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Numerical study of modified centrifugal cyclone

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Abstract. A cyclone separator is an equipment that separates particles contained in a liquid or gas without filters. Dust particles in flue gases can be separated using centrifugal forces and different particle densities so that the exhaust gases must be cleaned before being discharged into the environment. The selection of optimal geometric dimensions and operation parameters of industrial equipment is always a topical issue. In the work, numerical modeling and research of a modified centrifugal cyclone dust collector are carried out. A modified centrifugal cyclone was developed by one of the article's authors at the Institute of Mechanics and Seismic Resistance of Structures of the Academy of Sciences of the Republic of Uzbekistan, which has a high efficiency of at least 98%. The study was carried out in the Comsol Multiphysics 5.6 engineering software package using the Flow Simulation add-on, designed to simulate hydrodynamic processes. The relevance of the chosen research topic was indicated. The standard k-ε model is chosen as a turbulence model, which is often used in engineering problems. The computational experiment was carried out at three flow rates in the centrifugal cyclone. Based on the obtained numerical data, it is shown that the efficiency of the modified cyclone is significantly higher than that of the classical cyclone.

1 Introduction

Atmospheric pollution by emissions from chemicals, construction, engineering, and other industries has become a truly international problem. One of the most common man-made air pollutants is suspended dust particles in industrial enterprises' exhaust gases. The solution to the problem of reducing dust emissions into the environment lies in the improvement of existing, as well as the development and implementation of new gas cleaning equipment. At the same time, in some industries (such as the production of coloring pigments, cement, and carbon black), it is required to solve not only the problem of efficient separation of dust from the gas flow but also its classification and return to production, since particles of a certain size are the target product. Purification is necessary not only for industrial gases but also for the air entering internal combustion engines. It is known that mining is carried out either in quarries or in mines. In those and other cases, vehicles and technical facilities are operated in conditions of high dust content, which is a harmful environment for their engines and power plants. Therefore, the period of uninterrupted operation of operated equipment in such conditions is significantly less than under normal conditions [1-4].

Inertial dust collectors of the "dry" type are most widely used in industrial enterprises since they are easy to manufacture and operate, reliable, have low hydraulic resistance, and can operate at elevated temperatures and high initial dustiness. However, the existing designs of inertial apparatuses cannot always effectively capture fine dust. [5,6].

It should be noted that the development of inertial dust collectors is necessary not only to reduce dust emissions into the environment or protect internal combustion engines but also to stimulate the development of other technologies. For example, inertial dust collectors can be used as a separator for separating powder materials into fractions, as well as a hydrocyclone for extracting solids from liquids, etc.

Despite the many different designs of inertial dust collectors used in industry, the problem of retaining fine dust is still far from being solved. Because the efficiency of inertial dust collectors for standard dust usually does not exceed 85%. Despite the development of various inertial dust collectors, they are still inferior in efficiency to bag filters. However, it is known that bag filters cannot be used everywhere. Therefore, developing even more efficient inertial dust collectors is an important problem because they are durable and can be used in virtually all technological processes. In many cases, to improve the efficiency of a device, it is not the development of a fundamentally new one but the modification of an existing one. Therefore, in this work, we study the modified cyclone. The study is mainly of a comparative nature, i.e., the efficiency of the classical cyclone is compared with the modified one. Figure 1 shows a classic centrifugal dust collector (cyclone) schematic diagram.

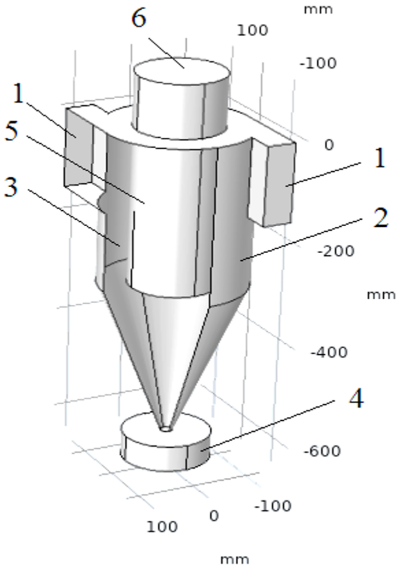


Fig. 1. Classical centrifugal dust collector. 1 is inlet to the spiral air intake, 2 is cylindrical dust collector body, 3 is conical dust collector body, 4 is bunker, 5 is cleaned air exhaust pipe, 6 is cleaned air outlet.

The device works due to the suction of air by the vacuum fan through the exhaust pipe 5. Therefore, the dusty air flow is sucked into the spiral air intake 1, which acquires rotational motion and moves downward between the cylindrical body 2 and the air exhaust pipe 5. In this area, due to centrifugal force, dust particles will move to the inner surface of the cylindrical body 2. In the area where the conical part of the body begins, the air flow is separated from the dust because air will tend to the inlet of the outlet pipe 5, and dust particles, pressing against the inner surface of the cone, move by inertia into the hopper, where they settle.

It has been said above that the dust collection efficiency of such a device for standard dust is not high. Therefore, to increase the efficiency, one of the authors of this article developed the design of a highly efficient centrifugal dust collector [7], the schematic diagram of which is shown in Figure 2. As can be seen from the figure, a feature of the modified centrifugal dust collector is that it contains such elements as flow stabilizer 7 and an inner cone. It can be seen from the figure that the flow stabilizer is a branch pipe that is inserted into the inlet of the outlet pipe. Therefore, a certain part of the air enters the outlet pipe through the coaxial space between the branch pipe and the outlet pipe and the rest through the sections of the branch pipe. Thus, the nozzle distributes the incoming air flow into the outlet pipe in height, which reduces the resulting harmful reverse vortices (Fig. 2). This, in turn, reduces the entrainment of fine dust particles. An analysis of a classic centrifugal dust collector (Fig. 1) shows that dust collecting on the inner surface of the cone forms a layer of a certain thickness. It is clear that with an increase in this layer's thickness, particles' entrainment into the discharge pipe will also increase. Therefore, one way to increase the dust collector's efficiency is to reduce the thickness of the dust layer. The inner cone in the modified dust collector just serves this purpose (Fig. 2) [7,8]. Because large particles of dust, gathering near the wall, enter the space between the cones, and small particles accumulate on the surface of the inner cone. In this case, small particles form a significantly smaller layer. Therefore, the entrainment of dust particles will also be significantly reduced.

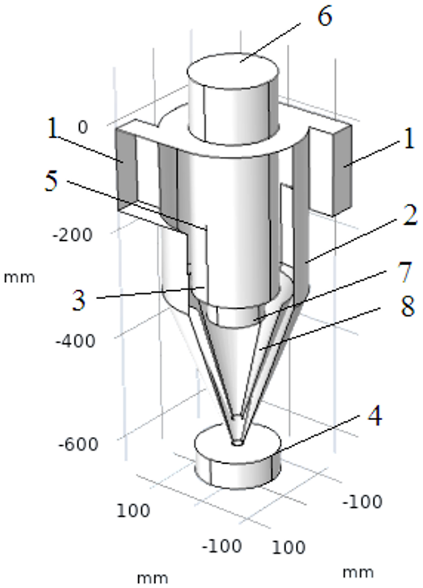


Fig. 2. Modified centrifugal dust collector. 1 is inlet to the spiral air intake, 2 is cylindrical dust collector body, 3 is conical dust collector body, 4 is bunker, 5 is pipe for the removal of purified air, 6 is cleaned air outlet. 7 is flow stabilizer, 8 is inner cone

This work aims to simulate two-phase flow in centrifugal dust collectors and compare the dust collection efficiency of classical and modified cyclones. Simulations of aerodynamic processes of two-phase flow inside the dust collectors were carried out based on the Comsol Multiphysics 5.6 software package, where the k-ε turbulence model was used. Any aerodynamic equipment is characterized by such an important parameter as resistance. The importance of this parameter lies in the fact that the consumption of energy supplied from the outside directly depends on the aerodynamic resistance. Therefore, when designing dust collectors, calculation and experimental resistance measurement is necessary. The aerodynamic resistance of cyclones is determined by the formula.

$$\Delta P = \xi \frac{\rho v^2}{2} \tag{1}$$

where ξ=20D is drag coefficient, D is pipe diameter, ρ is density of drag, ν is velocity of drag. The calculation of aerodynamic drag was shown in detail in the dissertation work [7].

2 Methods

To study the flow dynamics, we consider a system of hydrodynamic equations. In this case, we will assume that the bulk density of particles in the main flow zone is negligibly small compared to the density of the gas flow. Indeed, in real dust collectors, the dust density does not exceed 10 gr/m3, and the air density is 1,29 kg/m3. However, the dust density near the wall due to accumulation can greatly exceed this indicator. But this happens in a rather narrow layer, the size of which can be neglected in comparison with the characteristic parameters of the dust collector. Forces acting on dust particles in centrifugal dust collectors. Of the external forces acting on a particle in centrifugal dust collectors, the main force is the centrifugal force. Let us estimate the particle acceleration obtained as a result of the action of this force

$$a_c = \frac{V_c^2}{R} \tag{2}$$

where V_c is circumferential speed, R is the circle's radius in the particle trajectory.
Consider the characteristic values for these parameters, if V_c=13 m/s, R=0.1 m,
then for acceleration, we get

$$a_c = 1690\, m/s^2 \tag{3}$$

As we can see, centrifugal acceleration is more than free-fall acceleration. In addition to these forces, other forces of various natures also arise in dust collectors. These forces are considered below, and their estimates are given. To evaluate these forces, their accelerations are compared with the acceleration of the centrifugal force. This is necessary to identify which are important for constructing a mathematical model for the transport of particles and aerosols. Forces of Magnus and Sefmen acting on dust particles. The presence of gradients of the averaged and fluctuating components of the velocity of the longitudinal motion of the gas results in the appearance of a special form of transverse motion of particles, which is called the upward migration of particles in the literature. This form of particle motion is based on the so-called Magnus effect - the emergence of a transverse force acting on a streamlined body in the case of its rotation around an axis perpendicular to the motion. The reason for the occurrence of the transverse force is the pressure drop from the side, where the sum of the tangential components of the velocities of the flow and rotation of the body reaches a maximum. The transverse force is always directed towards this maximum. In a shear turbulent gas flow, the flow around particles occurs not only due to their settling under the action of gravity but also due to the phenomenon of longitudinal sliding of particles and the pulsating nature of the gas flow. The rotation of the particles is due to a shift in the speed of their relative motion or, more rarely, by a collision with the walls, accompanied in the case of solid particles by a kind of "skid".

This means that the phenomenon of upward migration of particles is characteristic of both vertical and horizontal turbulent flows. In this case, the velocity vector of the upward migration of particles in some cases is directed towards the axis of the flow, and in others, on the contrary, towards the wall.

To determine the numerical value of the transverse force acting on an aerosol particle in an in-line turbulent gas flow, the solutions of Rubinov and Keller [9] or Sefman [10] are usually used in theoretical works, which is not quite correct. Rubinov and Keller [9] gave a solution for the transverse force acting on a small self-rotating spherical particle moving in a boundless shear viscous flow:

$$F_L = \frac{\pi}{8}\rho d^3\left[\Omega \times U_{pm}\right], \tag{4}$$

where Ω is particle angular velocity, a U_{pm} is the relative speed of its forward movement (sliding speed).

However, for the case of an aerosol flow in a tube, as Cox and Brenner showed [11], this result cannot be directly applied since here, the rotation of the particle is not imposed from the outside but follows from the shear motion of the gas itself.

This circumstance was taken into account by Sefman [10], and he gave the following solution for the transverse force acting on a freely rotating spherical particle moving in a viscous flow with a linear velocity shift (Couette flow):

$$F_{Sef} = 1.6\rho d^2\left[\frac{\nu}{\Gamma}\right]^{\frac{1}{2}}\left[\Gamma \times U_{pm}\right], \tag{5}$$

To find out how intense the upward migration of particles is, we find the acceleration of the particle experiencing the lifting force. If m_p is weight, ρ_p is density, a a_{Sef} is acceleration of the particle caused by the Sefman force, then the acceleration is

$$a_{Sef} = \frac{F_{Sef}}{m_p} = \frac{9.6}{\pi}\frac{\rho \Delta U_{pm}}{\rho_p d}\sqrt{\nu\frac{dU}{dy}} \tag{6}$$

The velocity gradient has a maximum in the viscous sublayer and has the value

$$\frac{dU}{dy} = \frac{U_*^2}{\nu} \tag{7}$$

and to find the sliding speed, we use the formula

$$\frac{\Delta U_{pm}}{U_m} = 1220 CmdU_m^{0.4}, \tag{8}$$

substituting these expressions into formula (3), we obtain

$$a_{Sef} = 3730\frac{\rho C_m U_*}{\rho_p}U_m^{1.4} \tag{9}$$

As in the previous section, we will evaluate this expression for the characteristic parameters of the air cleaner U_m=10 m/s, D_e=0.06 m, for them, we get $Re_D \approx 4\times10^4$ and $U_* \approx 0.53$ m/s.

The Kenningham coefficient for large particles is equal to one. Therefore, for the main particles with a density $\rho_p \approx 2\times10^3$ kg/m^3 we have an estimate for the acceleration range $a_{Sef} \approx 7 - 40\ m/s^2$.

Thus, the acceleration caused by the lifting force is significantly less than the main acceleration - centrifugal.

For the numerical study of the problem posed, the system of Navier-Stokes equations averaged over Reynolds is used [12, 13]. The system of equations does not consider the forces due to the effects of turbulent migration, Sefman, Magnus (lift), and Coriolis because they are significantly less than the centrifugal force.

Thus, for mathematical modeling of the processes of transfer of dust particles and aerosols in dust collectors, it is sufficient to consider the centrifugal, gravitational $\overline{G}$, Archimandial $\overline{F_a}$, and Stokes force $\bar{F}$.

$$\begin{cases} \frac{\partial \bar{U}_i}{\partial t} + \bar{U}_j \frac{\partial \bar{U}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \bar{G} + \frac{\partial}{\partial x_j}\left[(\nu+\nu_t)\left(\frac{\partial \bar{U}_i}{\partial x_j}+\frac{\partial \bar{U}_j}{\partial x_i}\right)\right], \\ \frac{\partial \bar{U}_{pi}}{\partial t} + \bar{U}_j \frac{\partial \bar{U}_{pi}}{\partial x_j} = \sum_{k=1}^{n} F_k = \bar{G} + \overline{F_A} + \bar{F}, \\ \frac{\partial \rho_m}{\partial t} + \bar{U}_{pi}\frac{\partial \rho_m}{\partial x_j} = D\frac{\partial}{\partial x_j}\left[\frac{\partial \rho_m}{\partial x_j}+\frac{\partial \rho_m}{\partial x_i}\right], \frac{\partial \bar{U}_j}{\partial x_j} = 0. \end{cases} \tag{10}$$

Here $\bar{U}_i$is respectively axial, radial, and tangential components of the air flow velocity; $\bar{U}_{pi}$is similar velocity components for m-th dust fractions;$\bar{p}$ is hydrostatic pressure; ρ is gas density; ν, ν_t are molecular and turbulent viscosities; $\rho_m$is dust mass density*;* m- number of dust fractions; $D = \frac{\rho}{S_c(\rho+\rho_\rho)}(\nu+\nu_t)$ is diffusion coefficient for the solid phase*,* $Sc = 0.8$ *is* Schmidt number.

The force of gravity is defined as follows.

$$\bar{G} = m_p\, g = \frac{1}{6}\pi d_e^3 \rho_p g \tag{11}$$

where $m_{\text{ч}}$ is particle mass,g is acceleration of gravity, d_e is equivalent particle diameter, ρ_p is particle density.

$$\overline{F_A} = V_p \rho g = \frac{1}{6}\pi d_e^3 \rho g \tag{12}$$

The aerodynamic force $\bar{F}$ was determined through the Stokes parameter for turbulent flow:

$$\overline{F} = \frac{1}{2} C_D S \rho\left(\overline{U} - \overline{U_{\mathrm{pi}}}\right)\left|\overline{U} - \overline{U_{\mathrm{pi}}}\right| \tag{13}$$

where C_D is drag coefficient determined through the Reynolds criterion, those $C_D = C_D$ (Re); S is particle midsection area, $S = \frac{\pi d_e^2}{4}$

If the particle lags behind the flow $\left(\overline{U} < \overline{U_{\mathrm{pi}}}\right)$, the aerodynamic force will accelerate the particle and help equalize the velocities $\overline{U}$ and $\overline{U_{\mathrm{pi}}}$. Otherwise – force $\overline{F}$ slows down the particle.

In [14], the k-ε turbulence model was described in detail. The turbulence model k-ε in tensor form is as follows:

$$\begin{cases} \dfrac{\partial \rho k}{\partial t} + \bar{U}_j \dfrac{\partial \rho k}{\partial x_j} = \dfrac{\partial}{\partial x_j}\left[(\mu + \dfrac{\mu_t}{\sigma_k})\dfrac{\partial k}{\partial x_j}\right] + P_k - \varepsilon\rho, \\ \dfrac{\partial \rho \varepsilon}{\partial t} + \bar{U}_j \dfrac{\partial \rho \varepsilon}{\partial x_j} = \dfrac{\partial}{\partial x_j}\left[(\mu + \dfrac{\mu_t}{\sigma_\varepsilon})\dfrac{\partial \varepsilon}{\partial x_j}\right] + C_1 \dfrac{\varepsilon}{k} P_k - C_2 \rho \dfrac{\varepsilon^2}{k} \end{cases} \quad (14)$$

where P_κ is energy generation of turbulent pulsations, the turbulent viscosity is calculated as $\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}, \nu_t = C_\mu \frac{k^2}{\varepsilon}$

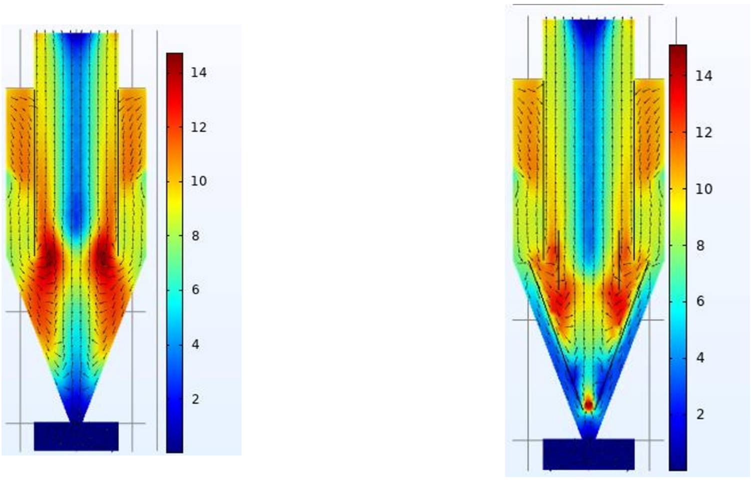
According to modeling the kinematics of particle motion in a turbulent two-phase flow, no single representation would allow one to correctly describe an object [15]. The model based on the concept of "trajectory particles" is considered incorrect due to the lack of consideration of the factor of interaction between Reynolds stresses and particles. On the other hand, the advantages of the Lagrangian approach, which is closer to real processes and makes it possible to obtain the necessary information about the particle trajectories, the residence time of the particles in the apparatus, and the minimum size of particles to be captured, are indisputable [16–19]. In this regard, the Lagrangian approach was used to model the efficiency of a centrifugal dust collector in this work.

The numerical solution of the presented systems of equations was carried out in the physical variables velocity–pressure by physically splitting the velocity and pressure fields [20]. The numerical solution of the transport equation is carried out on a hybrid checkerboard difference grid by the control volume method. The same method was used when solving systems of equations (10-14) numerically.

The computational experiment was carried out at three flow rates 1) $U_0 = 7m/s$, $U_0 = 10m/s$, 2) 3) $U_0 = 13m/s$. The total density of the solid phase at the inlet was equal to $\rho_m = 10g/m^3$ and distributed uniformly over the cross-section.

3 Results and Discussion

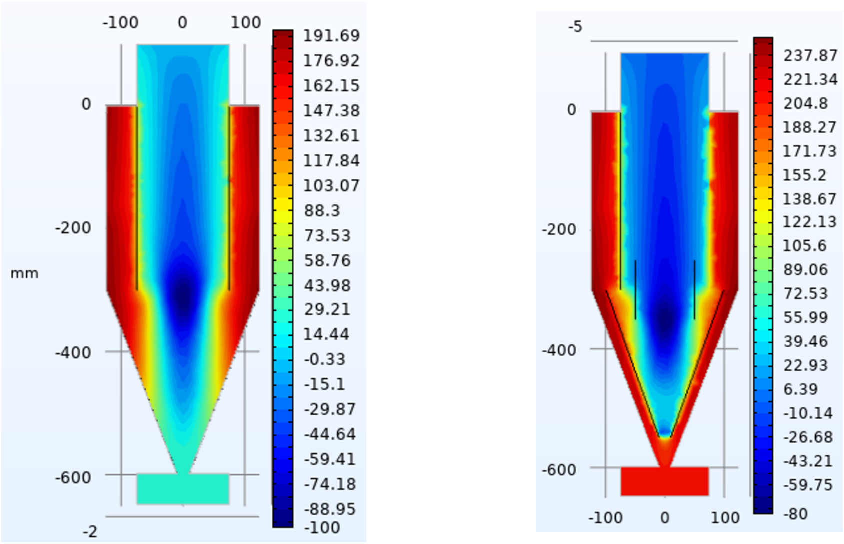
The main factors affecting the dust collector's efficiency are the gas flow rate in the inlet pipe, the size and density of dust particles. Therefore, comparisons were made in the work at input velocities 1) $U_0 = 7m/s$, 2) $U_0 = 10m/s$, 3) $U_0 = 13m/s$. On fig. 3 shows isolines and vectors of the velocity field in dust collectors.



a) b)

Fig. 3. Isolines and vectors of velocity field in dust collectors at $U_0 = 7m/s$. a) Classical centrifugal dust collector, b) Modified centrifugal dust collector

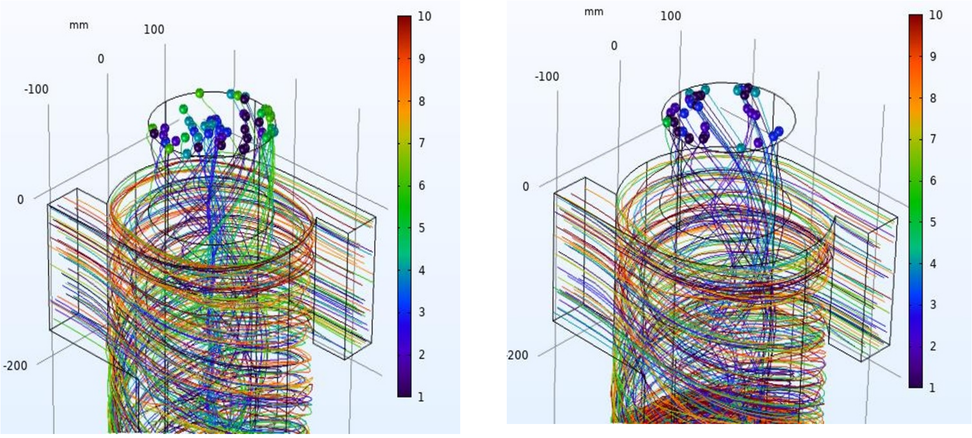
In fig. 4 shows pressure isolines in dust collectors.



a) b)

Fig. 4. Isolines of pressure of central part of dust collector at $U_0 = 7m/s$, a) Classical centrifugal dust collector, b) Modified centrifugal dust collector

Fig. 5 shows the trajectories of particles (colored according to their size) in the upper part of the dust collectors at speed at the entrance to the apparatus $U_0 = 7m/s$.



a) b)

Fig. 5. Trajectories of particle movement (colored according to their size) in upper part of dust collector at speed at inlet to apparatus $U_0 = 7m/s$. a) Classical centrifugal dust collector, b) Developed centrifugal dust collector

To determine the efficiency of dust collectors, in Fig. 6 shows the percentage values of outgoing dust particles of a certain fraction at the inlet air speed $U_0 = 7m/s$.

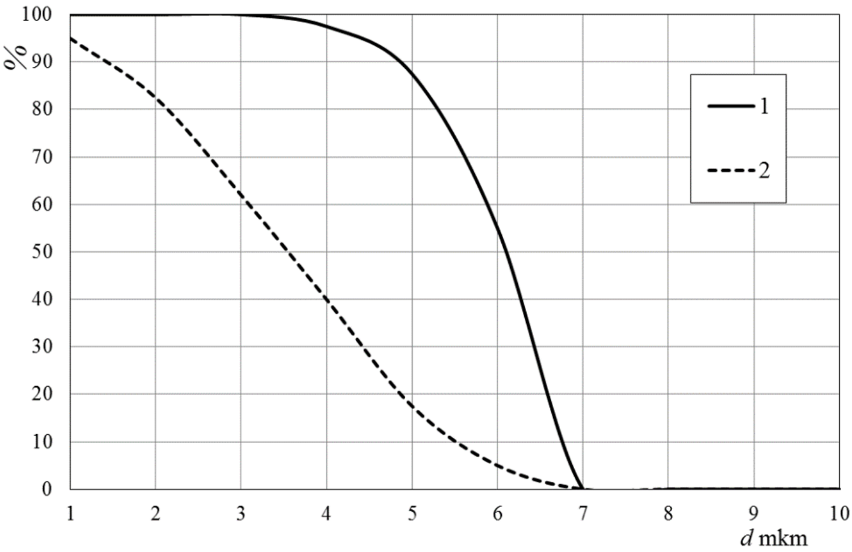
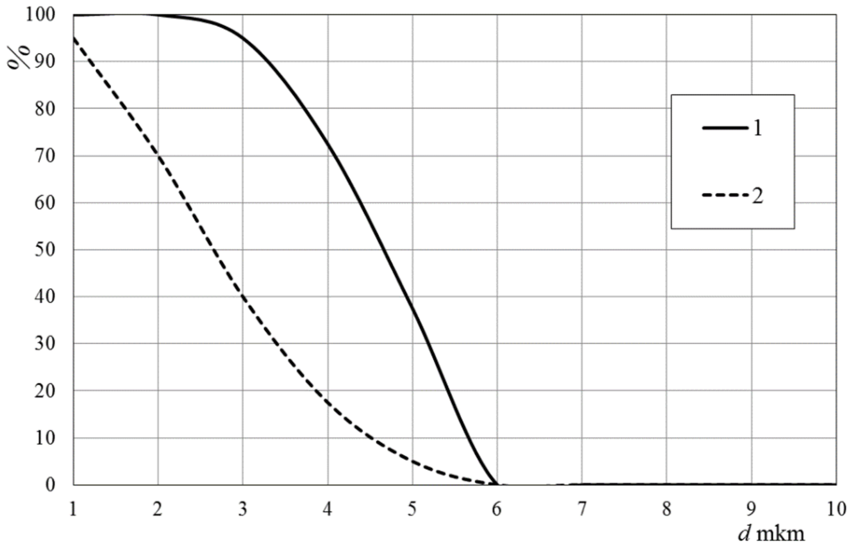


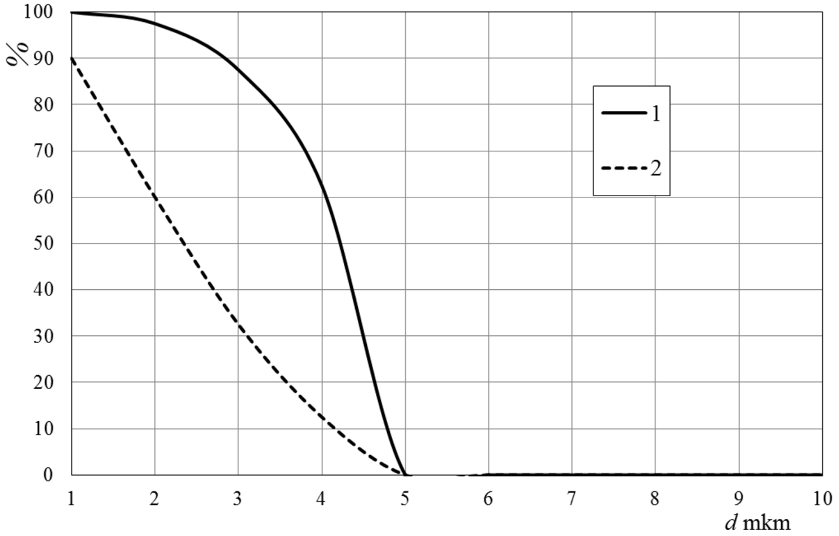
Fig. 6. Percentage of particle emission from dust collectors at a) $U_0 = 7m/s$. 1) Classical centrifugal dust collector, 2) Developed centrifugal dust collector

From Fig. 6, it can be seen that both dust collectors completely capture particles larger than 7 microns. The advantage of the modified [8] dust collector is manifested for particles smaller than 7 microns. For example, for particles of 4 microns, a classic centrifugal dust collector captures only 2%, and a modified centrifugal dust collector 60%.

To increase the efficiency of dust collectors, calculations were made for inlet air velocities $U_0 = 10{,}13m/s$. On Fig. 7 shows the numerical results of dust particle entrainment.



a)



b)

Fig. 7. Outgoing particles from dust collectors when a) $U_0 = 10m/s$, b) $U_0 = 13m/s$. 1) Classical centrifugal dust collector, 2) Developed centrifugal dust collector

The above graphs show that the increase in air flow rate from 7 m/s to 13 m/s leads to a decrease from 40% before 10% ash for particle diameter 4 microns; that carryover is reduced by four times.

Fig. 8 shows the aerodynamic drag of cyclones.

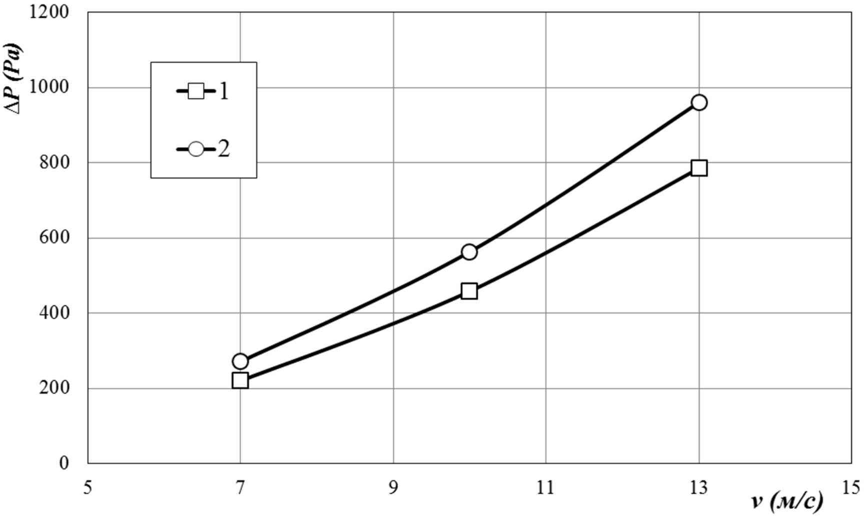


Fig. 8. Cyclone resistance.1) Classical centrifugal dust collector, 2) Developed centrifugal dust collector

Fig. 8 shows the resistance of the designed centrifugal dust collector is 18% more than the classical centrifugal dust collector. This does not affect the efficiency of the developed centrifugal dust collector.

4 Conclusions

In this work, the Comsol Multiphysics 5.6 software package was used to simulate the aerodynamic processes of a two-phase flow inside a classical and modified centrifugal dust collector. In this case, the k-ε turbulence model was used. The results confirm that the modified centrifugal dust collector is more efficient than the classical cyclone. Thus, it can be argued that modeling aerodynamic processes using modern software packages is an effective tool for designing various dust collectors.

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