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**Pitak I.,
Shaporev V.,
Pitak O.,
Briankin S.,
Vasilyev M.**

GENERALIZATION OF THE AERODYNAMIC CHARACTERISTICS OF THE CYCLONE AND VORTEX CHAMBERS DURING THEIR FUNCTIONING

Об'єктом дослідження є циклонні та вихрові камери. Пиловловлювачі у виді циклонів та вихрових камер є перспективними для дослідження процесу та удосконалення їх конструкцій. Одними з найбільш проблемних місць є очистка аеродисперсних систем, високий гідравлічний опір, складна експлуатація і установка, необхідність в потужному тягодуттєвому пристрої.

Методи, що застосовуються для очищення аеродисперсних систем від пилу, туману та шкідливих домішок, і необхідна ефективність очищення визначаються санітарними і технологічними вимогами. Також вони залежать від фізико-хімічних властивостей самих домішок, від складу та активності реагентів, від конструктивного рішення пристроїв, які застосовуються для очищення. У зв'язку з цим застосовують різні технології та методи очищення.

В ході дослідження:

– виконано аналіз стану теоретичного опису процесів «сухого» очищення аеродисперсних систем і відомих конструкцій;

– виконано аналіз методів розрахунку ступеня очищення газу від пилу;

– доведено, що сучасні методи розрахунку не враховують деякі параметри а саме:

а) характерної структури закрученого потоку;

б) згасання інтенсивності закрутки по мірі віддалення потоку від завихрювача;

в) зміни густини газу у радіальному напрямку під впливом відцентрових масових сил;

г) зміни розподілу дисперсних часток за розмірами після проходження аеродисперсної системи завихрювачів;

– запропоновано розглядати, при розрахунках та дослідженнях, пилоочисний пристрій як комплекс;

– доказано, що запропонована конструкція найбільш повно відображає особливості процесу «сухого» очищення пилогазового потоку;

– отримано рівняння, яке попередньо дозволяє оцінювати тангенційну складову швидкості обертання аеродисперсної системи в циклоні;

– доведено, що тангенційна складова швидкості обертання аеродисперсної системи у вихровому апараті змінюється в залежності від інтенсивності вихору і його затухання.

Завдяки дослідженню динаміки потоку можливо підвищити ступінь очистки потоку, вдосконалити конструкцію пилоочисного обладнання.

Ключові слова: *аеродисперсний потік, вихрова камера, циклонний апарат, методи очищення від пилу.*

1. Introduction

The current ecological state of Ukraine is due to the excessive concentration of hazardous industries, outdated and inefficient environmental equipment, which is installed at the final stages of technological lines that produce a variety of products. The low reliability of environmental protection equipment and its low efficiency in functioning at enterprises of increased environmental risk determine the extreme urgency of constant attention to activities and ensure the environmental safety of the country. For example, according to [1], the amount of substances released into the atmosphere in the form of dust is 380–400 thousand tons per year, which is about 15–20 % of all hazardous substances emitted into the atmosphere. In addition, depending on the previous technological cycle (generation, processing) in gases emitted into the atmosphere, toxic gas impurities are present. These impurities are in the form of: NO_2, SO_2, CO and others, and the gas-dust flow can have a sufficiently high temperature, which in certain production processes can reach 900 K. All of the above increases the environmental hazard. Therefore, one of the pressing problems facing industry today is the improvement of technologies and techniques for environmental protection in general, and in particular, the reduction of dusty atmospheric air.

2. The object of research and tis technological audit

The object of research is cyclone and vortex chambers. Dust collectors in the form of cyclones and vortex chambers are promising for studying the process and improving their designs. It is in these devices that swirling vortex flows occur. Due to the study of flow dynamics, it is possible to increase the degree of flow purification, to improve the design of the dust purification equipment.

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A typical construction of a dry dust collector is a vortex dust collector with a cylindrical separation chamber (Fig. 1).

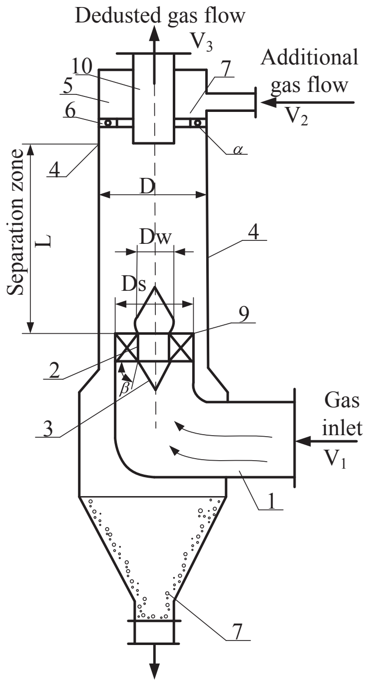

Fig. 1. Diagram of a vortex dust collector with concentrated vane gas injection

In Fig. 1, flue gas enters the gas inlet 1 and is swirled by the vane swirler 2. The fairing 3 slightly pushes the flow to the wall of the apparatus and favors the flow of the bladed vortex hub through the gas flow. Under the action of the centrifugal force, the particles in the swirled gas flow move to the walls of the body 4. Simultaneously, the same dusted or purified gas is supplied to the dispensing chamber 5 and, using a swirler 6, made in the form of nozzles (6 pcs.) with a slope of 45°, enters the working cavity apparatus. The additional gas flow from the swirler 6 spins the main flow in the same direction as the swirler 2 and simultaneously blows dust particles from the walls into the hopper 7. The additional gas flow during the spiral flow around the main flow gradually penetrates into it. The annular space around the inlet pipe can be equipped with a sawblading washer 9, which is designed to ensure the irreversible release of dust into the discharge device (conveyor). From the hopper, dust enters the containers of finished products, and purified gas through the exhaust pipe 10 into the atmosphere.

Advantages of using vortex devices: work with dust-gas mixtures that have a high temperature, the apparatus has a sufficiently high degree of purification; the possibility of regulating the process of gas purification from dust by regulating the secondary air flow.

Among the disadvantages of cyclones and vortex dust collectors are: high hydraulic resistance, complex operation and installation, the need for powerful blowing devices.

3. The aim and objectives of research

The aim of research is analysis of the basic designs of devices for dry purification of gas-dust flows in which swirling flows and states of theoretical description of process features are realized.

To achieve this aim, it is necessary:

1. To prove that modern calculation methods do not take into account some parameters.
2. To suggest for consideration, in calculations and studies, a dust purification device as a complex.
3. To obtain an equation, first let estimate the tangential component of the rotation velocity of the aerodisperse system.

4. Research of existing solutions of the problem

Industrial gas emissions are an aerodisperse system in which the particles of dust (solid phase) is a dispersed phase, and the gas is solid. The enterprises of chemical, processing or any other branch of industry are manufactures with complex technological processes and technological complexes. Thermal, mechanical, or chemical processes can be used in these industries, accompanied by the formation or evolution of gas flows that contain particles of a solid phase [2, 3].

In [4–7], data on the characteristics of aerodisperse systems submitted to treatment facilities for purification the gas flow from dust in some industries or technological production schemes are presented. The results of the analysis of the data are shown in Fig. 2, and in Tables 1, 2.

As the above results show, the continuous part of the aerodisperse system in its composition in most cases is a gas close to the surrounding air. In some technological processes, the main component of the continuous part is water vapor, carbon dioxin, their mixtures, or possibly another gas, depending on the type of process. The main parameters characterizing a continuous particle are the gas flow rate and, accordingly, the rate of its supply to the purification apparatus, as well as the temperature, density, viscosity, which affect the hydrodynamics in the purification apparatus.

The dispersed particle, as the data show, represents various solid particles of generally round shape, the concentration of which in the continuous phase ranges from 3–5 to 90–500 g/mm^3. In the majority of cases, according to published sources [4–7], the concentration of a dispersed particle in gas flows varies in the range 3–10 g/nm^3.

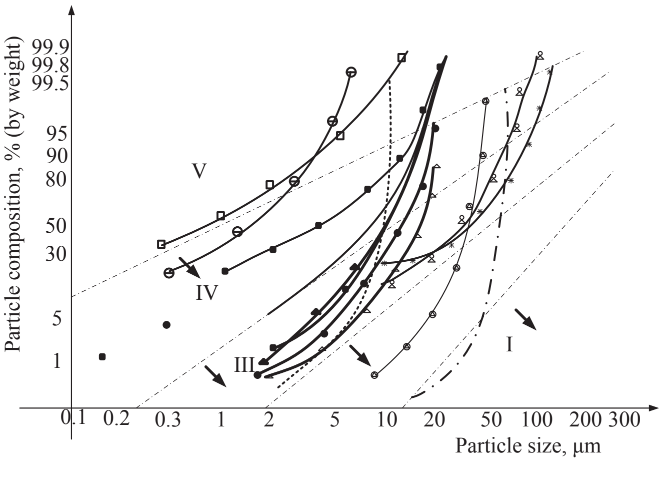

Fig. 2. Classification nomogram for determining the dust group

Table 1

Characteristics of some aerodisperse systems based on survey results (averaged indicators)

No.	Characterization of the gas-dust flow for purification											
	Amount of gases supplied for purification, nm^3/h	Solid part									Disperse part	
		CO_2, %	H_2O, %	N_2, %	O_2, %	CO, mg/nm^3	NO_x, mg/nm^3	SO_x, mg/nm^3	Density, g/cm^3	Viscosity, m^2/s·10^{-6} (* – Pa·s)	Type	Concentration, g/nm^3
1	1000	30–32	10–12	54–55	1–2	0.05	–	–	1.07	2.45	MgO	20
2	1500–3000	15–17	–	65–75	10–12	100–200	70–80	50–80	1.21	2.45	ZnO	5–6
3	15600	26–28	15–16	56–58	1.1–1.3	0.05	50	–	1.2	2.45	$CaO+CaCO_3$	6–7
4	3000–4000	–	93–94	3–6	1–3	–	–	–	1.19	147*	$Ca(OH)_2$	15–20
5	3000	92–93	5–6	1.0–1.1	1.1–1.2	–	–	–	1.25	97*	Na_2CO_3	90–500

Table 2

Physical and chemical properties of solid particles

No.	Flow temperature, °C	Physical and chemical characteristics		
		Density, g/cm^3	Particle size interval, m/cm	Specific surface, m^2/g
1	400	3.58	0.5–5.0	10.0
2	520–550	5.70	0.3–5.0	8.0
3	230–270	2.93	5.0–10.0	1.5–2.0
4	120–150	2.24	1.0–6.0	15.0–20.0
5	120–150	2.16	2.0–10.0	1.0–3.0

The determining parameters characterizing the dispersed phase are the density, the particle size, the specific surface, and the adhesiveness. The latter parameter should probably correlate with the specific surface area and the angle of the natural slope of the material. For example, it has been established [6] that the zinc content of ZnO, $Ca(OH)_2$ particles, which have a specific surface area of about 10–15 m^2/g, is (500–600 Pa) and the angle of natural outflow (static) is 70–80°. When the specific surface area decreases to 1 m^2/g, the stickiness index increases by a factor of 6–8, and the angle of the slope decreases by a factor of 1.5–2.0. In general, the air-dispersed system for entering the dust-collecting apparatus can move in pipes or channels with any type of channel section, its curvature and length. Probably this section of the pipeline can be characterized as an inlet branch to the apparatus-dust collector and there must be a fully developed turbulent flow in it, assuming motion to be axially symmetric [8].

A current is formed in the pipe with a completely closed boundary layer. The profiles of the averaged velocities at any intersection depend on the number *Re* or the degree of flow turbulence. Studies have established that the presence of a dispersed phase in an aerosolized system in an amount of up to 100 g/nm^3, changing the velocity level, does not affect the character of their distribution [9, 10] as compared to a continuous phase without an aerosol.

In addition to the above, the gradual movement of the aerodisperse system along the axis of the branch pipe, it is possible to create a detachment flow with the appearance of vortices, that is, axially symmetric overflow flow with the appearance of a vortex cord may arise [11].

Thus, when the aerodynamic system moves in the nozzles, an intensive rearrangement of the fields of all gas-dynamic parameters can be observed before entering the dust collector apparatus, including the effect of redistribution of the total energy in the flow.

Therefore, the above physicochemical parameters of the dispersed part of the aerodynamic system when moving in the nozzles before entering the dust collector can influence the agglomeration of solid particles. It can also influence the possibility of chemical destruction of gas impurities and the distribution of the solid phase along the cross-section of the nozzle. These indicators affect the process, depending on the motion of the system, its temperature, the effect of a complete redistribution of the energy of the flow.

5. Methods of research

The methods used to clean aerodisperse systems from dust, fog and harmful impurities, and the required purification efficiency are determined primarily by sanitary and technological requirements. They also depend on the physicochemical properties of the impurities themselves, as well as on the composition and activity of the reagents, and on the design of the devices used for purification. In connection with this, various technologies and methods of purification are used.

One of the main characteristics determines the choice of the type of equipment for purification of gas flows is the particle size of the dispersed phase. Large particles can be easily separated from a continuous gas phase and a simple apparatus can be used for this. But if the particles are small, then this may require the use of either sophisticated apparatuses, or several of these devices installed in series. Also such characteristics as the diffusion coefficient, the surface area of the particles, the line width of the X-ray spectrum, and so on depend on the particle diameter of the aerodisperse system. But modern methods for analyzing the dispersion of gas-dust mixtures do not allow determination of the mass or number of particles of the same size. As a result of such analyzes, the yields of fractions are usually determined, which are expressed in fractions or percentages of the total mass or total number of particles. In addition, the total yields are also determined, that is, the dispersed composition of the aerodisperse system is in most cases determined by the particle density distribution function in the gas flow.

When the gas-dust mixture moves through pipelines or processing lines, different forces act on the dispersed particles. The motion of particles can be rectilinear, while the particle can be accelerated or slowed down, or curvilinear, that is, under the action of forces that can change the initial direction of motion of the particle.

In the curvilinear motion of the aerodynamic system, the inertia force starts to act on the part, which increases the velocity of the dispersed phase. In this case, the particles move from the axis of motion, and a sudden change in the direction of motion, in front of some object or in a curvilinear channel, can lead to a collision of particles with such objects or the channel wall. So, these are the main mechanisms used in the design of gas purification separation equipment. When a body moves in a gas, it always feels resistance from the environment that is accelerated by the action of its motion. And the forces of resistance depend both on the properties of the medium (density, viscosity), and on the velocity of the body. By the type of the main mass force acting on dispersed particles when separated in a gas flow, dry dust collectors belong to the so-called mechanical dust collectors. They are dust separation or dust precipitation chambers, inertial apparatuses, cyclones and multicyclones, rotoclones, vortex chambers. The use in the process lines of chemical processing plants of such equipment for dry gas purification from dust is characterized by a low degree of resolution, which provides a rough purification of the gas-dust mixtures.

Despite the latter, dust collectors in the form of cyclones and vortex chambers (devices) are considered promising for studying the process in them and improving their designs in that they realize swirling cyclones, vortex flows. Investigating flow dynamics and thermal problems, it is possible to increase the purification degree of the dust and gas flow, as well as to improve the design of the dust collector.

But despite the widespread use of cyclones and vortex chambers, the following is noted in the area of centrifugal trapping of solid particles from gas flows. The theory of the functioning of these devices has not yet been improved and does not allow to calculate the apparatus of various designs, and in addition to improve the process itself.

The processes of dry purification of technological waste gases are rather complicated processes and in many cases are non-stationary. In order to design and efficiently operate dry gas purification systems from dust, appropriate mathematical models are needed. These models should take into account not only the hydrodynamic conditions, but also the change in the physicochemical properties of dust particles and their size during the course of the process.

6. Research results

The theory of physical and chemical aggregation of particles of variable mass [12, 13] in such hydrodynamic conditions provides a substantiation of the agglomeration process. The main mechanism of this process is the collision of particles, the appearance of defective zones in the city of contact of particles during a collision, the formation of crystalline «bridges» between particles in the agglomerate. The probability of collision of particles depends on *Re*, that is, on the diameter of the nozzle and the mass flow of the aerodisperse system. In [14, 15] for aerodisperse systems (Tables 2, 3), the agglomeration process in the nozzles was experimentally proved before the system was introduced into the dust collector. It is shown that, for example, particles ($CaO+CaCO_3$) are formed in agglomerates with a value of 35–40 μm, while at the inlet to the branch pipe the particles of the solid phase had a size of 5–10 μm. A similar phenomenon was observed in system 2, where the ZnO particles increased from 8–10 to 45–60 μm. This phenomenon is related to the agglomeration process and was observed by the authors of the patent [16] in the manufacture of highly dispersed TiO_2 by oxidation of $TiCl_4$ at a temperature of 1000 °C. Considering the sufficiently high temperatures of the aerodisperse systems (Tables 2, 3) moving in the nozzle in [17, 18]. Thermodynamic calculations have been carried out and kinetic regularities of the possibility of destruction of gas impurities in the continuous phase have been studied. It has been established that in the presence of H_2O vapors in an amount corresponding to the stoichiometric ratio of impurities, destruction of impurities proceeds, for example, by the type:

$$CO+H_2O\rightarrow CO_2+H_2,$$

$$2H_2+O_2\rightarrow H_2O. \qquad (1)$$

At 400–500 °C, and NO_x and SO_x, at lower temperatures – 280–350 °C. That is, homogeneous catalysis is possible, the intensity and velocity of which is completely determined by the conditions of transport in the flow of matter and energy:

$$Pa=f(Re;\ Pr_T;\ Pr_D), \qquad (2)$$

where *Pa* – equilibrium criterion, *Re* – Reynolds criterion of aerodisperse systems; Pr_T – Prandtl criterion, for heat exchange:

$$Pr_T=\gamma/a,$$

where a – thermal diffusivity; γ – coefficient of kinematic viscosity; Pr_D – Prandtl criterion for material exchange:

$$Pr_D=\gamma/D_C,$$

where D_C – the diffusion coefficient of gas impurities.

Thus, the inlet pipe and the processes observed inside it, when passing through the air-dispersed system before entering the main apparatus, must be considered as a preliminary preparation of the aerodisperse system before it is processed in the apparatus. The hydrodynamic regimes in the inlet pipe and the parameters of the turbulent, vortex motion of the aerodisperse systems are described by the Navier-Stokes equation for the corresponding initial and boundary conditions. As noted, the main apparatus-dust collectors are cyclones and vortex chambers [19].

When analyzing the trajectory of motion of dust particles, it can be concluded that in general, the process of air purification in the proposed apparatus is as follows.

Dusty air mixture tangentially enters the body of the device through the inlet pipe and continues its movement from top to bottom to the sawblading branch, without changing the direction of its movement. On the way to the apparatus such a mixture moves rectilinearly, the dust content of the gas flow along the section of the apparatus remains practically uniform and the velocity of the dust particles is equal to the rate of entry of the gas flow into the apparatus. After entering the apparatus under the action of a centrifugal force, solid particles are thrown back to its outer wall, the concentration of which in the peripheral zone of the body is impeded by the phenomenon of ricochet of the particles as a result of their contact with the wall. Consequently, at a significant flow velocity, the initial velocity of rotation of the particle increases, its lift force and the magnitude of its radial displacement under the influence of this force. In this case, the motion of individual particles reflected from the wall is absorbed by particles that move to the wall, and this occurs in the entire flow.

The solid parts of the dust, trapped by the radial flow, hit the blinds of the separator, reflect from them, jump in a moving flow, strike the next shutters, etc. This occurs until they enter a flow that moves along the outer wall and transports them to the exit from the apparatus to the hopper. The dusty air thus purified passes through the openings between the blinds and dust particles into the hopper.

The initial conditions for such devices are the characteristics of the air-dispersed system after the inlet branch pipe. Boundary conditions: the velocity vanishes on a fixed rigid boundary; the velocity of the dust-air flow at the inlet to the dust collector is stable and is 20–25 m/s [19].

For this case, assuming that $\mu = \text{const}$, the Navier-Stokes equation can be written in the form [19]:

$$\left.\begin{aligned}\frac{dVx}{d\tau} &= x-\frac{1}{\rho}\cdot\frac{\partial\rho}{\partial x}+\nu\Delta Vx+\frac{\nu}{3}\frac{\partial}{\partial x}\cdot div\nu\overline{Vx},\\ \frac{dVy}{d\tau} &= y-\frac{1}{\rho}\cdot\frac{\partial\rho}{\partial y}+\nu\Delta Vy+\frac{\nu}{3}\frac{\partial}{\partial y}\cdot div\nu\overline{Vy},\\ \frac{dVz}{d\tau} &= z-\frac{1}{\rho}\cdot\frac{\partial\rho}{\partial z}+\nu\Delta Vz+\frac{\nu}{3}\frac{\partial}{\partial z}\cdot div\nu\overline{Vz}.\end{aligned}\right\} \quad (3)$$

For the material description of turbulent mass transfer, it is expedient to use the k–ε model of turbulence, the value of which is determined from the following equations:

$$\left.\begin{aligned}&\frac{dk}{d\tau}+\overline{V}(Vk)=\frac{1}{\rho}\cdot\nabla\left[\left(\mu+\frac{\mu_T}{\sigma_k}\right)\cdot\nabla k\right]+\frac{G}{\rho}-\varepsilon,\\ &\frac{d\varepsilon}{d\tau}+\nabla(V\varepsilon)=\frac{1}{\rho}\cdot\nabla\left[\left(\mu+\frac{\mu_T}{\sigma_\varepsilon}\right)\cdot\nabla\varepsilon\right]+\frac{\varepsilon}{k}\left(C_1\cdot\frac{G}{\rho}-C_2\cdot\varepsilon\right),\\ &G=\mu_T\cdot\frac{\partial V_i}{\partial x_i}\left(\frac{\partial V_i}{\partial x_i}+\frac{\partial V_i}{\partial x_i}\right),\end{aligned}\right\} \quad (4)$$

where Vx, Vy, Vz – velocity in the corresponding directions, m/s; x, y, z – dimensionless coordinates; k – turbulent energy, m^2/s^2; ε – dissipation rate of turbulent energy, m^2/s^2; ρ – density of air, kg/nm^3; μ_T – dynamic viscosity, Pa·s.

Part of the dust during its movement in a swirling flow under the above conditions is: gravity forces $\overline{F}_G$, center force $\overline{F}c$, and medium resistance force (Stokes force) $\overline{F}_S$. $\overline{F}_S$ is determined by the formula:

$$\overline{F}_S = 3\pi\mu_G d_p \overline{V}_p X, \quad (5)$$

where $\overline{V}_p$ – particle sedimentation rate, m/s; X – dynamic coefficient of dust particle shape – 2.9; $\overline{F}_S$ – equal to the sum of external forces and is directed in the opposite direction and is calculated by the formula:

$$\overline{F}_S = \overline{F}_G + \overline{F}_C, \quad (6)$$

where $\overline{F}c$ – center force, is:

$$\overline{F}_C = m_p\cdot\frac{\overline{V}_{DT}^2}{R} = \frac{\pi d_p^2}{6}(\rho_p-\rho_g)\frac{\overline{V}_{DT}^2}{R}, \quad (7)$$

where m_p – particle mass, kg; ρ_p – density of dust particles, kg/m^3; ρ_D – density of the solid particle, kg/m^3.

Thus, it can be argued that V_p basically depends on $\overline{F}_C$ whether there is a force that determines the tangential component of the rotation velocity ($\overline{V}_{DT}$) of the aerodisperse system in the apparatus. The latter value $\overline{V}_{DT}$ depends on the method of injection of the aerodisperse system after the branch pipe into the cyclone apparatus, that is, from the method of swirling the input flow. Swirling of the input flow in the cyclone can be accomplished in various ways. As already noted, by tangential input of the entire flow of the aerodisperse system, or the flow is divided into several parts and each part is introduced tangentially at different angles [20]. Another way to swirl the flow is establishment of a screw-like cover with a branch pipe that intensively swirls the flow [21]. By fixing the rotor at a velocity of 4300 rpm, it accelerates the aerodisperse system along a torus-shaped channel and tangentially supplies the flow to the cyclone [22]. By establishing a cochlear swirler [20] and others.

Most of the currently known schemes and methods for aerodynamic calculation of cyclonic and vortex devices, for example [23–25], provide for the independence of the distribution of the tangential component of the flow velocity from the longitudinal coordinate. Attempts to numerically analyze the swirling flow in the graft regions on the basis of the general equations of motion [26, 27] do not confirm the experimentally significant deformation of the ω_p profile. In literary sources, $\overline{V}_{DT}$ is most often expressed as ω_p, so let's move on to this reproduction later. This especially happens depending on the size of the outlet branch from the cyclone of the purified flow, and is associated mainly with the influence of the reverse flow. In addition, in many cases, this is also due to the fact that the features of the flow in the zones are not fully taken into account, are analyzed, especially in the zones of the flow input. Analysis of the ω_p experimental distributions in terms of radius and zones [23–27] proves that from the beginning, when a flow is introduced into the cyclone, a zone of «quasi-solid» rotation is observed. Then a «quasi-potential» zone is observed in which the main process of separation of the aerodisperse systems into a dispersed part and a continuous one is realized. In this case, $\omega_{p\max}$ is reached at some distance behind the zone of «quasi-solid» rotation. It can be argued that the value of $\omega_{p\max}$ and its position uniquely depends on the swirling method of the vortex flow and the configuration of the annular channel that is formed between the body of the apparatus (cyclone) and the branch pipe of the cleaned gas outlet. To calculate ω_p in the graft regions, proceeding from the conditions for the existence of a maximum angular velocity $\bar{\omega}_x$ (x – coordinates along the annular channel), which is reached on the radius:

$$0 \le \eta_\omega \le 1,$$

where η_ω – the dimensionless radius, equal to:

$$(r - r_3)/(r_{p\max} - r_3),$$

where $r = D_p/2$, m; $r_3 = D_B/2$, m; D_{DC} – diameter of the device camera, m; D_B – diameter of the branch pipe of the gas outlet, m.

Under these conditions, an equation describing the conditions for the stability of the motion of a gas rotating [28] in the graft regions of the cyclone flow can be used. The radius η_ω will be the boundary of the zones with conservative ($0 \le \eta \le \eta_\omega$) and active ($\eta > \eta_\omega$) by the nature of the action of inertial mass forces on the flow:

$$\frac{\partial \bar{\omega}_x}{\partial \eta} = \frac{\partial}{\partial \eta}\left[\frac{1}{\eta}\cdot\left(\frac{2\eta}{1+\eta^x}\right)\right] = 0, \tag{8}$$

$$\eta = \eta_\omega = \frac{1+\eta_\omega^x}{1-(x-1)\eta_\omega^x}, \tag{9}$$

where x is recommended in the range of 1.87–2.0.

The analytical relation η_ω with the basic geometric parameters of the cyclonic chamber and the longitudinal coordinate (x) can be obtained using the screw model of gas flow in the graft regions. To do this, let's write the vectors of the equation for the averaged motion of a viscous unchanging flow in the Helmholtz form, that is, in the form of swirling transfer [29]:

$$\frac{\partial\langle\omega\rangle}{\partial\tau} = \nabla x\left(\langle v\rangle\cdot\langle\omega\rangle\right) + \nabla x\left(v'\cdot\omega'\right) + v\cdot\nabla^2\langle\omega\rangle. \tag{10}$$

For stationary screw flow:

$$\frac{\partial\langle\omega\rangle}{\partial\tau} = 0;\ \langle v\rangle\cdot\langle\omega\rangle = 0,$$

where ω – the angular flow velocity; v – the total linear flow rate.

Taking into account the connection between the pulsational and averaged component of the angular velocity $\omega' = L\dfrac{\partial\langle\omega\rangle}{\partial r}$ (L – turbulence scale), according to the theory of the Taylor swirling transfer, and for $= r_\omega$:

$$\omega'_m = 0 \text{ and } \left(v'_x\cdot\omega'\right)_m = 0. \tag{11}$$

A stroke means a ripple, not a value. Therefore, equation (10) is written relative $\bar{\omega}_{xm}$ (averaging symbols are omitted) and is simplified in the dimensionless form and goes over to the elliptic form:

$$\frac{\partial^2\bar{\omega}_{xm}}{\partial\eta_3^2} + \frac{1}{\eta_3}\cdot\frac{\partial\bar{\omega}_{xm}}{\partial\eta_3} + \frac{\partial^2\bar{\omega}_{xm}}{\partial x^2} = 0. \tag{12}$$

Using relation (9), let's find:

$$\bar{\omega}_{xm} = \frac{1}{\eta_\omega}\left(\frac{2\eta_\omega}{1+\eta_\omega^x}\right)^{\frac{1+\eta_\omega^x}{1-(x-1)\eta_\omega^x}} \ge \frac{2}{1+\eta_\omega}. \tag{13}$$

The replacement error for the last ratio does not exceed 4 %. Taking into account the independence of the variables η_3 and x, the general solution (12) with respect to η_ω can be obtained by splicing the equations $\left[\eta_\omega = \eta_\omega(\bar{x})\right]$; $\eta_3 = 0$; $\eta_\omega = \eta_\omega(\eta_3)$; $\partial\eta_\omega/\partial x = 0$. Taking into account the boundary conditions of the problem, which take into account the swirling law of the input flow. As a result, it is possible to obtain the following calculated expression:

$$\eta_{\omega,x} = \frac{2}{1+K_x\cdot Ln\cdot\eta_3}, \tag{14}$$

where

$$K_x = \frac{1}{5}\left\{1-2\left[\left(1-\frac{X-X_n}{1-X_n}\right)\left(\frac{1-X_n}{1+\eta_{@}}+X_n\right)+\frac{X-X_n}{1-X_n}\right]\right\};$$

$X = \bar{x}/E_p$ – dimensionless puncture coordinate; $\bar{x} = x/r_m$ – dimensionless current radius; η_r – dimensionless radius of zero value of unproductive static pressure.

At the value $K_x = K_p = \text{const}$, a self-similar distribution $\overline{W} = \overline{W}(\eta)$ along the X coordinate is observed. Obviously, in cyclone chambers with different ways of swirling the input flow and different design characteristics of the outlet branch pipe of the purified gas, the boundary conditions will be formed differently and possibly more complex. The latter conditions will affect the exponent K_x in equation (14). Equations (13) with a small error can be used to calculate $\bar{\omega}_{xm}$ and predict the length of the cyclonic chamber and, accordingly, to determine $\overline{Fc}$ and V_p. Thus, the reduced models of equation (8)–(14) allow to estimate preliminary the tangential component of the rotation velocity W_φ of the aerodisperse system in the cyclone along the longitudinal coordinate. This opens the possibility of changing the structural profile of the dust deposition zone and the ratio of this zone to the hopper part in order to increase the efficiency of the dust collector.

As is known [29], the swirled gas flow after the swirler is a complex three-dimensional one. The velocity vector of the flow is decomposed in a cylindrical coordinate system into three components: axial, tangential (rotational) and radial. The presence of a rotational component just leads to the appearance in the flow of centrifugal forces and the formation of a radial gradient of static pressure. To perform design calculations, it is necessary to know the angular velocity of the flow $\omega_1(z)$ in an arbitrary section of the separation chamber at a certain height (z) in the inner layer. The equation of the angular momentum of the gas is determined by the relationship [30]:

$$M_1(z) = \int_0^{r_x}\rho\cdot Vs_1\cdot 2\pi\cdot r\cdot \mathrm{d}r\cdot\omega_1(L)\cdot r^2. \tag{15}$$

After integration and the corresponding transformations, the extracted equation for determining the angular velocity of rotation of the flow in the separation chamber will look like this:

$$\omega(z)=\frac{2M_{in}\cdot r_x^2}{\rho\cdot(L_1+L_2)\cdot r^4}, \qquad (16)$$

where L_1 and L_2 – primary and secondary flows, m^3/s; H, z – the separation height and the distance to the considered section, m;

$$L_1(z)=L_1+L_2\left[1-\left(1-\frac{z}{H}\right)^{k-1}\right];$$

$$L_2(z)=L_2\left[1-\left(1-\frac{z}{H}\right)^{k+1}\right];$$

$$M_{in}=0{,}5\pi\cdot\rho\cdot V_z\cdot V_\varphi\cdot r_0,$$

where k – the empirical coefficient (for $k=0$ the radial velocity is distributed as described in the theory [30], for $k\geq 0$ the radial velocity increases down the chamber, for $k\leq 0$ the radial velocity decreases to the bottom of the chamber); r_o, r_x, r – radius: separation chamber, flow separation, current, respectively, m; V_z, V_φ, V_r – axial, tangential, radial flow velocity, m/s.

It should be noted that in the formula for determining M_{in}, the velocity V_φ corresponds to the tangential component of the wrapped flow, which is observed immediately behind the swirler in the gas supply pipe in the section close to it. Thus, other things being equal, the value of $\omega(z)$ depends on the component V_φ, which uniquely depends on the hydrodynamic conditions in the gas supply pipe in the swirler zone and immediately after it.

The two-phase flow in the dust collector model can be considered when making the following assumptions:

- dust particles are solid, they can interact with each other due to intense collision and developed specific surface of particles only in the swirler zone. It is here that the maximum values of V_φ, V_r are observed and the quasi-solid rotation of the dust-gas flow is present;
- after the swirler region (zone), the particles do not interact with each other;
- a particle, touched the wall of the body of the camera of the apparatus, it is considered as captured;
- at the inlet to the dust collector the gas-dust flow has a uniform velocity field;
- distribution of dust particles along the section of the inlet pipe of the dust collector is uniform, the resistance to movement of particles in the gaseous medium is described by the Stokes law;
- the tangential component of the velocity of the particle coincides with the tangential and axial components of the velocity of rotation of the gas flow, radial velocities due to the action of inertia forces are different.

In this case, two dimensionless parameters of the problem are distinguished: the degree of initial swirl of the flow:

$$\eta=V\varphi_0/Vz_0,$$

where $V\varphi_0$ is the tangential velocity at the exit from the vortexing; $V\varphi_0$ – while in the core of the flow leaving the swirler $\omega=V\varphi_0$ the degree of channel obstruction $\Psi=\dfrac{D_{BT}}{D}$.

Thus, the vortex flow in the gas supply pipe after the swirler can be characterized by the notion of vortex intensity. The most accurate expression for it:

$$m=\frac{B}{FR}=\frac{2\pi\cdot\rho\int_0^R V\varphi\cdot Vz\cdot r^2\cdot \mathrm{d}r}{\left(2\pi\cdot\rho\int_0^R Vz^2\cdot r^2\cdot \mathrm{d}r\right)\cdot R}, \qquad (17)$$

where B – flow of momentum torque; F – flow of an axial pulse; R – nozzle radius; ρ – gas density; V_z – axial velocity component; $V\varphi$ – tangential velocity component; r – current coordinate along the radius of the branch pipe.

An analysis of the hydrodynamic conditions in such vortex device makes it possible to draw conclusions. The maximum angular velocity of rotation of the flow in the separating chamber of the apparatus depends on the hydrodynamic processes occurring in the nozzle of the supply of the aerodisperse systems in the separation space of the apparatus. The tangential component of the flow velocity in the supply pipe of the aerodisperse system determines the intensity of the flow rotation in the separation chamber, and accordingly the forces acting on the dust particle and the rate of its deposition. Distinctive in comparison with the cyclone apparatus is that the swirl of the flow in the branch pipe of the vortex apparatus is carried out by the installation of vane or ring swirlers with tangential slots (nozzles). They can also be performed at different angles. In literary sources, where the results of investigations of hydrodynamic structures are shown in the motion of a specific aerodisperse system, there is practically no flow swirl in the nozzles of its supply to the separation part of the vortex device. This is essential when questions arise: the location of the swirler from the outlet of the branch pipe, the effect of the inclination angle of the blades or nozzles, as well as the degree of blockage of the channel. Based on the analysis of literary sources, it is possible to predict the following. In the nozzle of the introduction of the air-dispersed system into the separation chamber of the vortex apparatus under appropriate conditions, it is possible to achieve the effects of changing the aerodisperse system due to coagulation, destruction of gas impurities, and so on. That is, in the vortex apparatus, the nozzle of the introduction of the aerodisperse systems in the separation zone looks like a preparatory system that determines the conditions for the deposition of dust in the separation zone.

When selecting or analyzing the functioning of dust collectors in which swirling flows of air-dispersed systems are realized, it is necessary to consider a set of devices:

- nozzle of the introduction of aerosol disperse systems into the apparatus;
- the intensity and method of swirling the flow as it enters the separation particle. Hopper system with the deduction of deposited dust to it. From the point of view, only such integrated approach can indicate the ways of a truly significant increase in the efficiency of the dry-purification process of the aerodisperse system.

When developing a method for calculating the purification degree of aerosol disperse systems, it is necessary to take into account changes in the axial and rotational velocity, density and static gas pressure in the radial and longitudinal directions of the separation chamber. It is also necessary to take into account changes in the distribution of dust particles in size after passing the gas-dispersed flow. It can be proposed to obtain functions describing the field of the averaged velocity of an axisymmetric swirling turbulent flow, such dependences:

$$W = Wx \cdot \left[\frac{2 \cdot \left(\frac{r}{r_\varphi} \right)}{\left(1 + \left(\frac{r}{r_\varphi} \right)^2 \right)} \right]^J, \qquad (18)$$

$$U = \frac{W \cdot \left(\frac{r}{R} \right)^n}{\mathrm{tg}\varphi}, \qquad (19)$$

where R – the radius of the channel in which the swirling flow moves, m; n – the exponent of the law of variation of the inclination (attack) angle of the swirler, depending on the radius of the channel; φ – the swirl angle of the swirler at the periphery, deg; W_x – maximum value of rotational velocity, m/s; j – an exponent that depends on the initial integral swirling parameter; r – radius of the channel coordinate, in which the swirling flow moves, m; r_φ – radius, at which the rotating velocity is maximum, m.

Taking into account changes in the swirling flow over the entire channel radius, and as the swirling flow is removed from the swirler $L_x(r_k) = L$ (r_k – current particle radius), equations (20) can be proposed:

$$L_x(r_k) = \int_{R_0}^{R} \frac{U(\Phi, r, x)\mathrm{d}r}{\sqrt{\frac{8}{3}} \cdot \frac{\rho_T - \rho_D(P, r, x)}{\rho_D(P, r, x)} \cdot \frac{r_k}{\xi\left(r_k \cdot \mu_D \cdot \rho_D(P, r, x) \cdot \rho_T \cdot k \cdot W(\Phi, r, x)\right)} \cdot \frac{W(\Phi, r, x)^2}{r}},$$

where $U(\Phi, r, x)$ – axial component, m/s; $W(\Phi, r, x)$ – rotating component, m/s; $\rho_D(P, r, x)$ – gas density as a function of statistical pressure, radius and relative longitudinal coordinate, kg/m^3; ρ_T – density of dust particles, kg/m^3; $\xi\left(r_k \cdot \mu_D \cdot \rho_D(P, r, x) \cdot \rho_T \cdot k \cdot W(\Phi, r, x)\right)$ – the coefficient of local resistance of the medium, as a function of the particle radius (the coefficients of the dynamic viscosity of the gas, the density of the gas, solid particles, the specific content of particles in the gas, the rotating component of the flow velocity. The degree of gas purification in the apparatus can be calculated by the formula:

$$\eta_p = \frac{\int_{r_{\min 2}}^{r_{\min 1}} r_k^3 \cdot N(r_k)\mathrm{d}r_k}{\int_{r_{\min}}^{r_{\min 1}} r_k^3 \cdot N(r_k)\mathrm{d}r_k}, \qquad (21)$$

where $r_{\min 1}$ – the minimum radius of dust particles emitted in the sedimentary section of the separator, m; $r_{\min}$ – the minimum possible radius of dust particles in the flow, m; $N(r_k)$ – the particle size distribution function.

The change in the distribution of the dust particles with the size after passage of the swirler takes into account in formula (21) at the level of determining the functions $N(r_k)$ in terms of the mean modal radius R_p. This indicator, in addition to other factors, depends on the equivalent diameter of the channel in which the flow moves. Therefore, to calculate $N(r_k)$, it is necessary to use the smallest value with $R_{av}(d_f)$ and $R_{av}(d_{eq})$, where d_f – the internal diameter of the gas inlet to the separator; d_{eq} – the equivalent diameter of the free intersection of the vortex.

The positions presented in formulas (18)–(21), based on the analysis of the considered literary sources.

7. SWOT analysis of research results

Strengths. The analysis of the obtained results of dust collection research in vortex devices testifies the expediency of using such devices as highly efficient dust collectors for dry gas purification. Due to the study of flow dynamics, it is possible to increase the degree of flow purification, to improve the design of the dust purification equipment.

Weaknesses. The methods of dust removal of gas flows are considered. Among the shortcomings of cyclones and vortex dust collectors are: high hydraulic resistance, complex operation and installation, the need for powerful blowing devices.

Opportunities. The opportunities for the introduction of vortex tubes and vortex chambers are opened and the possibility of reducing the industrial negative impact on the atmosphere. Advantages of using vortex devices: work with dust-gas mixtures that have a high temperature, the apparatus has a sufficiently high degree of purification; the possibility of regulating the process of gas purification from dust by regulating the secondary air flow.

Threats. By results of researches it is offered to consider at calculation and researches, a dust purification device as a complex. This complex includes: a branch pipe for supplying the air-dispersed system to the separation part of the dust collector; a device for swirling the flow at the entrance to the apparatus; the design of the apparatus (separation part); hopper for dust deposition.

It is proved that the proposed design most fully reflects the features of the process of «dry» purification of the dust and gas flow and opens the way for significant improvement.

This opens the prospects for the introduction of vortex tubes and vortex chambers and allows to reduce the industrial negative impact on the atmosphere. The enterprise will need to increase the capital costs for the installation of new treatment equipment.

8. Conclusions

1. It is proved that modern methods of calculation do not take into account some parameters, namely:
   - the characteristic structure of the swirling flow in the longitudinal and transverse direction of the channel in which the swirling flow moves;
   - extinction of the swirling intensity as the flow is removed from the swirler;
   - change in gas density in the radial direction under the action of centrifugal mass forces;
   - change in the distribution of dispersed particles in size after passage of the aerosolized system of swirlers;
   - the processes, flowing and the characteristic structure of the flow in the nozzle of the supply of the aerodisperse systems to the apparatus of the dust collector are not taken into account.

2. In calculations and studies, it is proposed to treat the dust purification device as a complex. This complex will include the following components:

– nozzle for feeding the air-dispersed system into the separation part of the dust collector;
– device for swirling the flow at the entrance to the apparatus;
– apparatus design (separation part);
– hopper for dust sedimentation.

3. For the cyclonic chamber, taking into account its geometric parameters and the longitudinal coordinate, the obtained equation allows to estimate the tangential component of the rotation velocity of the aerodisperse systems in the cyclone along the longitudinal coordinate. It is proved that this component varies depending on the intensity of the vortex and its damping.

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***Pitak Inna**, PhD, Associate Professor, Department of Chemical Technique and Industrial Ecology, National Technical University «Kharkiv Polytechnic Institute», Ukraine, e-mail: ipitak5@gmail.com, ORCID: http://orcid.org/0000-0002-5073-2942*

***Shaporev Valery**, Doctor of Technical Sciences, Professor, Department of Chemical Technique and Industrial Ecology, National Technical University «Kharkiv Polytechnic Institute», Ukraine, e-mail: fiola2008@mail.ru, ORCID: http://orcid.org/0000-0003-1652-4688*

***Pitak Oleg**, PhD, Associate Professor, Department of Labour Protection and Environmental, National Technical University «Kharkiv Polytechnic Institute», Ukraine, ORCID: https://orcid.org/0000-0001-5912-4604*

***Briankin Serhii**, Head of Course of the Faculty of Military Training, National Technical University «Kharkiv Polytechnic Institute», Ukraine, e-mail: serzh2082@ukr.net, ORCID: https://orcid.org/0000-0003-0444-9107*

***Vasyliev Mykhailo**, PhD, Associate Professor, Department of Chemical Technique and Industrial Ecology, National Technical University «Kharkiv Polytechnic Institute», Ukraine, e-mail: mike_v@i.ua, ORCID: http://orcid.org/0000-0003-4635-9257*