-law dependences of the coefficients c_1 and c_2 of the sigmoid function on the inlet gas flow velocity W were also revealed (Fig. 6):

$$\begin{cases} c_1 = 0.07W^{0.54}, \\ c_2 = 73.9W^{-0.16}. \end{cases} \tag{7}$$

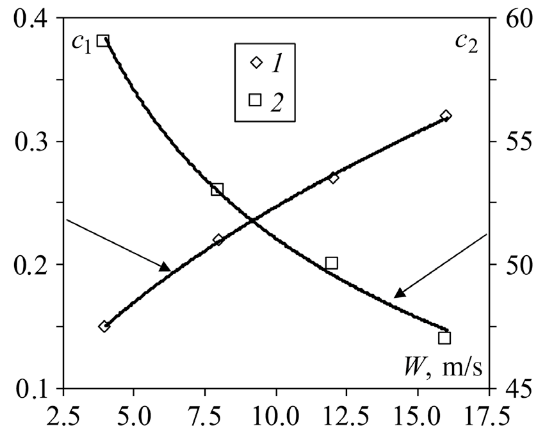

Fig. 6. Dependences of the coefficients of the sigmoid function c_1 (*1*) and c_2 (*2*) on the inlet velocity of the gas flow in the multi-vortex classifier–separator.

Thus, the systems of Eqs. (6) and (7) jointly form an engineering method for calculating a multi-vortex classifier–separator, according to which the efficiency of trapping bulk material based on silica gel is predicted depending on the inlet velocity of the gas flow and the required size of the near-mesh grain. The design of a multi-vortex classifier–separator significantly affects the production of granulometric fractions of silica gel particles. Moreover, the fractional composition of silica gel is affected by the inlet velocity of the gas flow due to a change in the structure of the gas flow in the annular space (and, consequently, in the transport channels).

CONCLUSIONS

1. The multi-vortex classifier–separator with a conical transition in the inner tube is effective for fractionating particles (fine, medium, and coarse) in narrow size ranges.

2. The use of several serially connected multi-vortex classifiers–separators is promising for obtaining (high-efficiency) narrow fine particle fractions with a near-mesh grain size of less than 30–40 μm.

3. The use of an inner pipe without a conical transition in the classifier provides the possibility of fractionating bulk materials based on silica gel with a near-mesh grain size of 30–40 μm.

4. An engineering method for calculating a multi-vortex classifier–separator has been developed to determine the efficiency of the apparatus, taking into account the inlet velocity of the gas flow and the required coarseness of the near-mesh grain.

This work was financially supported by the Presidential Scholarship for Young Scientists and PhD Students SP-3577.2022.1.

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