CLEANING DUSTY AIR FLOW WITH A ROTARY CYCLONE FROM DISPERSED PARTICLES

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Resume

The research presented in this article is aimed to show the prospective direction of increasing the efficiency of cleaning dusty air flows from light impurities and dust on mobile grain separators by using a rotary cyclone with a multi-disc after cleaner. An increase in the efficiency of the process of cleaning the dusty air flow in dust collectors is provided by an additional effect on dispersed particles for their intensive redistribution in the working areas. The developed rotary cyclone has two working zones: the main zone and the post-cleaning zone. The rotary cyclone consists of a bladed impeller, a main cylindrical channel, a sedimentation chamber and an after-cleaner. The overall air flow purification coefficient of the rotary cyclone varies between 87.5 to 92.5 %.

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1 Introduction

The technological process of grain cleaning machines is accompanied by the release of dust, which is dangerous for workers in the service work area, according to the requirements of the ISO 14644-4 standard [1]. The service area is considered to be a space of a height of 2 meters and higher above the floor level, on which the working personnel is located.

To maintain the normalized dustiness, grain cleaning machines are equipped with aspiration systems and dust collectors, which comprise a system of elements removing dispersed particles from the air flow, unloading device, regulating equipment and fan, (EN 481:1993 and ISO 7708:1995 [2-3]).

The further increase in the productivity of grain separators that causes an increase in the concentration of fine particles of impurities and dust, is restrained by the insufficient efficiency of the aspiration systems in cleaning the air flow. The classical improvement of aspiration systems dust collectors, their individual elements, was exhausted and limited by the design features of mobile grain separators.

The conducted review of designs and methods for the efficiency improvement of air flow cleaning of existing devices showed that the most promising way to improve the efficiency of aspiration systems is to combine devices with different operating principles [4-6]. The authors offered the construction of a rotary cyclone with an active rotor on which a bladed impeller is installed. It is designed to give dispersed dust particles a trajectory that takes them away through the blinds from the working area of the device. Dispersed particles remaining in the dusty air stream are also removed through the louvers with the help of a disk pre-cleaner. The cleaned air flow between the discs and the hole inside the discs passes to the outlet nozzle.

Grounding on evaluation and analysis of the research results, a forward-looking direction of increasing the efficiency of cleaning dusty air flows from light impurities and dust on mobile grain separators by using the developed rotary cyclone with a multi-disc after-cleaner, is justified [7-10]. Increasing the efficiency of the dusty air flow cleaning process in dust collectors requires additional influence on dispersed particles to ensure their intensive redistribution in the work zones.

2 Sources review

Despite the sufficient theoretical and experimental material on the study of cleaning processes in devices with swirling dusty flows, a significant part of the phenomena cannot be explained within the framework of the formed ideas, and the task of the efficiency improvement of cleaning the dusty air flow from the dispersed phase, especially on mobile grain separators, remains unresolved. Existing calculation methods do not consider the complexity of the general hydrodynamic picture of separation of a multiphase dusty air flow, as well as the interaction of these flows with each other. This substantiates the necessity to research the main technological parameters of the air flow cleaning process to create high-performance, economical and environmentally friendly rotary cyclones - dust collectors with further forecasting their effectiveness [11].

Unlike experimental studies, numerical modelling allows to vary a number of factors (speed of rotation, viscosity of the air flow, initial properties), which have an important impact on the formation and swirling currents behavior. Changes in mathematical modelling associated with the use of computing technologies and programs, make it possible to implement constructive solutions of individual apparatus modes and to identify optimal hydrodynamic conditions of the process of dusty air flow centrifugal cleaning.

The research of hydrodynamic processes in rotating cyclones is based on a system of Navier-Stokes equations [12-14], supplemented by the equations of non-discontinuity of a symmetric dispersed rotating air flow fixed axis.

Solving the system of Navier-Stokes equations is mathematically difficult, which necessitates the adoption of a number of not quite correct assumptions. This reduces the adequacy of the proposed real hydrodynamic picture analytical descriptions in rotary cyclone devices and, ultimately, leads to significant discrepancies between the results of calculations and experimental data. Regarding this, the physical experiment, as noted in [15], is still the main way of obtaining reliable information about the structure and characteristics of rotating flows. In turn, the most significant drawback of experimental studies of the velocity field is their low accuracy, which is due to the use of probe measurement methods [16]. This explains the obtaining of contradictory results and conclusions by individual authors, which is a restraining factor in the development of analytical, generalizing approaches to the description of the dispersed air flow hydrodynamics in the dust collectors. The use of numerical modelling methods is especially relevant in the problems of mechanics of multiphase flows with the study of related problems of the dusty air flow. It is also necessary to consider statistical approaches for direct numerical modelling dispersed flows and turbulence problems.

An efficient numerical method is a solution of multidimensional purely hyperbolic equations, or equations of a parabolic type containing hyperbolic parts. Mathematical models are used to describe spatially non-stationary problems of the flow of multiphase media; the construction of a computational algorithm for solving similar types of problems in which is quite complex and, as a rule, is solved in stages [17].

One of the most efficient methods of mathematical modelling air flow movement is the use of hydrodynamic equations: the equation of motion continuity and the dynamic equation of an incompressible fluid motion (Navier-Stokes equation) [18-19].

Navier-Stokes equation defines a system of forces acting in a gas (liquid) in the coordinate axes direction [19]. This equation considers the effect of four forces: gravity, pressure, internal friction (viscosity), and the rotating cyclone. The gravitational force is an external factor, and other forces are the result of the environment acting on a selected elementary volume. The equation does not consider external actions on the system and therefore must be supplemented with boundary conditions. Along with the boundary conditions, the initial conditions are given to characterize the system state at the initial moment of the process.

The problem may be solved by computational methods or by experimental methods. As it is described above, the computational methods are usually based on the finite element method. A standard finite element method is applied to strength analysis of many kinds of structures [20-23]. However, the fluid dynamics requires more complicated definition of initial and boundary conditions [24-26].

Analyzing the state of the problem, with regards to improving the productivity of mobile grain cleaning machines and a review of their existing designs of aspiration systems, revealed the following shortcomings: limitation of technological indicators of work (loading the grain cleaning separator); most of the studies were carried out for individual parameters of dust collectors that were subject to optimization; experimental approval is partially or completely absent; the obtained mathematical expressions are complicated or have no further practical use; lack of intermediate removal of captured dispersed particles and dusty air flow additional purification [27-29]. A promising direction of increasing the dusty air flow cleaning process efficiency from light impurities and dust is the creation of a rotary cyclone with a multi-disc after cleaner, enabling to increase the efficiency of dusty air flow cleaning without changing the basic dimensions of serial mobile separators of the OVS-25 and SVS-25 type.

3 Research aim and tasks

The aim of the work implies increasing the efficiency of the of the dusty air flow cleaning process of mobile grain aspiration systems of separators by substantiating the parameters of the developed rotary cyclone with an after-cleaner.

Research objectives:

- to justify the criteria for optimizing the process of cleaning the dusty air flow, to build the objective function and determine the rational design parameters of the proposed rotary cyclone of mobile grain separators;
- to evaluate the impact of the design and technological parameters of the developed rotary cyclone on the particles' velocity field of the dispersed phase in the working zones;
- identify the speed of the air flow and dispersed particles, evaluate the adequacy and effectiveness of the obtained dependencies of dusty air flow cleaning process through the experimental studies and production approval of the rotary cyclone.

4 Theoretical studies of the dynamics of the dusty air flow dispersed phase in a rotating cyclone

The grain dust is characterized by a wide interval of particle dispersion. Such dispersed particles can flow around in transitional and turbulent regimes; however, the number of such particles is insignificant.

The influence of turbulent pulsations, affecting the movement of finely dispersed particles is taken into account based on equation [30-32]:

$$\frac{1}{\tau}\frac{dr}{dt} - \Omega_0^2 r + \frac{C(t)}{m_s} = 0\,, \qquad (1)$$

where C*(t)* is the coefficient of random influence, which is the delta of the correlation function of time with a zero-mean value; Ω_0 - angular velocity of swirler rotation, [rad/s]; m_S - mass of dispersed particle; [g].

Turbulent pulsations influence only the movement of finely dispersed particles d_s < 5 µm [32-33], for the separation of which it is necessary to use an additional device - a pre-cleaner. Dispersed particles of a size of d_s = 200 µm are significantly deflected and some of them fall on the blinds of the main channel and further into the sedimentation chamber.

Finely dispersed particles practically do not have time to deviate to the walls of the main channel. Simultaneously, the trajectories of larger dispersed particles are significantly deviated, and some of them fall through the blinds of the channel to the sedimentation chamber, where their sedimentation takes place. Simultaneously, the highly dispersed particles are not able to accelerate. Then, the turbulent nature of the flow becomes significant. That is, up to the pre-cleaner zone, calculations can be carried out using the Stokes formula for almost any grain dust particles of any size.

During this process, some dispersed particles obviously will reach the walls of the main channel before entering the pre-cleaner zone. For this, it is necessary that their entrance radius meets the condition:

$$r_0 > \frac{\frac{D_0}{\Omega_0}\sqrt{\frac{U_0}{8 l_0 \tau}}}{\left(1+\frac{1}{\beta}\right)e^{(\beta-1)\frac{L_0}{2\tau U_0}} + \left(1-\frac{1}{\beta}\right)e^{-(\beta-1)\frac{L_0}{2\tau U_0}}}\,, \qquad (2)$$

where U_0 is the speed of the air flow at the entrance to the cyclone, [m/s]; l_0 - width of pre-cleaner, [m]; L_0 - length of the main working zone of the developed rotary cyclone, [m]; τ - relaxation time of a dispersed particle in the air flow, [s]; D_0 - the diameter of the rotary cyclone inlet nozzle, [m].

In addition, we assume a uniform distribution of dispersed particles at the entrance to the rotary cyclone across the cross section of the flow.

Then, the efficiency of separating the dispersed particles from the dusty air flow in the main working area of the developed rotary cyclone is defined by the expression:

$$\eta_1 = 1 - \\ - \frac{2\frac{1}{\Omega_0^2}\frac{U_0}{l_0\tau}}{\left[\left(1+\frac{1}{\beta}\right)e^{(\beta-1)\frac{L_0}{2\tau U_0}} + \left(1-\frac{1}{\beta}\right)e^{-(\beta-1)\frac{L_0}{2\tau U_0}}\right]^2}\,. \qquad (3)$$

The efficiency of the dispersed particles separation of a size of 50 µm to 120 µm, in the main channel of the

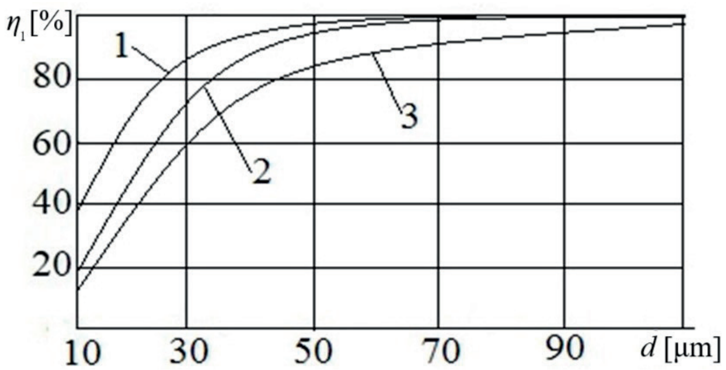

Figure 1 *Dependencies of the dusty air flow cleaning efficiency in the main channel of the developed rotary cyclone on the speed of the air flow: 1 - U_0 = 5 m/s; 2 - U_0 =10 m/s; 3 - U_0 =15 m/s (Ω = 105 rad/s; D_0 = 0.1 m; l_0 = 0.3 m)*

developed rotary cyclone (Figure 1), is in the range of 85 to 100 %. Insufficient efficiency of finely dispersed particles separation up to 50 µm in size is explained by the limitation of the main channel dimensions of the rotary cyclone and the insignificant weight of the particles themselves. This requires the use of an additional dust separator. Reducing the speed of the air flow, in the range under investigation, helps to increase the cleaning coefficient of the main channel of the developed rotary cyclone by 35 to 45 %.

The efficiency of dispersed particles separation of a size of 50 to 120 µm, in the main channel of the developed rotary cyclone (Figure 1), is in the range of 85 to 100 %. Insufficient efficiency of separation of finely dispersed particles up to 50 µm in size, is explained by the limitation of the main channel dimensions of the rotary cyclone and the insignificant weight of the particles themselves. This requires the use of an additional dust separator. Reducing the speed of the air flow, in the range under investigation, helps to increase the cleaning coefficient of the main channel of the developed rotary cyclone by 35 to 45 %.

After the dispersed particles reach the pre-cleaner zone, the force of the air flow, directed radially towards the axis, begins to act on them. In addition, the centrifugal force, directed radially from the axis, continues to act.

Down the equation for the radial component of ta dispersed particle velocity [33-35]:

$$\frac{dW_r}{dt} = -\xi\frac{3}{8}\frac{\rho}{\rho_s r_s}(W_r - U_r)^2 + \frac{W_\phi^2}{r}, \quad (4)$$

where U_r - speed of the air flow in the cyclone working area [m/s] and it is expressed as:

$$U_r = \frac{(D_0^2 - D_d^2)U_0}{8rl_0}, \quad (5)$$

further l_0 - width of the pre-cleaner [m]; D_d - diameter of the pre-cleaner discs' the central hole [m]; W_r - a component of the dispersed particle velocity in a radial direction [rad/s].

The equation for the acceleration in a radial direction of a dispersed particle has the following form:

$$\frac{d^2r}{dt^2} = -\xi\frac{3}{8}\frac{\rho}{\rho_s r_s}\left(\frac{dr}{dt} - Ur\right)^2 + r\cdot\Omega_0^2. \quad (6)$$

For the fine dispersed particles flowing in the laminar mode, Equation (5) can be written as:

$$\frac{dr}{dt} = \tau\cdot\Omega_1^2\cdot r - \frac{(D_0^2 - D_d^2)U_0}{8rl_0}, \quad (7)$$

where Ω_1 - rotation frequency of the pre-cleaner [rpm]. It is considered $\Omega_1 = \Omega_0$.

It turns out that, if the dispersed particle entered the zone of the pre-cleaner at a radius that satisfies the inequalities:

$$r > \frac{\sqrt{D_0^2 - D_d^2}}{\Omega_1}\sqrt{\frac{U_0}{8l_0\tau}}, \quad (8)$$

then, due to centrifugal forces, it will be thrown to the walls of the main channel and enter the chamber.

The dispersed particles, that will be closer to the channel axis, can be drawn into the pre-cleaner. Their further dynamics will be determined by the after-cleaner parameters. Simultaneously, a dispersed particle larger in size, which flows around in a turbulent mode, when inequality in Equation (8) is fulfilled, will also be thrown to the walls of the channel due to centrifugal forces and will enter the chamber.

Then, only the dispersed particles, the entrance radius of which when entering the pre-cleaner zone is:

$$r_1 > \frac{2\frac{\sqrt{D_0^2 - D_d^2}}{\Omega_0}\sqrt{\frac{U_0}{8l_0\tau}}}{\left(1+\frac{1}{\beta}\right)e^{(\beta-1)\frac{L_0 - l_0}{2\tau U_0}} + \left(1-\frac{1}{\beta}\right)e^{-(\beta+1)\frac{L_0 - l_0}{2\tau U_0}}}, \quad (9)$$

will reach a radius satisfying condition in Equation (8).

On the other hand, it is obvious that dispersed particles, whose entrance radius is the following:

$$r_2 > \frac{D_d}{\left(1+\frac{1}{\beta}\right)e^{(\beta-1)\frac{L_0 - l_0}{2\tau U_0}} + \left(1-\frac{1}{\beta}\right)e^{-(\beta+1)\frac{L_0 - l_0}{2\tau U_0}}}, \quad (10)$$

will not fall into the central hole of the pre-cleaner discs.

If it is assumed that the dispersed particles are uniformly distributed at the inlet along the cross section of the flow, then the separation efficiency of dispersed particles (without considering the particles that are separated before they reach the pre-cleaner zone) is equal to:

$$\eta_2 = 1 - \frac{\max\left(2\frac{1-(D_d/D_0)^2}{\Omega_0^2}\frac{U_0}{l_0\tau}, 4\left(\frac{D_d}{D_0}\right)^2\right)}{\left[\left(1+\frac{1}{\beta}\right)e^{(\beta-1)\frac{L_0 - l_0}{2\tau U_0}} + \left(1-\frac{1}{\beta}\right)e^{-(\beta+1)\frac{L_0 - l_0}{2\tau U_0}}\right]^2} \quad (11)$$

The dispersed particles, the diameters of which are close to the grain dust particles (considered in micrometers), are partially separated during their movement to the pre-cleaner (Figure 2). Then, the dispersed particles are directed between the plates of the shutter separator 3 to the settling chamber 6 (Figure 3).

Particles of a diameter of 20 to 100 µm are also partially separated during their movement to the pre-cleaner. Then, the remaining particles are separated during their rotation in the pre-cleaner zone.

Figure 3 shows the scheme of the developed rotary cyclone design elements, where Figure 3a depicts the entire model. Then, the device without the louver separator plates is shown in Figure 3b and Figure 3c depicts the detail of the multi-disc cleaner.

The research analysis on the dispersed composition of the grain dust [36-38] established the fractional composition:

- particles of sizes up to 1 µm comprise 8.3 %;
- particles of sizes from 1 to 5 µm comprise 16.6 %;

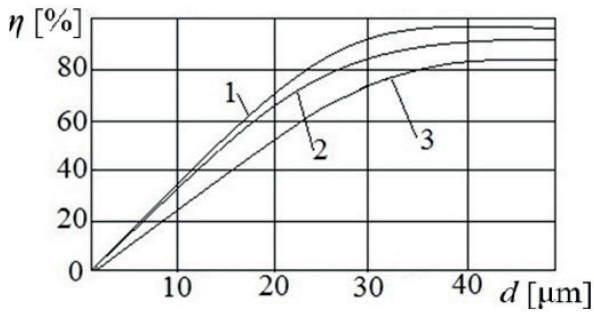

***Figure 2** Dependencies of the dusty air flow cleaning coefficient on the number of discs of the developed rotary cyclone post-cleaner: 1 - n = 9 units, l_0 = 0.0315 m; 2 - n = 6 units, l_0 = 0.021 m; 3 - n = 3 units, l_0 = 0.0105 m (U_0 = 10 m/s; D_0 = 0.1 m; D_d = 0.01 m)*

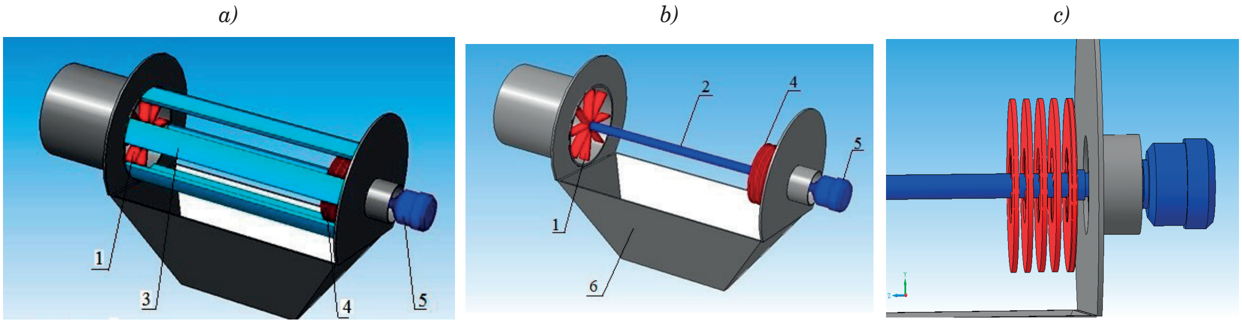

***Figure 3** The scheme of the developed rotary cyclone design elements: 1 - impeller; 2 - shaft; 3 - louver separator plates; 4 - multi-disc pre-cleaner; 5 - electric motor; 6 - deposition chamber*

***Table 1** Research results of the purification coefficients of the developed rotary cyclone dependence on the air flow velocity from the rotor speed*

Air flow velocity U_0 [m/s]	Cleaning coefficient η [%]		
	W = 105 [rad/s]	*W* = 210 [rad/s]	Cyclone design parameters
6	93.1	91.1	
7	93.2	91.2	
8	93.3	91.4	*n* = 6 pcs.;
9	93.4	91.5	*h* = 1 mm;
10	93.5	91.8	*α* = 20°;
11	93.6	92.1	*b* = 20 mm
12	93.7	92.5	
13	93.8	92.8	

- particles of sizes from 5 to 10 μm comprise 24.8 %;
- particles larger than 10 μm - 50.3 %.

Numerical calculation of the optimal mathematical expressions established that the fine-dispersed fraction up to 1 μm is almost not separated. The efficiency of removing large-dispersed particles (over 1 μm) reaches 67.9 to 79.2 %.

5 Research results of the dispersed phase dynamics of the dusty air flow in a rotating cyclone

Studies of the developed rotary cyclone efficiency involved determining the coefficient of dusty air flow purification with varying values of the following important factors: air flow velocity U_0, the distance between the disks h, angle of inclination of the swirler blades α, the width of the louver opening b, motor rotor speed Ω; the number of discs of purifier n.

The research proved the dependencies of the developed rotary cyclone cleaning coefficients on its design and technological parameters (Figure 4).

Analysis of research (Table 1) shows that the maximum efficiency of the air flow cleaning process is η = 93.1 to 93.8 %, at air flow velocity U_0 = 6 m/s to 13 m/s and at shaft speed Ω = 105 rad/s.

Thus, within the range of the studied air flow rate (Table 2) U_0 =6 to 13 m/s, maximum cleaning coefficient is 91.1 to 92.8 %, which is 2.3 to 2.5 % more than at α = 30°.

__Table 2__ Research results of the purification coefficients of the developed rotary cyclone dependence on the air flow velocity from the tilt angle of the impeller blades

Air flow velocity U_0 [m/s]	Cleaning coefficient η [%]			
	α = 10°	α = 20°	α = 30°	Cyclone design parameters
6	90.2	91.1	89.0	n = 6 pcs; b = 20 mm; h = 1 mm; W =105 rad/s
7	90.5	91.3	89.1	
8	90.7	91.5	89.2	
9	90.8	91.7	89.4	
10	91.0	92.0	89.5	
11	91.2	92.1	89.9	
12	91.8	92.5	90.1	
13	92.0	92.8	90.5	

__Table 3__ Research results of the purification coefficients of the developed rotary cyclone dependence on the distance between the disks of the purifier

Air flow velocity U_0 [m/s]	Cleaning coefficient η [%]			
	U_0 = 6 m/s	U_0 = 10 m/s	U_0 = 13 m/s	Cyclone design parameters
0.5	90.0	89.2	89.0	n = 6 pcs.; α = 20°; b =15 mm; Ω =105 rad/s
0.75	91.9	91.2	90.8	
1.0	92.4	91.5	91.1	
1.25	91.1	90.2	90.1	
1.5	88.3	87.7	87.9	

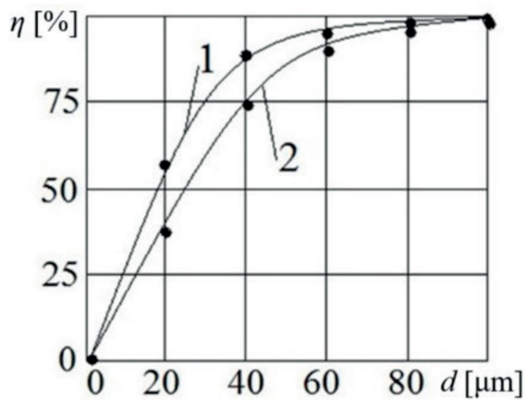

***Figure 4** Dependencies of the developed rotary cyclone cleaning coefficient on the size of dispersed particles: 1 - U_0 = 10 m/s; 2 - U_0 = 15 m/s (Ω = 1000 rpm; n = 6 units; b = 15 m; h = 1 mm)*

__Table 4__ Comparative analysis of the experimental and theoretical research results of the developed rotary cyclone

Cleaning stages	30-50 μm	100-150 μm	Total [%]	Experimental [%]	Theoretical new values [%]	Impeller rotations [rpm]	Flow velocity [m/s]	Error [%]
Before cleaning	50	50	100	-	-	-	-	-
After cleaning	13.1	2.6	15.7	85.3	85	1000	10	0.4
	18.2	3.0	21.2	78.8	78.2	500	10	0.8
	4.8	2.0	6.8	93.2	92	1000	6	1.3
	9.5	2.8	12.3	87.7	87.2	500	6	0.6

Analysis of the dependencies (Table 3) shows that the distance between the disks of the purifier, that provides maximum efficiency of the developed rotary cyclone η = 90.1 to 92.4 %, is h = 0.75 mm to 1.25 mm.

Experimental studies analysis proved that increasing the velocity of air flow, in the ranges under study, increases the cleaning coefficient of the developed rotary cyclone from 4 to 4.8 to 89 to 93.8 %. The obtained parameters of the rotary cyclone are: the angle of the blades α = 20°, the rotor speed Ω = 105 rad/s, the distance between the disks of the purifier h = 1 mm.

To obtain a complete picture, for increasing the efficiency of cleaning the dusty flow, the determination of the fractional cleaning coefficient (Figure 4) was carried out for the fractions of dispersed particles that were researched.

The analysis of dependencies (Figure 4) established that at the speed of the air flow in the developed rotary cyclone U_0 = 10 m/s to 15 m/s, the cleaning coefficient is η = 5 to 98 % for dispersed particles up to 90 μm in size. It should be noted that the developed rotary cyclone captures dispersed particles d_s = 1 μm to 40 μm with an efficiency of η = 5 to 87 %, which significantly affects the of the air flow cleaning process intensification in mobile grain separators.

The obtained experimental dependencies of the overall cleaning coefficient of the developed rotary cyclone from dispersed particles at the air flow rate typical for aspiration systems of mobile grain separators are shown in Table 4.

The discrepancy between the results of the experiments and the data of theoretical studies, concerning the efficiency determination of the dusty air flow cleaning process, does not exceed 3.8 to 4.3 %, confirming the adequacy of the developed mathematical modelling.

Determining the discrepancy between the results of researching the efficiency of the dusty air flow cleaning process was carried out with the variation of significant parameters: the frequency of the rotor rotation and the speed of the air flow at the inlet. Varying the parameters of the rotary cyclone, within the established ranges, results in a discrepancy of 0.4 to 1.3 % in the results of researching the efficiency of the dusty air flow cleaning process. This also confirms the adequacy of the developed mathematical modelling the dusty air flow cleaning process.

As a result of conducting experimental studies, the dependencies of the radial component change rate of the dispersed particles velocity and the dispersed particle radial coordinate in the main channel of the rotary cyclone were obtained.

6 Conclusion

It was established that the velocity components of the multiphase medium depend by 15 to 35 % on the design and technological parameters of the developed rotary cyclone, which confirms the possibility of dispersed particles redistribution and the dusty air flow cleaning process intensification. The ranges of component of the carrier and dispersed phases velocities were determined by solving the obtained mathematical models. It was established that the efficiency of the dusty air flow cleaning process on the developed rotary cyclone is 85 to 92 %.

The dependencies of the cleaning coefficient on the air flow velocity were experimentally proved. Increasing the velocity of the air flow in the range under study, increases the cleaning coefficient of the developed rotary cyclone by 4.0 to 4.8 to η= 91.0 to 93.8 %. The ranges of variation of the obtained parameters of the rotary cyclone were: the angle of the blades inclination α = 20°, rotor speed Ω = 105 rad/s, the distances between the disks of purifier h = 1 mm.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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