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EVALUATION OF THE EFFICIENCY OF A MULTI-CHANNEL DUST COLLECTOR USING NUMERICAL SIMULATION

С. Сурков, О. Бутенко, С. Смик, А. Карамушко. **Оцінка ефективності багатоканального пиловловлювача шляхом чисельного моделювання.** Багатоканальні пиловловлювачі засновані на раніше відомих конструкціях вихрових сушарок сипучих продуктів. Однак їх застосування для знепилення повітря є перспективним. У виконаних раніше дослідженнях цих апаратів з використанням чисельного моделювання не проводилася оцінка коефіцієнта пиловловлення, хоча він є найважливішим показником їх ефективності. У даній статті проведено чисельне моделювання багатоканальних пиловловлювачів. Першим етапом моделювання є розрахунок полів швидкостей та тисків газового потоку в досліджуваному апараті. На другому етапі виконано розрахунок великої кількості траєкторій частинок пилу різного діаметра з наступною статистичною обробкою. Розраховано коефіцієнти пиловловлювання і коефіцієнти гідравлічних втрат. Показано, що для достовірності результатів чисельного експерименту кількість частинок пилу повинна бути не менше 2000. Для визначення впливу зовнішніх напівоболонок на ефективність пристрою, ці напівоболонки було відкинуто, в результаті чого багатоканальний пиловловлювач перетворився на циклон. Порівняння характеристик показало, що за інших рівних умов апарати, які досліджуються, мають деякі переваги перед циклонами в уловлюванні дрібних фракцій пилу. Була висунута і спростована гіпотеза про те, що захоплення частинок в криволінійних каналах відбувається в основному за рахунок зіткнень частинок з передніми кромками металевих напівоболонок. Результати чисельного моделювання не підтверджують гіпотезу про те, що деякі частинки пилу обертаються по замкненим траєкторіям і утворюють фільтр для інших частинок. Формули інших авторів, які не враховують параметри частинок пилу, визнано непрацєздатними. Міркування деяких авторів про вплив вихрового ефекту Ранка-Хілша на процес пиловловлювання не можуть бути прийняті до уваги через малі дозвукові швидкості повітря в умовах експлуатації апаратів.
Ключові слова: інерційні пиловловлювачі, комп'ютерне моделювання, коефіцієнт пиловловлювання

S. Surkov, O. Butenko, S. Smyk, A. Karamushko. **Evaliation of the efficiency of a multi-channel dust collector using numerical simulation.** Multi-channel dust collectors are based on previously known designs of vortex dryers for bulk products. However, their use for air dust removal is promising. In earlier studies of these devices using numerical simulations, the dust capture coefficient was not evaluated, although it is the most important indicator of their efficiency. In this article, the numerical simulation of MCDC is carried out. The first stage of modeling is the calculation of the gas flow velocity and pressure fields in the device under study. At the second stage, a large number of trajectories of dust particles of different diameters were calculated with subsequent statistical processing. Dust capture coefficients and hydraulic loss coefficients were calculated. It is shown that for the reliability of the results of the numerical experiment, the number of dust particles should be at least 2000. To determine the effect of the outer half-shells on the efficiency of the device, these half-shells were discarded, as a result of which the multi-channel dust collector turned into a cyclone. The comparison of characteristics showed that, other things being equal, the devices being investigated have some advantages over cyclones in capturing of small fractions of dust. The hypothesis that the capture of particles in curved channels occurs mainly due to particle collisions with the front edges of metal half-shells was put forward and refuted. The results of numerical modeling do not support the hypothesis that some dust particles rotate along closed trajectories and form a filter for other particles. The formulas of other authors, which do not take into account the parameters of dust particles, are recognized as unworkable. The speculations of some authors about the influence of the Ranque-Hilsch vortex effect on the process of dust capture cannot be taken into account due to the low subsonic air velocities under the operating conditions of the apparatus.
Keywords: inertial dust catchers, computer simulation, dust capture coefficient

Introduction

One of the components of the task of increasing the level of environmental safety in Ukraine is to improve the quality of cleaning of the industrial gas emissions from polydisperse dust.

The efficiency of gas purification is mainly determined by the type of the dust collector, namely, the principle of its operation, design and operating parameters, as well as the properties of the dust to be captured – the density of the material of dust particles and the fractional composition. Most of the common industrial dust collectors provide a high degree of air purification from coarse dust fractions, and mainly small fractions are carried away from the apparatus. The best example of such a relationship is inertial catchers (cyclones). Their total capture coefficient rarely exceeds 80…85%, which does not meet modern environmental safety requirements. At the same time, due to the positive qualities of inertial collectors, such as reliability and efficiency, they are still quite widespread today. This is espe-

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cially typical for small industries, which use such devices to purify the dusty air in the production area (for example, in woodworking plants, workshops for the production and packaging of bulk materials, etc.). The modernization of purification equipment in such industries is hindered mainly by economic factors – against the background of very low emission charges in Ukraine, the purchase of modern equipment is usually economically unprofitable. At the same time, most of these industries are located on the outskirts of settlements, which adversely affects the environmental situation. Therefore, the problem of increasing the efficiency of cleaning gas emissions in inertial apparatuses remains relevant.

Analysis of publications on the topic of research

Many designs of inertial-type dust collectors are known. The possibilities of increasing their efficiency by optimizing the design are practically exhausted [1].

In [2], the design of a multichannel dust collecting apparatus (MCDC) is described. This design includes several cylindrical half-shells shifted relative to each other (Fig. 1). These half-shells form several curved channels connected in series, in each of which the flow turns by 180°.

According to [2] and the works cited therein, MCDC have certain advantages over previously known devices. However, in our opinion, the study of the features of the operation of such devices has not been completed in full.

The difference between the principle of operation of MCDC and other inertial dust collectors is not completely clear. In [2, 3], a hypothesis was put forward, according to which a large number of dust particles circulate in closed orbits. Such a flow of dust particles, supposedly serves as a natural filter for newly arriving particles, as it is shown in Fig. 1. This hypothesis was accepted as the basic working principle of the MCDC, although no convincing justification was provided.

The filtration hypothesis seems questionable, at least because secondary flows arise in the curved channel, hence the trajectories of particles cannot be closed [4]. Most likely, large particles will settle on the walls already in the external channels, while small particles will penetrate into the internal channels. Collisions between particles of different fractions seem unlikely.

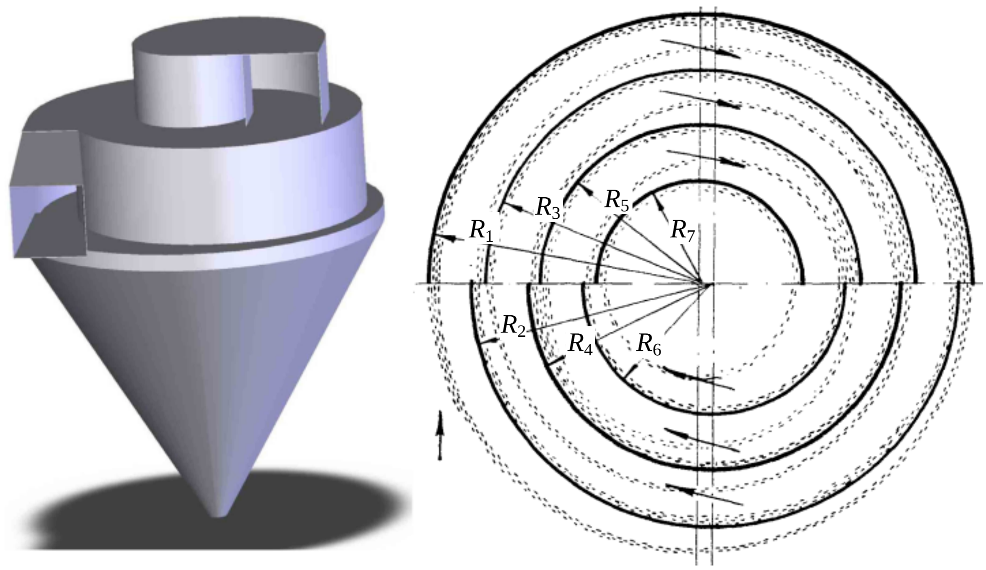

Fig. 1. General view of the MCDC and a diagram illustrating the proposed principle of its operation according to [2]

In [2, 3] a formula for the concentration of dust particles has been suggested but not substantiated:

$$C_{out} = \frac{C_{in}}{1 + 2^{n-1}}, \quad (1)$$

where C_{in} and C_{out} – respectively, the input and output concentration of solid particles in the dusty flow;

n – the number of curved channels connected in series.

Since in Eq. (1) the density and size of solid particles, as well as the design parameters of the apparatus, are in no way taken into account, its applicability for the design of apparatus and the assessment of the dust collection efficiency seems to be questionable.

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In [5 – 9], numerical simulation of flows in spiral channels was carried out. The fields of pressures, velocities and air temperatures were calculated. However, the simulation of the movement and deposition of dust particles on the walls of the apparatus has not been performed.

At the same time, as one of the results of the study, a decrease in the temperature of the gas flow with an increase in speed was called. In [6], it was said about the analogy between the field of dissipation of mechanical energy and the general picture of the trajectories of solid particles.

Thus, in previous studies, due to the insufficient amount of experimental data, which is caused by the complexity of physical modeling, the physical mechanism of particle trapping in the MCDC has not been completely clarified. The design parameters affecting the capture coefficient were not identified and the optimization of the device was not performed. As a result, there is a lack of general recommendations for the design and calculation of efficiency indicators of the apparatus. At the same time, the data [2, 3] testify to the unconditional promise of such a design and the expediency of its practical use. In addition, modern methods of aerodynamic numerical modeling make it possible to calculate the design and operational parameters of the MCDC in relation to specific production conditions (gas flow rate, fractional composition and initial dust concentration, particle density, etc.) without significant efforts.

Although the software used in [5 – 9] made it possible to simulate the motion of solid particles and estimate the collection coefficient by statistical processing, as it was done, for example, in [10], this part of the study has not yet been performed.

The goal of the work

To formulate general recommendations for calculating the design and efficiency indicators of MCDC by the method of numerical simulation of a gas flow with dust particles in the channels of the apparatus by using applied software products.

To achieve the goal, numerical modeling was made using the SolidWorks package. The turbulent air flow was simulated by the finite volume method using the $k - \varepsilon$ turbulence model.

Main part

Thus, the performed verification of the adequacy of the SW results showed their good agreement with the experimental data of different authors. The assumptions made by the developers are generally correct and do not lead to noticeable distortions of the results, and therefore the proposed software product is adequate for the task.

In the series of numerical experiments presented below, an average flow rate of 20 m/s was set as the boundary condition in the inlet section of the apparatus, and a static pressure of 101325 Pa was set in the outlet section. The degree accuracy of SolidWorks calculations was set to 4. Automatic thickening of the computational grid near the walls was ensured due to the fact that a minimum gap width of 1 mm was specified.

The results of the aerodynamic calculation are presented in the form of velocity fields in the given sections of the vehicle. For clarity, the air flow velocities were displayed using a vector and colored background shading (Fig. 2). Fig. 2, *a* shows the calculated distribution of air velocities in the vertical section, and in Fig. 2, *b* – in a horizontal section of the MCDC.

It can be seen that the air flow velocities reach maximum values in the central part of the apparatus, which can be explained by the action of the law of conservation of angular momentum.

In the course of numerical experiments, a slight decrease in the temperature of the air flow was noted with an increase in its speed. This relationship is well known. In the simplest case, the relationship between temperature and velocity in an adiabatic gas flow is expressed by the Bernoulli equation for a trickle of an ideal gas:

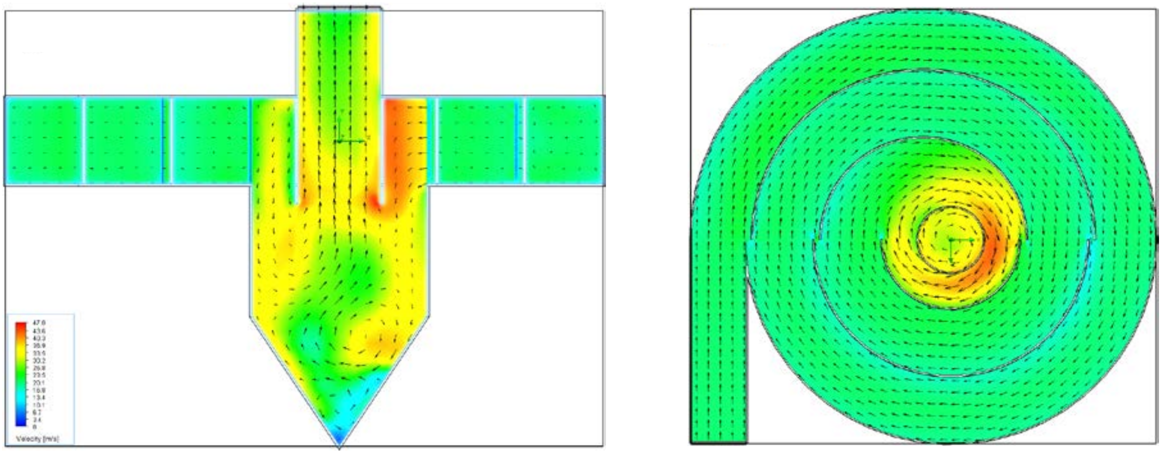
$$c_p T + \frac{u^2}{2} = \text{const}\,, \tag{2}$$

where c_p is the specific heat capacity of the gas at constant pressure, J/(kg·K);

T – the absolute thermodynamic temperature, K;

u – gas velocity, m/s.

It is obvious from Eq. (2) that a decrease in the flow temperature is not a feature of the investigated apparatus or the rotational motion of the gas, but follows from the fundamental laws of gas dynamics. The vortex Ranque-Hilsch effect, mentioned in [6], is also only a particular manifestation of Eq (2), but the temperature decrease in vortex tubes can reach tens of degrees.



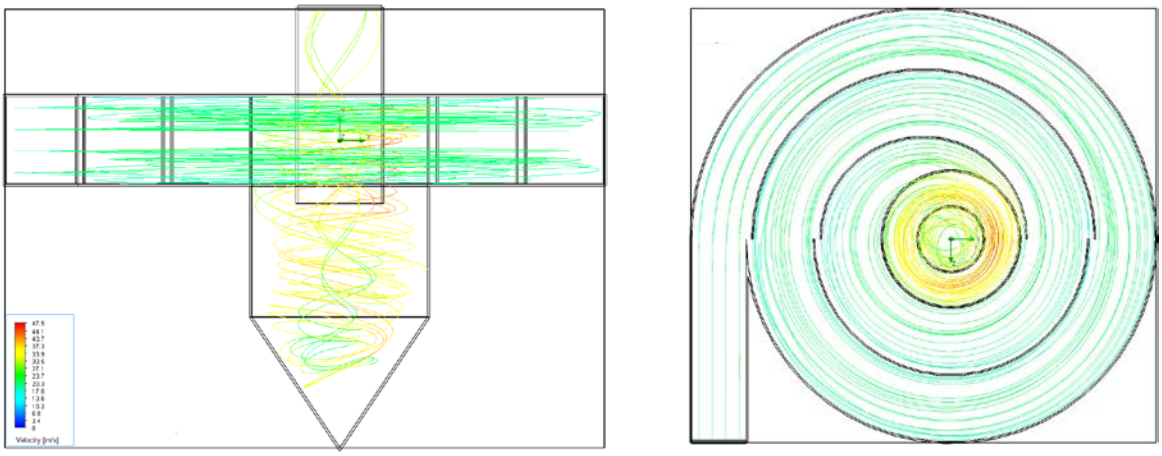
a *b*

Fig. 2. Calculated distributions of air velocities in the vertical (*a*) and horizontal (*b*) cross-sections of the MCDC

The most important task of modeling of the dust collecting apparatus should be the assessment of its efficiency, quantitatively characterized by the capture coefficient η, which is equal to the ratio of the mass of the captured dust to the mass that entered the apparatus.

Despite a large number of assumptions, most authors agree that the results of modeling various dust collecting devices, performed under the same assumptions and settings, allow comparing the characteristics of these devices with each other and choosing the optimal design [11].

When solving this problem, the assumptions and restrictions given above were accepted, the most fundamental of which was the condition of one hundred percent adhesion (trapping) of particles when they collide with the wall. The particle density was taken to be 2200 kg/m^3, which corresponds to the fly ash of most coals. Fig. 3 shows the calculated trajectories of particles with a diameter of 1 μm in the vertical and horizontal sections of the MCDC. The color of the trajectories represents the particle velocities. For clarity, only 16 particle trajectories are shown.



a *b*

Fig. 3. Calculated trajectories of particles with a diameter of 1 μm in the vertical (a) and horizontal (b) cross-sections of the MCDC

It can be seen from Fig. 3 that most of the particles have settled on the walls and only 7 of them are carried away from the apparatus through the upper branch pipe. However, for calculating of the capture coefficient, this amount of particles is obviously not enough.

Fig. 4 shows the trajectories of particles with a diameter of 9 μm for the same parameters as in Fig. 3. Again, only 16 trajectories are shown.

Comparison of the Figures 3 and 4 shows that the trajectories of the particles are fundamentally dependent on their size. Particles 1 μm in diameter (Fig. 3) in most parts of the trajectory move paral-

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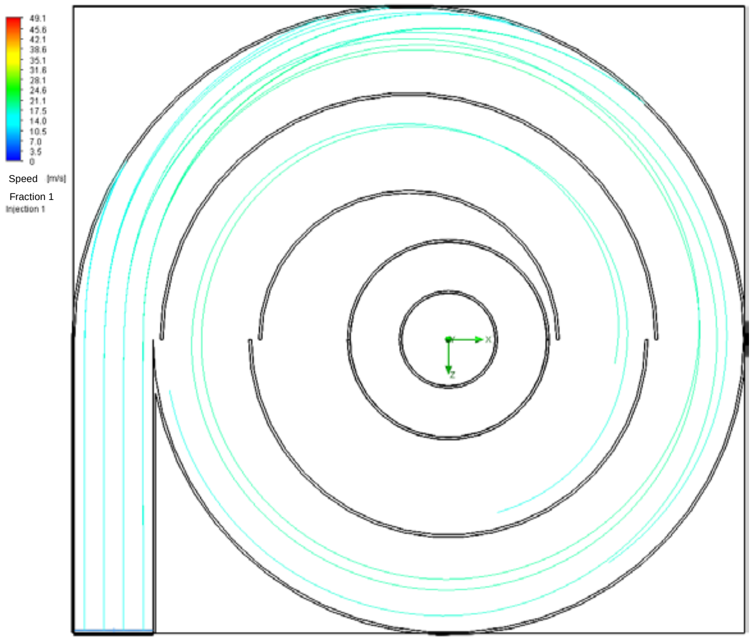


Fig. 4. Calculated trajectories of particles with a diameter of 9 μm in the horizontal cross-sections of the MCDC

lel to the walls. Most of the collisions with the walls occur in the center of the vehicle. In some cases, collisions of particles with the leading edges of the cylindrical half-shells can be observed.

The trajectories of particles with a diameter of 9 μm (Fig. 4) are less curvature. Most of the particles under investigation collide with the walls already at the first turn and do not reach the central part of the apparatus.

In addition, from Fig. 3 and 4 it can be seen that in no zone of the apparatus the trajectories of the particles are closed. In both cases, the flow pattern is not similar to the proposed one (Fig. 1). Thus, the hypothesis, that dust particles form a filter layer, has not been confirmed.

Due to such a significant influence of the particle size on their trajectories, the hypothesis of an analogy between the field of dissipation of mechanical energy and the general picture of the trajectories of solid particles, put forward in [6] seems questionable. The external similarity of the beam of trajectories with the field of dissipation of mechanical energy can be observed only for one certain particle size, and differ significantly for all other sizes. In addition, there is an obvious difference between the physical nature of the mechanical energy dissipation field, caused by the local characteristics of turbulence, and the particle trajectories obtained as a result of integrating the particle velocities over time.

Taking into account the assumption that the entire mass of dust consists of identical particles, the statistical processing of the results of numerical modeling makes it possible to obtain the dust capture coefficient as the ratio:

$$\eta = \frac{n_{set}}{n_{tot}}, \qquad (3)$$

where n_{set} is the number of particles settled on the walls;

n_{tot} – the total number of particles participating in the numerical experiment.

The total number of particles participating in the numerical experiment is set at the discretion of the user. However, for the engineering calculation of the MCDC it is first necessary to find out how many particles are sufficient. To answer this question, the dependence of the calculated capture coefficient η on a given number of particles was determined with constant geometry of the investigated apparatus, air velocity and characteristics of dust particles.

To process the results of calculating of a large number of particle trajectories, the function of exporting results from SolidWorks to Excel was used.

Fig. 5. shows a typical dependence of the capture coefficient of the MCDC on a given number of particles.

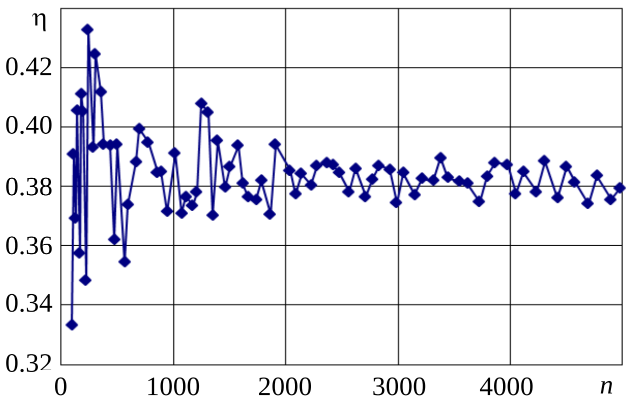


Fig. 5. Influence of the number of particles participating in the numerical experiment on the calculated capture coefficient η (diameter of the particles $d = 0.5$ μm)

As you can see, at $n < 2000$, the random scatter is large, which can be explained by the fact that the rows of particles, automatically arranged by the program at the corners of rectangular cells, collide with some solid surface, or, conversely, fall into the gap between the surfaces. At $n > 2000$, the scatter of the results associated with the error of the numerical experiment is significantly reduced and remains within 1 %. We can say that self-similarity in the number of particles is set in.

Thus, our further calculations of the capture coefficient were based on Eq (3). It was decided to set two values in further numerical experiments: $n_{tot} = 3000$ and $n_{tot} = 3050$, and to use the arithmetic mean of two calculated capture coefficients in the further analysis and plotting of graphs.

In [2, 3, 5 – 9], centrifugal force is considered as the main reason for the deposition of dust particles. However, it is well known, that the centrifugal force is defined as:

$$F_{cf} = \frac{mv^2}{r},$$

where v is the peripheral velocity of the particle, m/s;

m – particle mass, kg;

r – the radius of curvature of the trajectory, m.

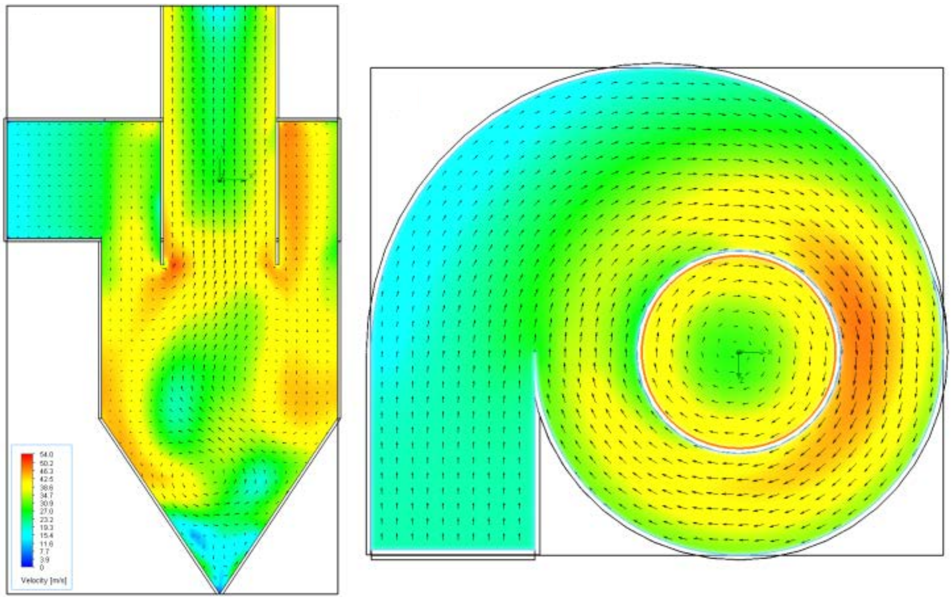
Thus, the centrifugal force will be maximal in the inner sections of the apparatus, where the radii of the half-shells are minimal and the air velocities are maximal. If centrifugal force is predominant then the deposition of particles on the walls will mainly occur in the inner half-shells, i.e. the role of peripheral channels would be minimal.

If we discard the system of semi-circular channels with large radii (Fig. 1), the well-known cyclone remains.

To estimate the contribution of large-radius half-shells, it was decided to compare the characteristics of the MCDC with the cyclone, which was obtained from the MCDC by discarding all the outer half-shells except the last one, which forms a tangential gas inlet into the cyclone.

The simulation of the cyclone obtained from MCDC in this way was carried out with the same software settings as the simulation of the original MCDC.

Fig. 6 shows the calculated distribution of gas velocities in the cyclone.



a *b*

Fig. 6. Distribution of air velocities in the vertical (*a*) and horizontal (*b*) cross-sections of cyclone, obtained from the MCDC by discarding the outer half-shells

For the initial design of MCDC and for the cyclone, the values of the capture coefficient at different particle diameters were calculated according to Eq (3). The results of the comparison are shown in Fig. 7.

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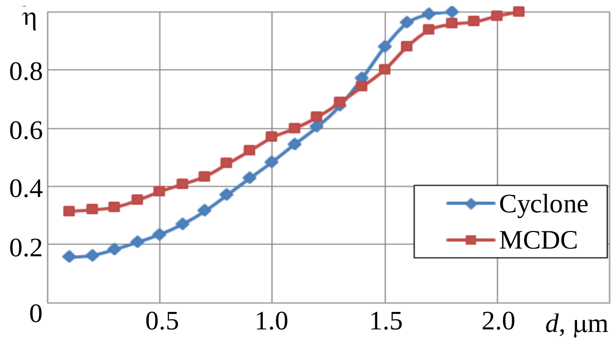

Fig. 7. Dependence of the capture coefficients by the cyclone and MCDC on the particle diameter

It can be seen from Fig. 7 that the capture coefficient in both apparatuses depends significantly on the particle diameter, which is typical for all inertial dust collectors. At the same time, Eq (1) at $n = 5$ gives us the capture coefficient 0.889, which does not depend on the particle diameter.

The graphs also show that the capture coefficient of both devices increase with the particles diameter growth, and at $d > 2$ μm approaches the maximum possible value of 1.0. At $d < 1.3$ μm, the calculated capture coefficient of the MCDC is greater than that of a cyclone, so the MCDC has advantages in capturing of small particles.

The reason for the increase in the coefficient of capture of small particles in the MCDC is not obvious. In the course of the study, it has been suggested that the main role in dust capture is played by particle collisions with the leading edge of the cylindrical half-shells. In this case, the dust capture coefficient should increase with increasing wall thickness, while the other dimensions of the apparatus remain unchanged.

Fig. 8 shows the graphs of dependence of the capture coefficient η for two particle sizes – 1 μm and 0.3 μm – on the thickness of the walls of the apparatus (and, therefore, on the thickness of the leading edge) with the geometry of the apparatus unchanged.

As can be seen from the graph, an increase in the capture coefficient with an increase in the thickness of the edge is not observed; therefore, the hypothesis of a significant effect of collisions of particles with the leading edge of the half-shell is not confirmed.

The hydraulic losses coefficients were calculated as:

$$\zeta = \frac{2\Delta p}{\rho v^2},$$

where Δp is total pressure loss in the apparatus, Pa;

ρ – gas density, kg/m^3;

v – gas velocity at the outlet of the apparatus, m/s.

The graph (Fig. 9) shows the dependence of the coefficient of hydraulic losses ζ on the wall thickness of the MCDC. For comparison, the cyclone coefficient of losses is shown.

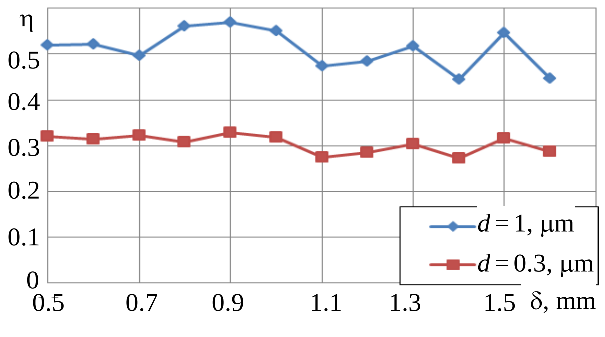

Fig. 8. Dependence of the coefficient of capture of particles with a diameter of $d = 1$ μm and $d = 0.3$ μm on the wall thickness

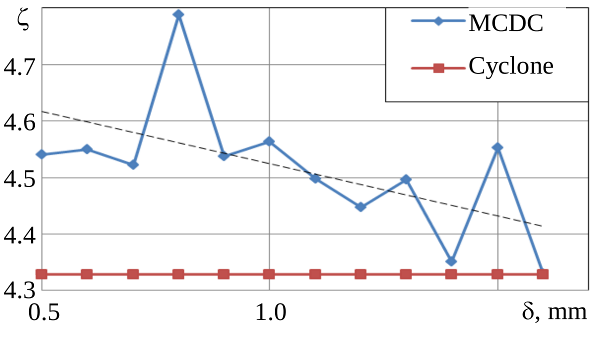

Fig. 9. Coefficient of hydraulic losses as a function of wall thickness

It can be seen from the Fig. 9 that the losses coefficient of the MCDC in the entire range of thicknesses is slightly higher than that of the cyclone. The linear trend line shows that ζ decreases slightly as δ increases. However, the increase in the loss factor will not lead to a significant increase in energy consumption.

Three-dimensional models of MCDC and cyclone, built in SolidWorks, allow estimating the metal consumption of structures. The calculation showed that with the same thickness of metal sheets and almost the same capture coefficient, the metal consumption of the MCDC is 3.5 times greater than the metal consumption of the cyclone. This metal consumption leads to a significant increase in the cost of the apparatus.

Numerical modeling performed does not allow evaluating such parameters of the apparatus as reliability and maintainability. Nevertheless, when designing industrial devices, they need to be given special attention.

Conclusions

When evaluating the effectiveness of inertial dust collecting devices, including MCDC, the use of numerical modeling is possible. The constraints and assumptions to which they are forced to resort do not have any significant effect on the result.

For greater reliability of the results, the compared devices should be simulated with the same settings and assumptions.

To exclude the influence of random parameters, the number of dust particles of a given size in a numerical experiment should be at least 2000.

Numerical modeling of the MCDC has been carried out. Calculated and shown on the graphs of the dependence of the capture coefficient on the size of dust particles at a given density of the particle material, as well as the coefficient of hydraulic losses.

In the course of numerical simulation, we did not need a hypothesis put forward in [6] about the predominant influence of mutual collisions of dust particles.

The formula for the MCDC dust capture coefficient proposed in [2, 3] does not take into account such important parameters as the size and density of dust particles. Respectively Eq (1) is not confirmed by the results of numerical modeling and therefore has no practical value.

In order to assess the effect of outer half-shells the results of MCDC modeling are compared with the parameters of the cyclone obtained from the MCDC by discarding the outer half-shells. The comparison showed that the multichannel dust collectors (MCDC) have some advantages in capturing fine dust fractions.

In the course of modeling, we put forward the hypothesis that the trapping of particles in curvilinear channels is mainly due to collisions of particles with the leading edges of the metal half-shells. But subsequently this hypothesis was rejected, as the research showed, that the thickness of the wall of the apparatus has practically no effect on the dust capture coefficient. Apparently the dust collection in the MCDC is the result of the complex three-dimensional motion of particles and is not completely clear.

Hydraulic losses in the MCDC are slightly higher than in a cyclone of the corresponding dimensions.

MCDC has a higher degree of collection of fine dust in comparison with conventional cyclones, and have approximately the same effectiveness for medium and coarse dust. Therefore, replacing cyclones with MCDC is possible for cleaning gas polydisperse streams with a predominant mass of fine fractions.

The disadvantages of MCDC include high metal consumption of the structure, relatively low resistance to emergencies and unsatisfactory maintainability.

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