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INFLUENCE OF THE INLET FLOW SWIRLER CONSTRUCTION ON HYDRODYNAMICS AND EFFICIENCY OF WORK

Досліджено вплив конструкції завихрювача і місця його установки в газоході для подачі газопилового потоку на ефективність роботи вихрового апарата. Доведено, що конструкція завихрювача при відповідних умовах дозволяють закрученому потоку досягати максимально можливої для даної конструкції кутової швидкості обертання газового потоку. Розроблена принципова конструкція вихрового пиловловлювача, яка дозволяє підвищити ефективність очистки за допомогою вихрового апарату до 98–99 %.

Ключові слова: *конструкція завихрювача, агломерація пилу, кутова швидкість обертання газового потоку.*

1. Introduction

The eastern region of Ukraine, as the most saturated with industrial enterprises of the chemical, metallurgical and construction industries, is a large industrial region of the country where ecologically dangerous areas of modern industrial production are densely concentrated. The volume of dust emissions to the atmosphere from such enterprises is growing every year due to the growth of sources, where dusty streams are formed, requiring cleaning.

The creation and development of new highly effective and more advanced types of environmental protection equipment is topical on the basis of theoretical justification and investigation of the phase separation process, in particular, the release of dust particles in systems with rotating flows. In particular, vortex devices with counter-twisted flows need to be improved, as well as technological equipment with active hydrodynamics for another purpose.

2. The object of research and its technological audit

The object of research is construction of a vortex dust collector.

Typical constructions of vortex dust collectors with a cylindrical separation chamber are shown for example in Fig. 1 and 2.

The first typical model [1] is a cylindrical separation chamber 1, in the upper part of which a secondary flow channel 4 (L_2) is provided, an outlet nozzle 3 for removing purified air (L_0). And in the lower part – the feed channel of the primary flow 5 (L_1), which is twisted into the swirler 6 and enters the separation chamber in the axial direction to meet the secondary flow. In the middle of the cylinder-conical dust collector 2 there is a swirler of the primary flow 6 from the washer 7 and axial piston pump 8, and the conical part of the bunker at the bottom is provided with a nozzle for removing the accumulated dust.

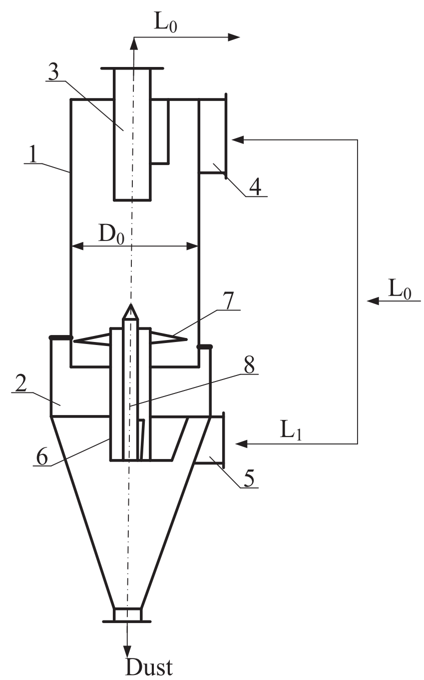

Fig. 1. Construction of the vortex apparatus: 1 – cylindrical separation chamber; 2 – dust collector; 3 – outlet nozzle; 4 – secondary flow channel; 5 – primary flow channel; 6 – primary flow swirler; 7 – washer; 8 – axial piston pump

Operation of the apparatus as a dust collector consists in the fact that a dusty flow in the form of an aerosol supplied from a dust generation source is fed to the separation chamber 1 by means of a traction fan 1. Simultaneously, through two channels – primary 5 (L_1) and secondary 4 (L_2), in which they are twisted in one direction they move towards each other. As a result of their interaction with the height of the separation chamber 1, the resultant swirling flow is formed. A rotating flow, from which, under the action of a complex system of forces, mainly centrifugal forces and drag forces, dust particles separate from the air. The flow moves radially from the axis of rotation to the side surface of the separation chamber, and then reaches the wall. In this case, the dust captured by the near-wall fraction of the secondary flow is transported down to the level of the washer 7 and enters through the annular gap formed between the washer 7 and the separation chamber 1 into the dust collector 2. The downstream secondary flow (L_2) at the level of the washer 7 is rotated by 180° and, gradually merging with the rising flow, in the form of a resultant vortex (L_0) with remnants of fine particles, moves upward, where through the outlet nozzle 3 is vented to the atmosphere or, if necessary, is directed to an additional treatment.

The second type of vortex dust collector is shown in Fig. 2 [2].

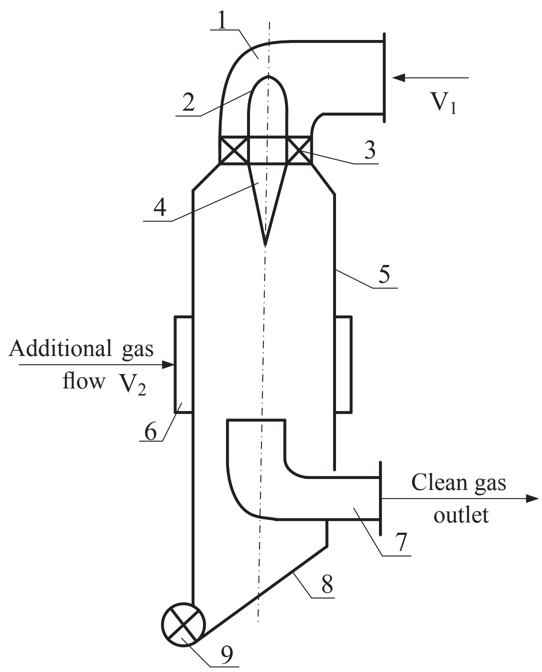

Fig. 2. Diagram of the vortex dust collector

The dust collector contains a gas duct of contaminated gas 1, a divider 2, swirler of the main gas flow 3 with a fairing 4, the body 5. The supply of an additional gas flow is performed by means of the device 6, and the clean gas outlet through the branch nozzle 7. In the conical part of the apparatus 8 dust is collected and discharged through the feeder 9. The structural feature of the vortex apparatus is that the two-phase flow, twisted by means of two swirlers, keeps rotation in the separation zone of the apparatus. In the central part of the apparatus in the mode of twisted in one direction flows, an effective dust separation is provided with a minimum hydraulic resistance of the used methods of the flow swirling.

The vortex dust collector is studied in the range $3\cdot10^6<Re<7\cdot10^6$, which corresponds to an average velocity in the apparatus of 8–15 m/s. Range of factors variation – concentration of products in gases, the inclination angle of the blades of the swirling main flow is selected according to the results of previous experiments and analysis of literature sources. During the experiments, the influence of the flux ratio in the radial direction is studied in two sections of the apparatus: immediately after the swirling and in the central part of the apparatus. The existence of critical regimes is established in which the efficiency of the separation process is low and is considered unacceptable and depends on the coefficient $k=V_1/(V_1+V_2)$, which for this case is approximately equal to $k=0.5$.

Due to the technological complexity of the process of collection of polydisperse dust, the mathematical modeling of the separation of dust particles in a system of counter-swirled flows is not sufficiently considered. Also, the influence of the physical and chemical properties of the dust on the separation process is not thoroughly considered, and as a result, there is no reliable engineering model for the selection and calculation of vortex dust collectors with a cylindrical separation chamber. The issues of the directions of constructive improvement and the arrangement of a rational technological scheme of the collection process have not been fully considered.

3. The aim and objectives of research

The aim of research is development of an improved (new) construction of a vortex dust collector.

To achieve this aim, it is necessary:

1. To investigate the effect of the swirler construction and the location of its installation in the gas duct on the efficiency of the vortex apparatus.
2. To investigate the aerodynamic processes, which are determined the particular nature of the flow rotation and its flow in the gas duct after the swirler, as well as the swirler construction.
3. To establish the characteristic flow regimes of the gas-dust flow in the duct after the swirler.

4. Research of existing solutions of the problem

An analysis of hydrodynamic studies of dust collection processes in typical constructions of dust collectors [1, 3] has shown that the main attention in the research of the process is given to determining the components of flow velocities in the separation chamber after the swirler, the influence on these parameters of the ratio of structural dimensions and the definition of hydraulic resistance. Undoubtedly, these research results are the basis for upgrading the main functional units of vortex devices with a cylindrical separation chamber and improving other performance parameters. In works [1, 3], with the coefficient $k=V_1/(V_1+V_2)=0.8$, which is considered the most rational for dust removal for various dust components (input dust concentration >5 g/nm^3):

- burden of glass production $d_n=(18\div20)$ μm;
- dolomite powder $d_n=(10\div16)$ μm;
- ground chalk $d_n=(6\div12)$ μm;
- quartz test dust $d_n=(6\div10)$ μm, dust collection efficiency is determined that within the particle size range from 6 to 10 μm does not exceed 90 %, and in the range from 12 to 20 μm is 91–92 %.

When using cyclones as dust collectors for such conditions, the dust collection efficiency is 75–80 % [1–3]. Thus, known studies confirm the advantage of the use of vortex devices for the process of «dry» cleaning of the

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dust-gas flow from dust before other types of apparatus for dry cleaning of the gas-dust flow. However, typical constructions of vortex dust collectors do not allow for dedusting gases with an efficiency of up to 99 % for dust particles smaller than 20 μm, in practice it is necessary to install additional wet cleaners after the dust catcher.

Analysis of the results of the studies given in [1, 3] shows that the distribution of the components of the flow velocity in the separation chamber depends on the swirling angle of the flow in the swirler. The swirling angle of the flow, in turn, depends not only on the angle of the blades, but mainly on the hydrodynamics and the nature of the rotation of the flow in the swirler itself and the zone close to it. In these zones, according to the theoretical foundations and practice [4], in almost all cases, the non-uniform distribution of velocities in a viscous gas is observed in flows of rotating, especially at high velocities at the entrance to the swirler. The non-uniform distribution of velocities along the radius leads to intensive dissipation of mechanical energy in the internal heat removal and to an uneven distribution of the inhibition temperature. The attainment of the latter conditions, depending on the physicochemical properties of the dust particles, can promote simultaneous coagulation of fine dust particles with the formation of larger dust agglomerates, precipitate quite rapidly. The latter is more or less observed when processing a gas flow that retained up to 10 g/nm^3 of fine-dispersed coal dust (<5 μm) [5–11]. The use of the features of the hydrodynamic regime of the gas-dust flow rotation in the swirled zone and immediately after it, in order to solve the problem of increasing the efficiency of the dust removal in the vortex apparatus, revealing the features of the mechanism and the destructive forces of the process is a promising task.

5. Methods of research

Let's consider the process of dry cleaning of the dust-gas flow in a vortex dust collector with a concentrated vane gas inlet for various constructions of vane swirlers.

Diagram of investigated vortex dust collector with a vane swirler is shown in Fig. 3.

Ducted gas flows into gas duct 1 and is swirled by blade vortex 2. Fairing 3 slightly pushes the flow to the wall of the apparatus and favors the smooth flow of the bladed vortex by the gas flow.

Under the action of centrifugal force, dust particles in a swirled gas flow move to the walls of the body 4. Simultaneously, the same dust, or the gas purified after the apparatus, is fed into the dispensing chamber 5 and, using a swirler 6 (made in the form of six nozzles with a slope of 45°), enters the working cavity of the apparatus.

The additional gas flow from the swirler 6 twists the main stream in the same direction as the swirler 2 and simultaneously blows dust particles from the walls into the bunker 7. The additional gas flow during the spiral flow around the main stream gradually penetrates into it. The annular space around the inlet duct can be equipped with a dust separating washer 9, which is designed to ensure the irreversible release of dust into the discharge device (conveyor). From the bunker, dust enters the capacity of the finished product, and the purified gas through the exhaust duct 10 into the atmosphere. The diagram of the stand for determining the aerodynamic characteristics is shown in Fig. 4.

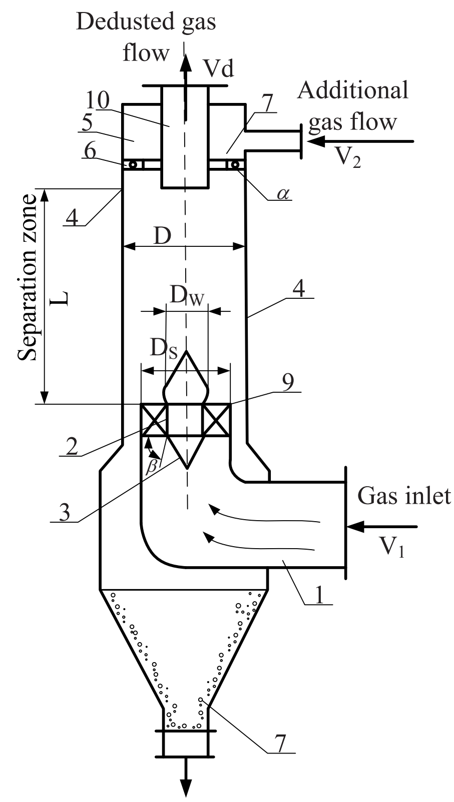

Fig. 3. Diagram of a vortex dust collector with concentrated vane gas injection

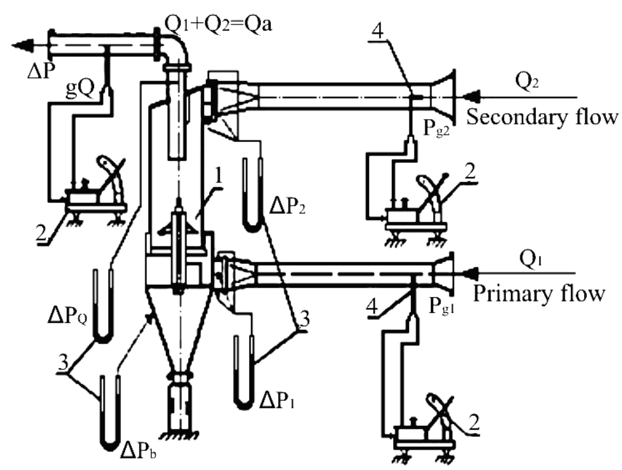

Fig. 4. Scheme of the stand for determination of aerodynamic characteristics: 1 – model Fig. 3; 2 – micromanometers with an inclined scale; 3 – liquid micromanometers; 4 – pneumometric tube of the Research Institute of Industrial and Sanitary Gas Purification construction

The diagram of the stand for determination of the overall efficiency of dust collection is shown in Fig. 5.

When constructing the model in Fig. 3, sizes of the vortex dust collector are chosen on the basis of the most rational parameters known from practice: $L/D=2.5\div3.5$; $D_s/D=0.6\div0.8$; $D_{hp}/D_s=0.3\div0.5$; $D_w/D=0.5\div0.8$. The inclination angle of the vortex blades is $\beta=30–60°$, the inclination angle of the secondary flow nozzles is $\alpha=30\div45°$.

It is chosen $D_s=5\cdot10^{-2}$ 2 m; $D=8\cdot10^{-2}$ m; $D_{hp}=1.5\cdot10^{-2}$ m; $D_w=6.5\cdot10^{-2}$ m; $L=24\cdot10^{-2}$ m.

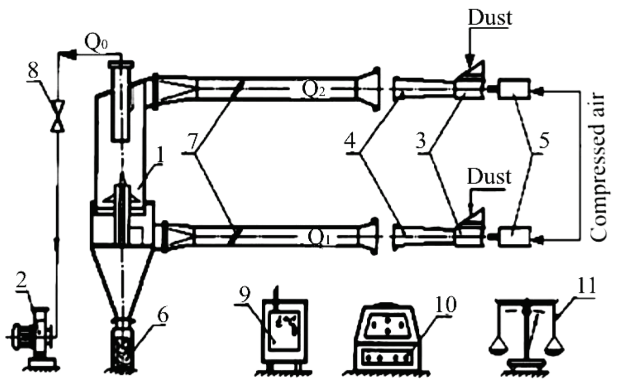

Fig. 5. Diagram of the stand for determination of the overall efficiency of dust collection: 1 – model Fig 3; 2 - high-pressure fan BBT-5; 3 – dosing system; 4 – diffuser; 5 – compressed air nozzle; 6 – dust collector; 7 – air flow regulator (throttle valve) 8 – slide valve of the common collector; 9 – drying cabinet; 10 – control panel; 11 – laboratory scales

Swirler diagram is shown in Fig. 6.

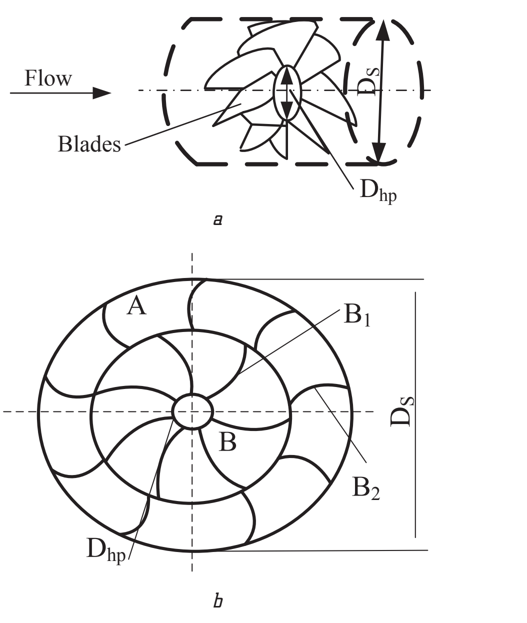

Fig. 6. Swirler diagram: *a* – made of sheet brass; *b* – for the organization of coaxial turbulent flows swirling in opposite directions

The swirler is made of sheet brass $0.5\cdot10^{-3}$ m thickness, the number of blades is 8. The second type of swirler (Fig. 6, *b* is the projection from above) provided for the organization of coaxial turbulent flows swirling in opposite directions due to the blades. The ratio of the cross sections of the external swirler *A* and internal *B* is approximately $A/B=1$. In the gas duct 1 Fig. 3 the swirler is installed both at the end of the gas duct at the level of the washer 9 and below the end at distances that are selected on the basis of investigations of the relative velocities along the length of the cylindrical part of the gas duct at the level of the end. Fig. 7 shows the diagram of measurements of the vortex gas flow parameters in the gas duct 1.

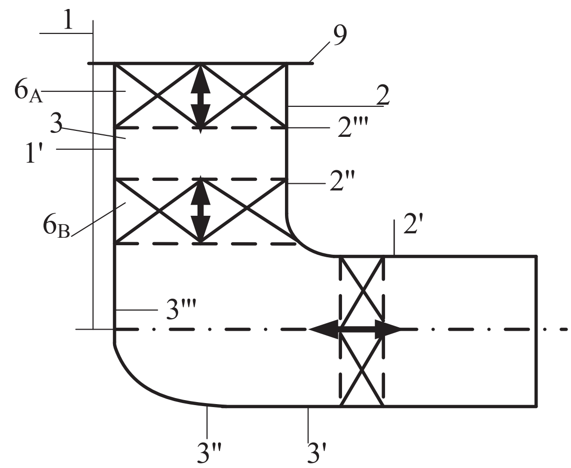

Fig. 7. Diagram of measurements of the vortex gas flow parameters in the gas duct 1, depending on the swirling position: 6_A – swirler is installed at the end of the inlet gas duct at the level of the washer 9; 6_B – one of the possible positions of the swirler 6, installed below the end of the inlet branch duct. Positions 1, 1′; 2′; 2″, 2‴, 3′, 3″, 3‴, where the sensors are installed

The parameters of the vortex flow are measured with the aid of three sensors: a two-tube sensor with a tube slope angle of 70° to measure a two-dimensional velocity field; most of the measurements are carried out using a cylindrical sensor, which is the simplest during calibration and operation. The diameter of the working part of the sensor is $3\cdot10^{-3}$ m. A five-channel sensor with a ball diameter of $5\cdot10^{-3}$ m is used to measure the three-dimensional velocity field. The calibration of all sensors is carried out in accordance with the procedures given in [6]. As is known [1, 4], the swirled gas flow after the swirler is a complex three-dimensional one. The velocity vector of a flow is decomposed in a cylindrical coordinate system into three components: a base, 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 construction calculations, it is necessary to know the angular velocity of the flow in an arbitrary section of the separation chamber at a certain height in the inner layer. The equation of the angular momentum of the gas is determined by the dependence [1, 4]:

$$M_1(Z)=\int_0^r \rho\cdot V_{s1}\cdot 2\pi\cdot r\cdot \mathrm{d}r\cdot w_1(L)\cdot r^2. \quad (1)$$

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

$$w(Z)=\frac{2M_{IN}\cdot r^2}{\rho(L_1+L_2)\cdot r^4}, \quad (2)$$

where L_1, L_2 – flow rate of primary and secondary flows, m^3/s;

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

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

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

where K – the empirical coefficient (for $K=0$, the radial velocity is distributed as described in the theory [1–4], for $K\geq 0$ the radial velocity grows down the chambers, and at $K\leq 0$ the radial velocity decreases to the bottom of the chamber); r_0 – radius of separation chamber, separation of flows; V_z, V_φ, V_r – axial, tangential, radial flow velocity, m/s.

In this case, it should be noted that in the formula for determining M_{IN}, the velocity V_φ corresponds to the tangential component that swirled flow, which is observed immediately behind the swirler and in the section close to it. Thus, other things being equal, the value of $w(Z)$ depends on the component V_φ, which in turn uniquely depends on the hydrodynamic conditions in the swirler zone and immediately after it. The latter further justifies the relevance and purpose of the study. When conducting a study during cold purges with clean air of the gas duct (which is a duct made of plexiglas from the straight section from the end to the bend and equal to 0.6 m), the measurement is carried out after the swirler in three sections:

I – 1.6 h_i/D_S; II – 3 h_i/D_S; III – 4,5 h_i/D_S,

where h_i – the distance from the swirler to the end of the gas duct. In studies of a two-phase flow in the dust collector model (Fig. 3), the following assumptions are made:

– the dust particles are solid, they can interact with each other due to the intensive collision and the developed specific surface of the particles only in the swirler zone, where the maximum values V_φ and V_r are observed and quasi-solidity of rotation of the dust-gas flow is observed;
– after the region (zone) of the swirler, the particles do not interact with each other;
– a particle that touched the wall of the separation chamber case, is considered to be caught;
– at the entrance to the dust collector the stream of the gas-gas flow has a uniform velocity field;
– distribution of dust particles along the section of the inlet duct of the dust collector is uniform;
– the resistance to movement of particles in a gaseous medium is described by the Stokes law;
– the tangential component of the velocity of particles coincides with the tangential and axial components of the velocity of the gas flow rotation, radial velocities due to the action of inertia forces are different.

Two dimensionless parameters are distinguished:
– the degree of initial flow swirling:

$$\eta=V_{\varphi 0}/z_\varphi,$$

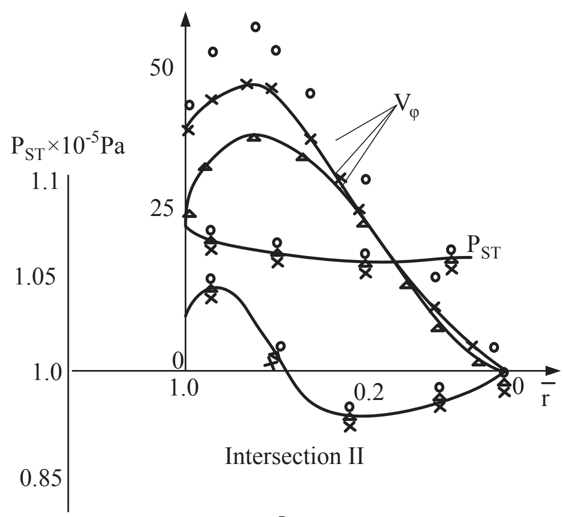
where $V_{\varphi 0}$ – the tangential velocity at the outlet from the swirler ($V_{\varphi 0}\geq 0$), while in the core of the flow leaving the swirler (B, Fig. 6, b) $\omega=V_{\varphi 0}$, and at the exit from the swirler (A, Fig. 6, a) $\omega=-V_{\varphi 0}$;
– the degree of loading of the channel $\varphi=D_{HP}/D$.

Initial conditions are the characteristics of the air and dust: air temperature 293 K, average diameter of dust particles: lime (CaO) – 2÷20 μm; calcium oxide hydrate [$Ca(OH)_2$] – 0.5÷10 μm; zinc oxide (ZnO) – 0.5÷15 μm. Density: air – 1.205 kg/m^3, CaO – 3360 kg/m^3, Ca(OH) – 2240 kg/m^3, ZnO – 2850 kg/m^3.

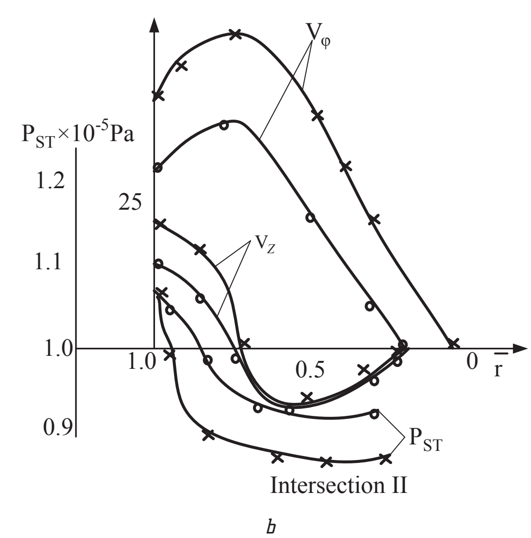
Boundary conditions: the average velocity V_{IN}, the dust-air flow at the inlet to the dust collector is stable and maintained in the interval 40÷80 m/s, which corresponded to the air flow rates respectively: $G=13.4\cdot 10^{-3}$ kg/s and $G=55.0\cdot 10^{-3}$ kg/s. At the indicated costs and velocities, the Reynolds number (Re) was $Re\approx 10^5\div 10^6$.

Comparing swirlers with different blade inclination angles (Fig. 6), it should be noted that in the V_{IN} study the velocity $V_\varphi(r)_{max}$ stratifies for different inclination angles of the blades and reaches a maximum when V_{IN} is the largest.

Fig. 8, b shows the distribution of $V_\varphi(r)$, $V_z(r)$, $P_{st}(r)$ for various gas flow rates while storing the entry velocity into the swirler. From Fig. 8, b, it is clearly seen that the aerodynamic flow characteristics with an inclination angle of β–45° improve. So the ratio for the angle β–45° is $_\varphi(r)_{\max}/V_{IN}\approx 0.73$, and for β=30° this ratio is equal to $V_\varphi(r)_{\max}/V_{IN}\approx 0.46$, the center negative pressure is $0.87\cdot 10^5$ and $0.97\cdot 10^5$ Pa, respectively.



a



b

Fig. 8. Distribution $V_\varphi(r)$, $V_z(r)$, $P_{st}(r)$ as a function of the inclination angle of the vortex blades for the air flow rate:
a – $G=40\cdot 10^{-3}$ kg/s; × – β=60°; ∘ – β=45°; ▲ – β=30°;
b – $G=13.5\cdot 10^{-3}$ kg/s; ✕ – β=45°; ∘ – β=30°

Fig. 9 shows the typical distributions $V_\varphi(r)$, $V_z(r)$, $P_{ST}(r)$ for the gas flow rate $G=40\cdot10^{-3}$ kg/s for different intersections along the length of the channel.

An analysis of the distribution curves is given in Fig. 8, 9, it can be argued that, after the swirler in the duct, almost to II, the intersection of the rotation of the flow passes as a quasi-solid. That is, the law $V\varphi = Cr$ is satisfied, and only a very thin boundary layer develops near the wall of the gas duct. Areas of inverse flows are also observed, and they are annular in the cross section close to the swirler. Further along the flow, the distribution $V_\varphi(r)$ becomes different, the zone of quasi-solid rotation is reduced, the absolute value of $V_\varphi(r)$ decreases due to friction of the gas flow into the walls and internal friction between the gas layers, the boundary layer grows. The character of the distribution of the axial velocity $V_z(r)$ also varies somewhat. The axial flow in the sections after the swirler is pressed against the wall, and the bulk of the gas flows by 1/3 of the radius. Further the flow expands, occupying already 2/3 of the radius. The static pressure distribution $P_{st}(r)$ in intersection II differs significantly from the distribution $P_{st}(r)$ in intersection III. At the same time, intersection II shows a fairly large zone of constant pressure reduction, which occupies almost half the diameter. Further in section III, this zone narrows and occupies 1/5 of the diameter. Such narrowing, as well as a small longitudinal gradient along the negative pressure at the center, is probably the cause of the appearance of backward currents. The transition $P_{st}(r)$ through the zero line always corresponds to the point where V_φ has the maximum value.

Fig. 10 shows the distribution of $V_\varphi(r)$, $V_z(r)$, $V_r(r)$, $P_{st}(r)$ in two sections for extending the gas duct after the swirler, as measured by the ball sensor.

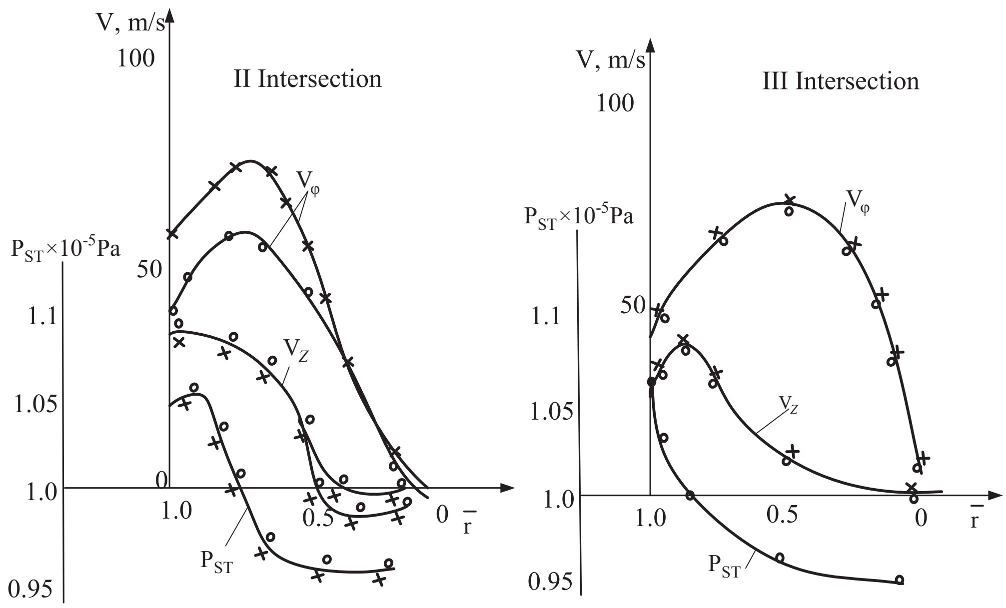


Fig. 9. Distribution of $V_\varphi(r)$, $V_z(r)$, $P_{ST}(r)$ for in different sections $G=40\cdot10^{-3}$ kg/s; × – $\beta=45°$; ∘ – $\beta=30°$

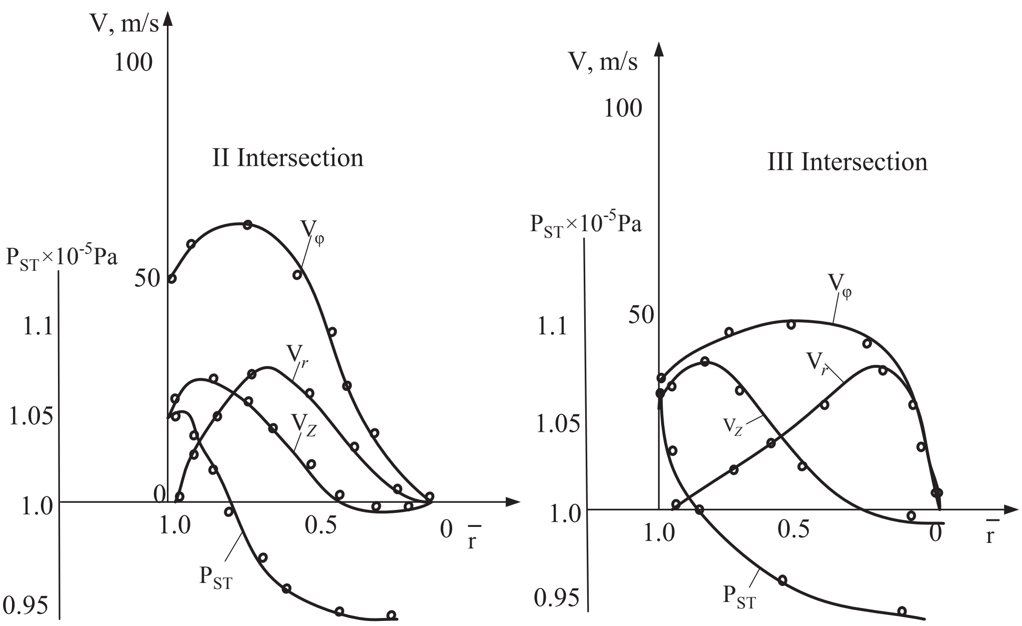


Fig. 10. Distribution of $V_\varphi(r)$, $V_z(r)$, $V_r(r)$, $P_{ST}(r)$ by extending the duct channel after the swirler: $G=40\cdot10^{-3}$ kg/s, $V_{IN}=80$ m/s, sensor layers, $\beta=45°$

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In Fig. 11 as an example, the results of measurements of the averaged axial and tangential components of the velocity and the pulsating component are given, using a swirler (Fig. 6, *b*) with the installation of vortex blades along the inner and outer contours, respectively, at angles $\beta_1 = 45°$ and $\beta_2 = 45°$. The average swirling angles of the flows at the entrance to the working part are at the same time by 10–15 % more.

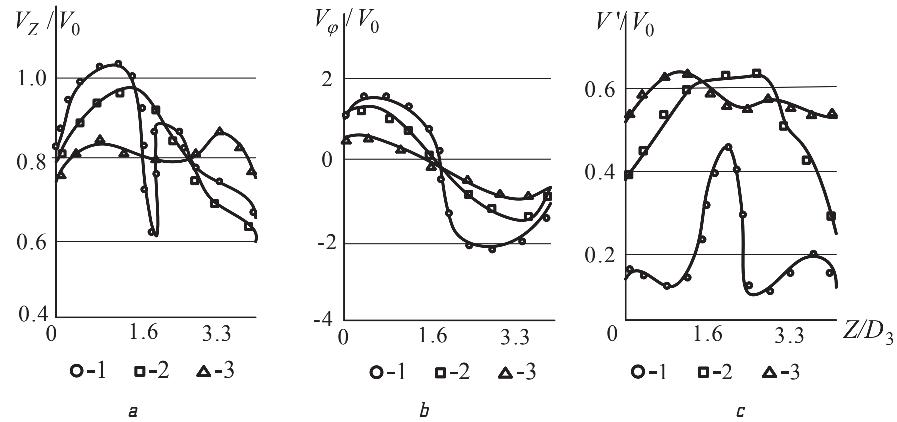

Fig. 11. Experimental profiles:
a – axial V_z; *b* – tangential V_φ; *c* – pulsating V' velocity components in sections I-III, $V_0 = V_{IN}$

The measurements are carried out according to the cross-sections:

I section $Z/D_s = 0$ (that is, immediately behind the swirler);

II section $Z/D_s = 1.6$, $Z = 0.08$ m;

III section $Z/D_s = 3.3$, $Z = 0.165$ m.

The speed $V_{IN} = 50$ m/s, $G = 26 \cdot 10^{-3}$ kg/s, $Re \approx 10^5$.

From Fig. 11 it can be seen that at a distance of about $Z/D_s = 3.3$ (0.165) from the swirler, the flows are almost completely mixed, which is reflected by the alignment of the profile of the axial velocity component and the significant weakening of the tangential component. Generation of turbulent pulsations passes near the interface of flows that can be explained by the presence of a radial gradient of the tangential component, the averaged velocity. The maximum value of turbulent velocity pulsations is achieved at a distance $Z/D_s = 2.5$ from the swirler and is approximately 20 % of the maximum difference of the tangential velocity component.

To compare the efficiency of the considered swirlers (Fig. 6, *a, b*) from the point of view of generating the maximum value of the turbulence energy K_m, which is determined by:

$$K_m = 0{,}04 \cdot \frac{V_z}{\alpha^2}; \quad \frac{K_{ma}}{K_{mb}} \le \frac{1}{4 \cdot (1-\alpha)^2}, \tag{3}$$

where $\alpha = F_1/F_2$, F_1 – the total plane of the holes between the blades.

Analyzing formula (3), it is possible to state that at $\beta = 45°$ ($\alpha < 0.5$) and the same losses, the maximum value of the turbulence energy is higher when using a swirler (Fig. 6, *b*).

6. Research results

The presented experimental data on hydrodynamics with the use of two types of swirlers (Fig. 6, *a*, *b*) suggest that in the zone of maximum velocities V_φ and V_r, after the swirlers, the agglomeration of dust particles may occur due to an intensive collision.

In addition, in order to obtain the maximum value of the angular velocity of the gas flow rotation in the separation chamber of the vortex dust collector (2), it is necessary to use the swirlers with $\beta = 45°$ and install it at a distance $Z/D_s = 1.6$ below the duct end (or washer 9, Fig. 3) $Z \approx 0.08$ m. This zone of quasi-solid flow rotation, that is, the zone where the maximum value of $V_\varphi(r)$, $V_r(r)$ and the maximum velocity coefficient $K = V\varphi_{max}/V_{BX}$ are reached. It is at these parameters on the model (Fig. 3) using the stand (Fig. 5) that the overall efficiency of dust collection is determined using the above substances as dust. The dosage of these substances in the air flow is approximately constant and equaled the concentration of dust particles in the flow at the level of $7 \div 8$ g/nm^3.

Table 1 shows the averaged results of studies on the efficiency of dust collection by a vortex apparatus, modernized in accordance with the recommendations given above.

Table 1

Dust collection efficiency by a vortex apparatus with a swirler (Fig. 6, *a*, *b*)

No.	Gas-dust flow rates at the inlet, kg/s 10^{-3}	Dust type and inlet concentration, g/nm^3	Characteristics of dust at the inlet			Indicators at the outlet from the apparatus			
			Density, kg/m^3	Specific surface, m^2/g	Dispersion, μm, (average size, μm)	Average particle size at the inlet, μm	Dust concentration at the outlet, g/nm^3	MPC of the sanitary protection zone, share	Dust collector efficiency, %
Swirler (Fig. 6, *a*)									
1	40.0	$Ca(OH)_2$, 7 g/m^3	2240	8.0	0.5–10.0 (5.0)	35±2	0.21	0.43	97.0
2	40.0	CaO, 7 g/m^3	3360	3.0	2.0–20.0 (10.0)	20±5	0.30	0.62	96.0
3	40.0	ZnO, 7 g/m^3	2850	10.0	0.5–15.0 (5.0)	50±5	0.14	0.29	98.0
Swirler (Fig. 6, *b*)									
1	40.0	$Ca(OH)_2$, 7 g/m^3	2240	8.0	0.5–10.0 (5.0)	42±3	0.10	0.2	98.5
2	40.0	CaO, 7 g/m^3	3360	3.0	2.0–20.0 (10.0)	22±1	0.07	0.14	99.0
3	40.0	ZnO, 7 g/m^3	2850	10.0	0.5–15.0 (5.0)	55±2	0.06	0.1	99.2

As can be seen from the data given in Table 1, the results are predicted concerning the increase in the efficiency of the vortex dust collector due to the agglomeration of dust particles. The attainment of the maximum values of the velocity components $V_\varphi(r)$, $V_r(r)$ at the outlet from the swirler is confirmed by the operation of the modernized vortex apparatus.

7. SWOT analysis of research results

Strengths. The creation and development of new highly efficient and improved types of gas cleaning equipment is promising, based on the theoretical justification and investigation of the phase separation process, the separation of dust particles in systems with rotating flows. The analysis of the obtained results of the swirler construction of the incoming flow on the hydrodynamics and the efficiency of the apparatus and the process of dust collection testify to the advisability of using vortex devices as highly efficient dust collectors for dry gas purification. It is shown that in the implementation of the exhaust gas purification process for a conventional blade vane fan with one-side swirling, the most effective blade angle is 45°. The swirler should be installed in the duct from the end outlet to the separation chamber below by $1.4 \div 1.6$ of the swirler diameter.

Weaknesses. In this work, hydrodynamics and the efficiency of the vortex apparatus and the dust collection process are investigated. Due to the technological complexity of the process of polydisperse dust collection, the mathematical modeling of the separation of dust particles in a system of counter-swirled flows is not sufficiently considered. Also, the influence of the physical and chemical properties of the dust on the separation process is not thoroughly considered, and as a result, there is no reliable engineering model for selection and calculation of vortex dust collectors with a cylindrical separation chamber. The issues of the directions of constructive improvement and the arrangement of a rational technological scheme of the collection process have not been fully considered. The dust collector contains a gas pipeline of contaminated gas and, as a result of operation, significant volumes of fine dust are formed, which must be disposed of using additional equipment.

Opportunities. The introduction of vortex devices as a cleaning equipment in industrial enterprises will reduce the industrial negative impact on the environment, namely, the atmosphere. An important issue is the reduction of the threat of global consequences through the introduction of engineering solutions for the purification of fine aerosol emissions.

Threats. The proposed basic construction of the vortex dust collector, which allows to increase the efficiency of cleaning with a vortex device to 98–99 %, will contain the capital costs for development, mathematical analysis and materials for the apparatus, but the capital costs for the enterprise will be one-time.

8. Conclusions

1. The influence of the swirler construction and the location of its installation in the flue gas flow duct on the efficiency of the vortex apparatus for vortex dust collectors with a cylindrical separation chamber is studied. It is shown that the aerodynamic processes that determine the nature of the flow rotation and its flow in the duct after the swirler achieve the maximum possible angular velocity of rotation of the gas flow in the separation chamber for this construction. This velocity is uniquely related to the maximum possible values of the velocity components $V_\varphi(r)$, V_r(r), which are reached in the swirler zone.

2. It is found that the blade vortex, which provides for the organization of coaxial turbulent flows in the duct, twisted in opposite directions, will allow more efficient agglomeration of dust particles. Based on the results of the research, a basic construction of the vortex dust collector is developed, which makes it possible to increase the cleaning efficiency with a vortex device to 98–99 %.

3. Characteristic flow regimes of the gas-dust flow in the duct are established immediately after the swirler, depending on its construction. It is shown that for a traditional vane swirler with one-side swirling, the most effective blade inclination angle corresponds to 45°, and its installation in the duct is necessary from the end outlet to the separation chamber lower by $1.4 \div 1.6$ of the swirler diameter. Under these conditions, before the exit of the gas-dust flow into the separator, agglomeration of the dust particles takes place and at the exit of the gas-dust flow from the end of the duct into the separation space, which should maximize the possible components $V_\varphi(r)$ and $V_r(r)$, which ensure the maximum value of the angular velocity of the flow in the separator.

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ВЛИЯНИЕ КОНСТРУКЦИИ ЗАВИХРИТЕЛЯ ВХОДНОГО ПОТОКА НА ГИДРОДИНАМИКУ И ЭФФЕКТИВНОСТЬ РАБОТЫ

Исследовано влияние конструкции завихрителя и места его установки в газоходе для подачи газопылевого потока на эффективность работы вихревого аппарата. Доказано, что конструкция завихрителя при соответствующих условиях позволяет закрученному потоку добиваться максимально возможной для данной конструкции угловой скорости вращения газового потока. Разработана принципиальная конструкция вихревого пылеуловителя, которая позволяет повысить эффективность очистки с помощью вихревого аппарата до 98–99 %.

Ключевые слова: конструкция завихрителя, агломерация пыли, угловая скорость вращения газового потока.

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INVESTIGATION OF THE TREATMENT EFFICIENCY OF FINE-DISPERSED SLIME OF A WATER ROTATION CYCLE OF A METALLURGICAL ENTERPRISE

Досліджені особливості очищення шламів водооборотного циклу металургійного виробництва. Виявлено, що надходження завислих часток в шламові води відбувається періодично і нерівномірно. Встановлено, що шлами газоочищення металургійного підприємства містять до 93 % дрібнодисперсної фракції твердої фази класу менше 20 мкм. Рекомендовано застосування лабораторних тестів якості шламу і ефективності флокуляції. В ході промислових випробувань встановлена можливість очищення шламу з ефективністю до 99 % флокуляційно-відцентровим способом із застосуванням методики лабораторних тестів.

Ключові слова: *газоочищення металургійного підприємства, дрібнодисперсні шлами, шлами газоочищення, модуль очищення.*

1. Introduction

According to various sources, more than 70 million tons of slimes have been accumulated at metallurgical enterprises in Ukraine, of which about a third are suitable for reuse [1]. At the metallurgical industry, the greatest amount of water is used as a cooler for steelmaking furnaces and converters, as well as for wet gas treatment systems. The wastewater that is formed is contaminated with solid suspended particles and has dissolved chemicals, for example, hardness salts. For example, the volume of sewage discharged by enterprises of ferrous and nonferrous metallurgy in Ukraine reaches 500 million m^3/year.

In industrial processes and technologies, the greatest amount of water is used as a coolant, solvent, transport agent. In metallurgy, wastewater is formed mainly after cooling of steel-smelting converters and after wet treatment of gases.

The amount of sewage and slime of wet gas treatment is up to 10 m^3 per 1000 m^3 of gas, which corresponds to approximately 4–5 m^3 per 1 m of melted steel.

The use of sewage in the water cycle system of enterprises because of the high content of chemical compounds in concentrations unacceptable by existing norms for circulating water requires their treatment. In order to reuse slime in gas treatment, they must be clarified to a residual suspended matter content of 150–200 mg/dm^3.

The discharge of contaminated sewage into the external slime collectors of metallurgical enterprises leads to secondary contamination of soils and groundwater with heavy

