Baltic J. Modern Computing, Vol. 12 (2024), No.3, 270-285
https://doi.org/10.22364/bjmc.2024.12.3.04

Mathematical and Computer Simulation of the Process of Movement of Respirable Dust Particles in the Working Area

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Abstract. Most air purification systems are formed on the basis of the "modular principle" using a waste-free production scheme, standardized dust collection equipment and ventilation systems. The disadvantages of such a complex, which is assembled from heterogeneous purification equipment, are the large overall dimensions of the devices, low individual performance and low gas flow rates in the devices, which limit the ability to purify large volumes of air, and therefore the task of preliminary verification of their capabilities arises. Modern computer simulation software makes it possible to study the movement of microscopic particles and determine the stable patterns of this process. This study focuses on the mathematical and computer simulation of the process of movement of respirable dust particles in the working area, based on the principles of designing efficient modular devices that maximize the use of centrifugal force to improve the performance of dust and gas cleaning equipment. The object of study is the proposed air purification device as a separate part of the overall purification complex. The subject of the study is computer simulation of the movement of dust particles in the air flow. The scientific and practical value of the research results is that for the first time the regularities of aerodynamic processes occurring in the cylindrical body of the "centrifugation module" were determined, which were obtained by mathematical and computer simulation methods, which confirms the effectiveness of air purification by the proposed device and makes it possible to introduce it into mass production.

Keywords: simulation, air purification, technological equipment, dust particles.

1. Introduction

Many production processes and air purification facilities are based on the "modular principle", which uses waste-free production schemes, standardized dust collection equipment and ventilation systems. The disadvantages of such a "modular complex", assembled from heterogeneous purification equipment, are the large overall dimensions of the devices, their low individual performance and low gas flow rates in the devices, which limit their capabilities when it comes to purifying large volumes of air. Therefore, the task of preliminary verification of the capabilities of any proposed purification systems arises. Modern methods of mathematical simulation and computer experimentation software allow us to study the movement of microscopic particles and determine the stable patterns that arise, as well as analyze not only the parameters of individual particles but also the macroscopic parameters of aerodynamic systems in general.

The main part of this complex of gas purification equipment is the process of dry particle separation in cyclones. The centrifugal force acting on the particle determines the equilibrium position of the particle in the flow and its separation (Birkhoff, 2015):

$$F = c_1 d_p^3 (\rho_p - \rho_{sp}) \omega^2 / r, \tag{1}$$

where c_1 is a constant; d_p is the diameter of the particle; ρ_p and ρ_{sp} are the densities of the particle and the space; ω is the angular velocity of the particle; r is the radius of its rotation.

Formula (1) shows, in particular, that high centrifugal forces and, consequently, high efficiency of the separation process can be achieved at high angular velocity of particles. However, it is worth noting that increasing the rotational speed in cyclones does not produce the desired effect due to the fact that the kinetic energy of turbulence increases, which intensifies the process of reverse mixing of the separated dust stream with the "clean" gas leaving the apparatus. In addition, at high inlet velocities, most of the dust falls out at a relatively short distance from the inlet, where it accumulates in large quantities on the cylindrical wall of the cyclone and increases its resistance. Therefore, the operating value of the cyclone inlet velocity is limited depending on the cyclone diameter.

Another important aspect is the origin and nature of the particles themselves. For example, machining of carbon-containing composite materials is characterized by a significant dust emission, which contains carbon fiber residues, nanotubes, coal dust and epoxy residues. At the same time, the processing of this type of material with an abrasive tool increases the amount of dust that is carried away from the cutting zone (Bayraktar et al., 2016). Such phenomena lead to the occurrence of occupational diseases, especially in the absence of personal protective equipment for workers in contact with carbon materials.

Existing computational complexes allow simulation the behavior of particles in various spatial configurations of the study area (Bai, 2017), while calculating statistical estimates of macroscopic parameters (density, temperature, pressure) in elementary volumes (Kumar et al., 2020; Biliaieva et al., 2019).

However, all of these studies have some, in our opinion, significant limitations that do not allow us to speak about the convergence of computer simulation results with the data obtained during the field experiment, since a number of important factors were not taken into account when entering the initial data, and most quantitative indicators need to be clarified. These factors include the volumetric dust consumption and its fractionation, which are the basis for the calculation as the initial data for this research.

This paper deals with the mathematical and computer simulation of the process of movement of inhaled dust particles in a purification device, based on the principles of designing efficient modular devices that use centrifugal force to increase the performance of dust and gas cleaning equipment. The object of study is the proposed three-dimensional model of the device ("module") for air purification, which is a component of the overall purification complex. The subject of the study is the simulation of the movement of dust particles in the air flow of the specified device. The main tasks that arise when designing such "modules" are to increase the rotation speed and residence time of the contaminated flow inside such a device. Therefore, this work focuses on mathematical and computer simulation, which has become the main tool for studying complex processes and systems today, and on which modern approaches to the design of products for various purposes are based. The article contains a mathematical description of the principles of creating air purification systems, designing a 3D model of a purification device, and computer simulation of aerodynamic processes occurring in its working area.

The scientific and practical value of the research results of this article lies in the fact that for the first time the regularities of aerodynamic processes occurring in the cylindrical body of the "centrifugation module" were determined by mathematical and computer simulation methods, which confirms the effectiveness of air purification by the proposed device and makes it possible to introduce it into mass production.

2. Methods, tools and approaches to research

The main research results of the article are based on the methods of critical analysis and logical generalization of the known results of scientific research in the field of simulation the technical mechanics of liquids and gases (Liu et al., 2019; Xiu et al., 2020; Zhou et al., 2022).

The research of this article is a logical continuation of the author's own theoretical and experimental studies in the field of mathematical and computer simulation, which are reflected in scientific articles (Chencheva et al., 2023; Salenko et al., 2020).

The results obtained were validated by conducting a full-scale experiment in the working area.

Computer simulation of particle motion can be divided into three stages:

1) determining the initial conditions;
2) changing the position of particles in space;
3) visualization of the results.

The initial conditions are the initial position of the particles, the number of particles, the initial vectors of the directions of movement in space, and the boundaries of the zones (in the form of continuous functions). The calculation step (the distance the particle travels in a given time period) and the calculation accuracy used to solve the problem of particle reflection from the zone boundary are also determined.

Each particle moves towards the boundary of the zone. Determining the new position of the particle after reflection involves the following steps:

1) selecting the boundary of the zone that the particle crosses in its trajectory;
2) determining the point of intersection of the particle trajectory and the boundary;
3) selecting the shortest distance from the initial position of the particle to the intersection point;
4) calculating the normal for the function at the intersection point;

5) calculation of the new direction vector.

All these parameters are calculated after each step (iteration).

Today, similar tasks are successfully solved in rolled steel cyclone chambers, where dispersed materials are subjected to heat treatment. The flow velocity at the chamber inlet reaches 190 m/s at a Reynolds number of Re=100000. Significantly higher centrifugal accelerations are achieved in centrifuges, machines that separate heterogeneous systems in a high-intensity centrifugal field, which exceeds the acceleration of natural dust particle deposition by tens of thousands of times. For example, in gas centrifuges for isotope separation, due to the high rotor speed, the linear velocity at the periphery can exceed 600 m/s. In this case, the product is concentrated near the chamber wall under high pressure, and a so-called vacuum core is formed in the rotor axis, which provides additional axial gas circulation inside the rotor.

However, these devices are very complex and expensive. For example, the main working element in a centrifuge is a hollow rotor that rotates rapidly around an axis, with finishing coatings, heat treatment and precision manufactured to aviation standards. The high quality of workmanship and cost of a whole range of auxiliary devices, such as rotor supports, magnetic bearings, motors, etc. Each of these devices is unique. Consistent operation of centrifuge components requires fine-tuning and highly skilled maintenance. These features practically exclude the use of centrifuges for the separation of suspensions from flue and corrosive gases, however, the method of achieving powerful centrifugal fields created by them remains a promising task for research and development.

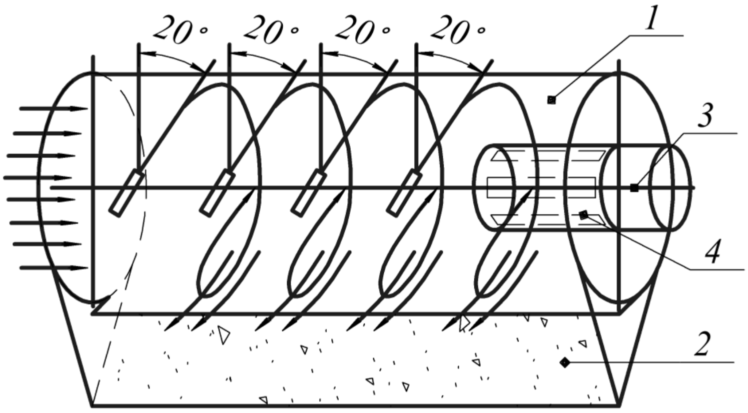

Figure 1. Schematic of suspended solids separation by gas centrifugation in a fixed vessel using high-speed hydrodynamic jets

In the proposed "centrifugation module", in order to preserve the above positive qualities of the centrifuge, it was decided to use a fixed body 1 – a cylinder with a cut-out 90° sector, which at the same time serves as a negative electrode. The proposed device is equipped with a rotor of the drive mechanism 3 with a positive electrode 4 placed on it. The cylindrical body 1 is mounted on the side sheets of the removable hopper 3 at a level 20° below the horizontal axis of the fixed body 1. On the right side, the side sheet is attached flush, and on the left side, it is overlapped with the body. In this case, on the left side, a part of the fixed body 1 in the form of a wing guided by the flow stream hangs over the collection hopper 2 (Fig. 1). During the centrifugation of gas flows, the "wing" directs the sludge and dripping liquid deposited on the walls of the fixed body 1 into the removable hopper 2.

The process of centrifugation of flue and corrosive gases in the proposed device is carried out by injecting hydrodynamic high-speed jets directed tangentially inside the fixed casing and co-directed with the flows of gases to be cleaned. To ensure the linear movement of the gas flow and the formation of a "vacuum core" along the casing axis, the hydrodynamic jets are fed with a 20° inclination to the vertical plane in the direction of the main flows inside the casing. The spiral motion of the jet allows the compacted sludge to be continuously discharged from the internal cavity of the fixed casing into the removable hopper.

The regularities of hydrodynamic processes occurring in the cylindrical body of the centrifugation module can be considered by analogy with cyclone piercing chambers operating at high flow rates.

All the mathematical dependencies used for the calculation are well-known in the context of applied technical mechanics of liquids and gases (Tannehill et al., 1997). At the same time, the equations are adapted in accordance with the research goal, taking into account the geometric parameters of the designed device and the conditions of its full functioning.

The volume of gas flow passing through the cross-section of the enclosure can be determined from the equation:

$$V_g = 2\pi r_o w_{mo} L = 2\pi r_c w_{mk} L_t, \tag{2}$$

where r_0 is the body radius; L_t is the length of the active turn of the gas vortex; r_c is the current radius; $w_{mk}=w_{mo}r_o/r_c$ is the radial flow velocity.

The resulting velocity vector is shifted relative to the angular velocity vector by an angle that causes the gas flow to move towards the axis and dust particles and condensate droplets to move towards the periphery of the chamber:

$$tg\alpha = w_{mk} / w_{nk} = w_{mo} / w_{no}, \tag{3}$$

where $w_{mk}=w_{mo}r_o/r_k$ is the angular velocity of the vortex flow.

The conditions for the movement of a particle along a circular trajectory are described by the equation that reflects the equality of the gas pressure force on the particle and the centrifugal force acting on it:

$$\psi \frac{\pi d_p^2}{4} \frac{w_{mk}^2}{2} \rho_g = \frac{\pi d_p^3}{6} \frac{w_{mk}^2}{r_c} \rho_p, \tag{4}$$

where $\psi=24v_p/d_p w_{mk}\rho_g$, and the physical properties of the gas are assumed to be at an average temperature.

The head loss during the flow into the apparatus is estimated by the formula:

$$\Delta P_1 = \frac{\rho_g}{2}\left(\frac{V_g}{\mu F_0}\right)^2, \tag{5}$$

where μ=0.85 is the flow coefficient; F_0 is the smallest cross-section of the Laval nozzle.

The head loss during vortex formation can be calculated using the formula:

$$\Delta P_2 = \frac{\rho_g}{2}\left[\left(\frac{D_0}{d_1}\rho\right)^2 - 1\right] w_{no}^2, \tag{6}$$

where D_0 is the diameter of the cylindrical body; d_1 is the diameter of the separator outlet.

The main hydrodynamic drag is concentrated in the fixed chamber, so a simplified formula can be adopted for the region Re=100000 (at an air velocity at the chamber inlet in the range of 190 m/s).

$$\Sigma\Delta P = 0.07\left(\frac{\Sigma F_0}{F_k}\right), \tag{7}$$

where ΣF_0 is the total area of the openings for the outlet of high-speed compressed air jets; F_K is the cross-sectional area of the chamber.

The leading role in the centrifugation process in the analyzed "module" is played by hydrodynamic accelerators with Laval nozzles, in which the compressed air outflow rate exceeds the Mach number (M>1). The opening angle of the jet plume in the open atmosphere is 23°, and in the compressed conditions of the plant vessel it reaches 50°. The compressed air flow rate from the Laval nozzle of a hydrodynamic accelerator can be determined by the formula for adiabatic flow:

$$\omega_1 = \varphi\sqrt{2g\cdot\frac{k}{k-1}\cdot\frac{P_1}{\gamma_g}\left[1-\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}\right]}, \tag{8}$$

where γ_g is the specific gravity of the gas in front of the nozzle at pressure P_1 ; φ is the leakage coefficient (for a nozzle with a cylindrical part and an angle of β=45° at l/d=0.18 φ=0.75, at l/d=0.56 φ = 0.9); k is the adiabatic coefficient (for two-atom gases and air, k=1.4); g is the acceleration of gravity; P_1 is the compressed air pressure before the nozzle; P_2 is the pressure before the nozzle outlet, equal to 101300 Pa.

Let us determine the air outflow rate from the nozzle of a hydrodynamic accelerator designed as a Laval nozzle and the compressed air flow rate per second under the conditions of air outflow into an environment with a pressure close to atmospheric pressure, i.e., where the pressure is lower than the critical pressure. In this mode of leakage, the pressure at the outlet of the nozzle is set equal to the critical pressure, and the leakage rate is equal to the critical rate, and the flow rate is maximum. The critical flow rate can be determined by the formula:

$$\omega_{cr} = \varphi\sqrt{2\frac{k}{k+1}RT_0}, \tag{9}$$

where R is the gas constant; T_0 is the gas temperature.

For comparison, the sound velocity at the nozzle outlet:

$$a_s = \varphi\sqrt{KRT_2}, \tag{10}$$

where , $T_2 = T_0\beta_{cr}^{\frac{k-1}{k}}$ $\beta = \dfrac{P_{av}}{P_0}$ are pressure ratios.

The compressed air consumption per unit hydrodynamic accelerator is determined by the formula:

$$m = m_{\max} = f\sqrt{2\frac{k}{k+1}\left(\frac{2}{k+1}\right)^{\frac{2}{k+1}}\cdot\frac{P_1}{V_0}}, \tag{11}$$

where P_1 is the air pressure in front of the nozzle; f *is* the nozzle cross-section; V_o is the specific volume of air in front of the nozzle.

$$V_0 = \frac{h_1 - u_1}{P_1}, \tag{12}$$

Here h_1 is enthalpy; u_1 is internal energy.

For two-atom gases, we have the following parameters under standard conditions: enthalpy h_1=283.2 kJ/kg; internal energy u_1=209.2 kJ/kg. From the relation for the ideal state of the gas $h=u+RT$, we find the gas constant:

$$R = \frac{h-u}{T} = \frac{283.2 - 209.1\cdot 10^3}{297.6} = 2524 \text{ kJ/kgK} \tag{13}$$

,

where T=273.6+20=293.6 K.

The ratio of the leakage pressure P_l= 0.5 MPa and the space into which the leakage occurs P_{av}=0.1 MPa is β=0.5/0.1=5. Then the critical pressure for air P_{cr}=0.528 MPa. Let's check whether the critical velocity at the nozzle outlet is really established:

$$P_0 = P_{cr} - P_l = 0.528 - 0.5 = 0{,}028 \text{ MPa} \tag{14}$$

.

Therefore, the pressure of the space is lower than the critical pressure and the jet speed should be close to the sound speed:

$$a_s = \sqrt{KRT_{air}} = \sqrt{1.4 \cdot 252.4 \cdot 293.6} = 322.1 \text{ m/s} \quad (15)$$

.

The specific volume of air at a pressure P_l=0.5 MPa is determined by the formula:

$$V_{air} = \frac{h-u}{P_l} = \frac{(283.2-209.1)\cdot 10^3}{5 \cdot 10^5} = 0.148 \text{ m}^3\text{/kg} \quad (16)$$

The specific volume of air inside the accelerator cone, i.e. in the leakage zone, is:

$$V_2 = \frac{h-u}{P_2} = \frac{(283.2-209.1)\cdot 10^3}{1 \cdot 10^5} = 0.741 \text{ m}^3\text{/kg} \quad (17)$$

Changes in compressed air temperature:

$$T_2 = T_0 \frac{2}{k+1} = 293{,}6 \frac{2}{1{,}4+1} = 244{,}6 \text{ K} \quad (18)$$

Let's determine the actual air leakage rate using the formula:

$$\omega_{cr} = \sqrt{2\frac{k}{k+1}RT_0} = \omega_2 = \sqrt{2\frac{1{,}4}{1.4+1}252.4 \cdot 293.6} = 272.2 \text{ m/s} \quad (19)$$

.

Thus, we can assume that the leakage rate is set equal to the local sound speed $a_{зв}$.

With a nozzle diameter of d=15 mm, the calculated area of the outlet section is f=0.000176 m^2. Then the compressed air consumption per unit hydrodynamic accelerator:

$$m = 0{,}000176\sqrt{2\frac{1{,}4}{1.4+1}\left(\frac{2}{1.4+1}\right)^{\frac{2}{1.4+1}}} \cdot \frac{5 \cdot 10^5}{0.0139} = 0.1348 \text{ kg/s or } 485.3 \text{ kg/h} \quad (20)$$

.

After returning to normal conditions, the volume flow rate for the individual hydrodynamic accelerator:

$$V = 483.5 \cdot 1.293 = 627.5 \text{ m/h}^3 \quad (21)$$

Compressor units are selected based on the total flow rate V. The total volumes of the receivers are selected to be 40 % larger than the output capacity of the compressors.

The main input data for the calculation are grouped in Table 1. The components of these data are the geometric parameters of the device and quantitative aerodynamic parameters.

Table 1: Initial data of preprocessing

Calculated area of the original section	0,000176 m^2
Specific air volume inside the accelerator cone	0.741 m/kg^3
Changes in compressed air temperature	244.6 K
Volumetric flow rate	485.3 kg/h
Dust fractionation	1–5 µm

Additionally, the phenomenon of gravity in the corresponding spatial computational grid, as well as dust fractionation, are taken into account. A limitation of the simulation is the representation of dust particles in the form of a sphere. At the same time, taking into account the irregular shape of the particles can only be considered as each individual act of its single interaction, which does not allow achieving the research goal of testing the performance and efficiency of the proposed device.

3. Research results

3.1. Computer model

Thus, the main technical characteristics of the centrifugation unit, which can be used in a "modular complex" for gas purification instead of typical cyclone devices with a larger diameter, have been determined. In particular, the speed at the nozzle outlet of the hydrodynamic device is more than 270 m/s. Further search for a basic unit was carried out with a view to ensuring a higher throughput capacity for gas flows, as well as increasing the efficiency of gas purification while reducing metal consumption, energy and cost costs.

The result of solving the set tasks using mathematical and computer simulation methods is the proposed installation for deep dust and sludge collection, which is assembled according to a modular scheme. The "modular complex" uses a single body – a larger diameter pipe with supply and discharge pipes and hoppers for dust and sludge removal. The casing is divided into separate component sections, such as a dust collecting chamber, a catalytic reduction chamber, a multifunctional adsorption "centrifugation chamber", and a draft blower unit, which is based on a gravity chamber for condensate and sludge collection.

The device comprises a large diameter cylindrical casing divided into 4 component modules (I, I, III, IV). Each module performs a specific function as a gas separation and purification stage and can be completed with a "modular complex" depending on the production needs.

Module I is a dust settling chamber for primary gas cleaning. It consists of an inlet pipe 1 with an elbow inserted at an angle of 30° into the body 2 of the dust removal chamber, a baffle diaphragm 3, a collection hopper 4 and a pneumatic conveying pipe 5. The velocity in the dust collecting chamber is within 10 m/s. Dust particles are deposited due to gravitational forces and changes in the direction of flow.

Thus, in the proposed multi-sectional dust and gas collection module, gases are separated and purified using high-speed compressed air flows at high centrifugal velocities corresponding to the level of centrifugation. Hydrodynamic accelerators installed tangentially at an angle of 20–25° to the vertical introduce high-speed compressed air flows into the internal cavity of the cylindrical casing and create a vortex (swirling flow), creating a vacuum (thrust) that reduces the overall aerodynamic drag of the plant. The use of dry catalytic neutralization of chemical impurities with a choice of adsorbents extends the versatility of the "modular complex", especially when capturing dioxins and polyaromatic hydrocarbons.

The possibility of dosed dispersion of water or adsorbents allows for the combination of dry, condensation and wet dust collection processes by selecting the optimum adsorbents depending on the composition of flue and corrosive gases.

The last stage of gas purification is a bladeless draft blower. In addition to gas purification and cooling, before being released into the atmosphere, the gas is provided with thrust throughout the cavity of the modular complex, which allows it to operate autonomously without the use of heavy thrusting devices in the high-temperature zone. The autonomous operation of the thrust-blower unit is ensured by the kinetic energy of the vortex flows in the centrifugation chamber and in the bladeless ventilation unit. The energy of the vortex flows is supplied by compressed air from the compressor unit.

Additionally, a device for purification of gas media, including positive and negative electrodes connected to a source of electrical energy, creates an electric field in the interelectrode space, and is characterized by the fact that the positive electrode is made in the form of a flat cylindrical body and is installed with the possibility of moving in the opposite direction of the gas space supply relative to the fixedly installed negative electrode and creating an electric field between the electrodes.

In addition, the device has a number of features that characterize it in certain cases of its execution, specific forms of its material embodiment or special conditions of its use, namely:

– the positive electrode can be mounted on a platform that is fixed to the rotor of the drive mechanism;

– the platform on the inner surface of the positive electrode can be equipped with a power supply, a voltage rectifier, a generator and a voltage multiplier connected in series;

– the device can be equipped with a hopper for collecting particles deposited on the positive electrode.

The technical result achieved by using this set of essential features of the device is that the movement of the positive electrode relative to the fixed negative electrode, which is the device body, provides an increase in the efficiency of polarization of particles of the contaminated gas space and their deposition on the outer surface of the positive electrode, as well as the possibility of continuous cleaning of this surface of the positive electrode without the need to stop the operation of the device.

The model of the proposed device as an initial structural element in section is shown in Fig. 2. It was built using SolidWorks 3D simulation software.

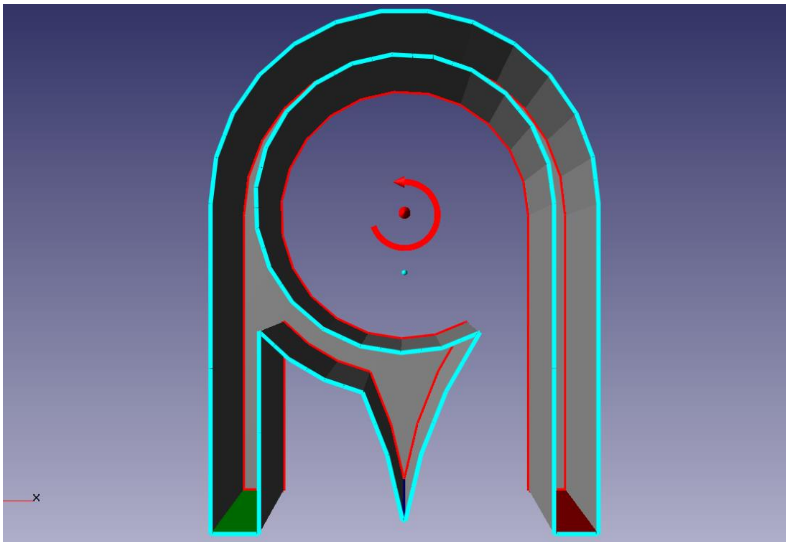

Figure 2: 3D model of an air purification device in a section with boundary restrictions

The device for purification of gas media contains a positive electrode and a negative electrode, the role of which is played by the device body. The positive electrode is made in the form of a flat cylindrical body and is mounted with the possibility of moving in the opposite direction of the gas supply relative to the fixed negative electrode (red circular arrow). The device is provided with a nozzle (green plane) for supplying the gas space to be cleaned into the space between the positive electrode and the negative electrode, as well as a nozzle (red plane) for discharging the cleaned gas space. The device contains a power supply, the output of which is connected to the input of a voltage rectifier, the output of which is connected to the input of a generator, the output of which is connected to the input of a voltage multiplier, the output of which is connected to the positive electrode. The device is equipped with a hopper for collecting particles removed from the gas space in the form of a cone (top is blue). The positive electrode is mounted on a platform mounted on the rotor of the drive mechanism (not shown). On the platform, on the inner surface of the electrode, there is a power supply, a voltage rectifier, a generator and a voltage multiplier. The device is equipped with a collection hopper for collecting particles deposited on the positive electrode.

The contaminated gas space is fed into the space between the negative electrode and the positive electrode, which rotates in the opposite direction to the gas space feed. The particles of the contaminated gas space, falling into the electric field created in the interelectrode space, are polarized and attracted to the outer surface of the positive electrode. The electrical circuit of the device, which consists of a power supply, a voltage rectifier, a generator and a voltage multiplier connected in series, creates a voltage of 1 60 kV or more on the positive electrode, which provides a high voltage of the electric field. The movement of the positive electrode relative to the fixed negative electrode towards the flow of the gas space to be cleaned, together with the high voltage of the electric field in the interelectrode space, significantly increases the efficiency of gas space cleaning.

The particles removed from the gas space under the action of their own weight fall into the hopper, which is subject to periodic cleaning.

3.2. Experimental validation of the model

To verify the theoretical positions, computer simulation was carried out using FlowVision software, the results of which are shown in Figs. 3–5. The simulation shows the movement of particles in the centrifuge in the form of vectors, complete fill and isolines (red – maximum values, blue – minimum or infinitesimal values).

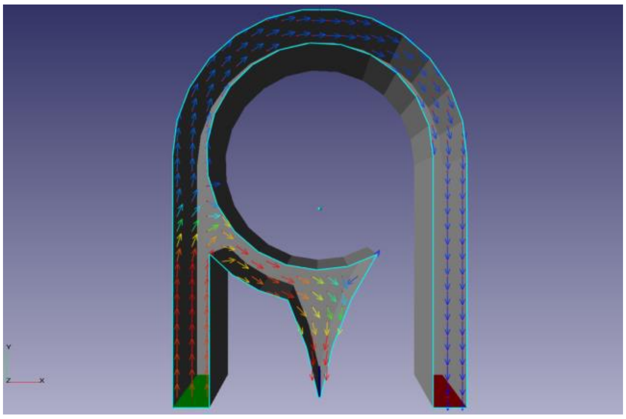

Figure 3. The velocity of particles in the air flow, displayed in vector form

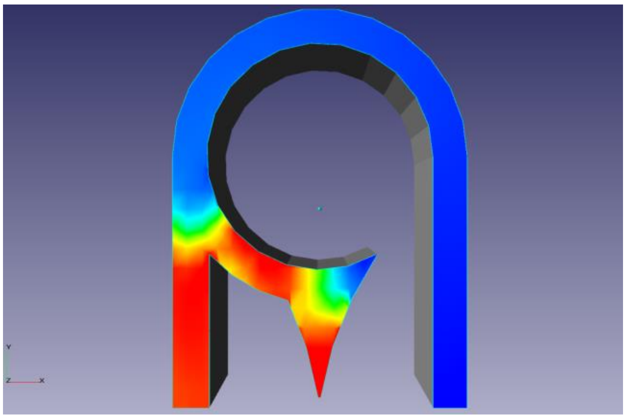

Figure 4. Concentration of particles in the air stream in the form of a complete flood

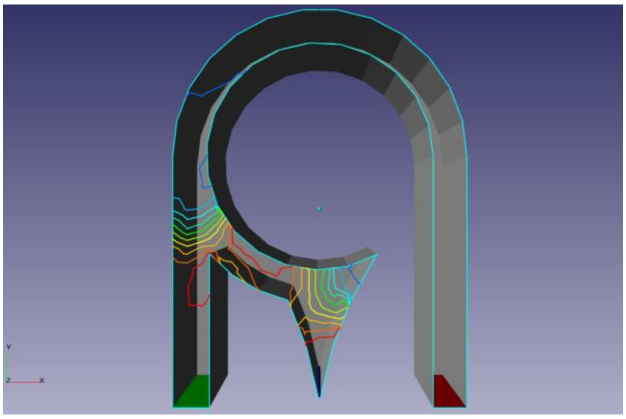

Figure 5. Concentration of particles in the air flow in the form of isolines

Based on the simulation results, it can be concluded that the flow of the gas space corresponds to the theoretically justified one and, therefore, can be used to clean the air from fine dust particles in the "modular type" plant described above, and, in combination with an additional electrostatic precipitator installed at the outlet, will ensure the final purification of compressed air streams and its subsequent ionization, since over time, individual dust particles that could not be separated by centrifugation remain in the air stream.

For example, there are many air treatment filters that are used in centralized and local ventilation systems for buildings and individual rooms. The vast majority of them are designed to clean the air from dust of a certain dispersion. The general disadvantage of such filters is their low efficiency, fixed level of air purification and changes in its ionic composition (deionization) due to electrification of filter materials (accumulation of static electricity).

In terms of air purification, an electrostatic filter is more efficient and flexible in use. The disadvantage of this type of filter is that it does not practically deionize the air completely. The most suitable is an air electrostatic filter with air ionization. This filter is the closest analogue and was chosen as a prototype. The main disadvantage of the filter is that, at an acceptable and controllable air purification efficiency, its deionization in the filter is compensated by ionization due to corona discharges. This leads to uncontrolled generation of harmful amounts of ozone (O_3) and nitrogen oxides (NO).$_x$

The technical problem to be solved by this utility model is to preserve the ionisation of natural air and to regulate the efficiency of air purification (dispersion of the absorbed dust) without the use of electrostatic effects. The goal is achieved by using a polymer with a non-electrifying surface as a filter material and adjusting the air purification efficiency by changing the filter material's seal. Fluor plastic was chosen as the filter material because it does not electrify during operation (it is astatic).

The filter is constructed as follows: fluor plastic is placed in a cylindrical body consisting of two parts and a bolted connection. It is covered from above and below with a mesh of any mesh size for air to pass through. A top view and a longitudinal section of such a filter are shown in Fig. 6.

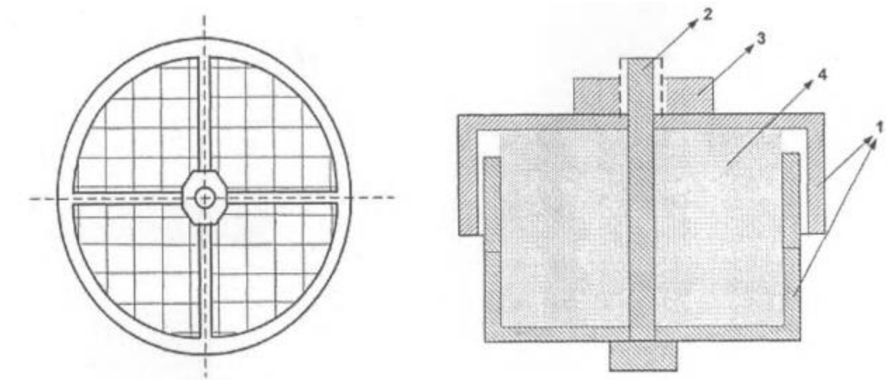

Figure 6. Electrostatic filter: top view and longitudinal section

The movable parts of the housing 1 hold the filter media 4 in the inner part by means of bolt 2 and nut 3. The change in the dispersion of the dust retained by this filter is regulated by compression of the filter material by means of the nut 3.

The use of computer simulation in the design of machines and mechanisms makes it possible to transfer the process of testing actually manufactured mechanisms to full-scale testing, which significantly saves material and time resources for the preparation and implementation of modern machines or mechanisms in production and guarantees their quality and reliability during operation.

4. Discussion and suggestions for future research

The generalized results of the study are important in several aspects that need to be highlighted. Firstly, the mathematical description of aerodynamic processes occurring in the dust collector made it possible to establish quantitative indicators of the key parameters of the functioning of the entire system, taking into account the geometry of the proposed device. Secondly, computer simulation made it possible to determine the velocity of particles in the dust collector and their concentration in its working area. It is worth noting that these data are fully consistent with theoretical data, which indicates that the proposed device is sufficiently efficient in air purification. Thirdly, the analysis of the patterns of particle concentration distribution showed that a certain amount of particles does not settle in the conical dust collector as a result of centrifugation, but continues to move in the air flow. This led to the recommendation to install an electrostatic filter at the outlet of the dust collector for the final purification of the respirable fraction of dust. The presented study complements the known data on the movement of particles in a two-phase flow in terms of a better understanding of the aerodynamics of the process. Thus, modern software tools allow us to obtain results that demonstrate full agreement with full-scale experiments, making it possible to implement technological systems by designing and testing both the geometry of the proposed devices and their operating conditions. Prospects for further research should be related to the assessment of the impact of all types of physical interactions, in particular, in combination with air ionization/deionization factors, which will require additional calculation modules that take into account mathematical dependencies, which have not yet been fully derived.

5. Conclusions.

As a result of the comprehensive study, the following can be noted:

1) the developed computer model allowed us to establish the parameters, characteristics, requirements and limitations of a real dust removal device. The velocity of particles in the air flow was determined and displayed in vector form, as well as the concentration of particles in the air flow, which is displayed in the form of complete fill and isolines;

2) the flow of the gas space corresponds to the theoretically justified flow and, therefore, can be used to clean the air from respirable dust particles in a "modular type" installation;

3) over time, some dust particles that could not be separated by centrifugation remain in the air stream, so an additional electrostatic precipitator must be installed for final cleaning;

4) the assembly of cleaning devices in a "modular complex" allows to create a universal multi-stage plant that ensures complete dust and ash collection and gas neutralization. The sectional, "modular" layout reduces metal consumption, device cost and maintenance;

5) the practical implementation of the "modular complex" allows to increase the efficiency of separation and purification of flue and corrosive gases within a wide range of dust and gaseous pollutants, significantly reduce the degree of air pollution, as well as the cost of construction and maintenance of treatment facilities;

6) the use of the proposed device in comparison with all known analogues provides the possibility of effective cleaning of gas environments from industrial and household dust, as well as combustion products;

7) tests of the efficiency of the electrostatic precipitator using special equipment have shown that the level of air ionization after passing through such a filter practically does not change (within the error of the device), preserving its natural qualities. The electrostatic precipitator, when adjusted to the standard level, absorbs dust of any dispersion encountered in production conditions;

8) trial operation of the developed filter demonstrates its functionality, ease of manufacture, the ability to pass air in any direction with the same effect and the economic feasibility of using it in both centralized and local ventilation systems, buildings and premises.

All of the above makes it possible to make a general conclusion about the sustainable operation of the designed technological system, which can be recommended for implementation in the production sector to create a safe working area for employees.

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Received February 27, 2024, revised July 9, 2024, accepted August 27, 2024