Experimental Optimization of Dust Collecting Equipment Parameters of Counter Swirling Flow with Coaxial Leadthrough for Air Ventilation System and Dust Elimination

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Abstract. The article substantiates the rationality of the use of the noncoaxial conical part of the separation chamber of the VPC dust collectors (VIDC-series dust collector), which makes it possible to improve the efficiency of the use of the secondary swirled flow. The results of the experimental determination of the kinematic flow structure of swirling flow in the separation chamber of the dust collector with opposite rotational flotations. A semi-empirical method is proposed to determine the influence of design parameters of the primary input of the VZP dust collector on the efficiency of dust capture. The results of experimental studies confirming the positive impact of the proposed constructive solutions on the efficiency of the dust collector with opposite rotational flotations.

1. Introduction
Production of building materials is a complex technological process associated with the production and use of crushed finely dispersed materials, which causes dust air pollution [1-4]. Traditionally used inertial dust collectors often do not provide increased requirements for the cleaning quality of fine dust emissions of construction industry enterprises.

Introduction of the most effective methods of cleaning dust pollution, such as wet dust collection, electrostatic precipitators, etc. is constrained by their technological complexity, and as a result, increasing capital and operating costs.

2. Relevance
In recent years, at the construction industry enterprises, vortex dust collectors on counter swirling flows (CSF) have been widely used as dust-collecting dry-cleaning agents [5-7]. The introduction of such dust collectors is due to the following several advantages compared to cyclonic: a higher degree of fine dispersed dust capture; a lower degree of abrasive wear of the device; a greater specific capacity; less sensitivity of fractional efficiency to fluctuations in gas flow and dust concentration in it; the possibility of more efficient cleaning of hot gases and control of dust collection process by changing the ratio of gas flow through flows, and in some cases, lower costs [7, 8].

At the same time, the efficiency of the dust collectors on the counter-swirling flows is much more dependent on the design parameters and aerodynamic mode of operation, in comparison with conventional inertial dust collectors of cyclone type in view of a more complex design.

At the moment, the influence of such important characteristics on the process of dust collection as the proportion of the flow rate of the dust collector fed to the bottom inlet, the flow rate of the gas fed for cleaning, the concentration of the solid phase in the dust and gas stream, the ratio of the concentrations of the primary and secondary flows, etc. have been studied in sufficient detail [3, 9]. The results of research on the design characteristics of CSF devices are characterized by a much...
smaller volume, and basically, they are reduced to the development and research of various layout schemes for aspiration and dust-free ventilation systems.

3. Problem statement

During the analysis of the design features of the CSF and vortex inertial dust collectors (VIDC) series, the general design fault of construction, is noted: the branch of the secondary swirling flow has a large aerodynamic resistance and introduces significant distortions into the structure of the swirling flow, especially in the near-wall region of the lower part of the separation chamber. In addition, in the devices of the VIDC series, a significant part of the rotational energy of the secondary flow is lost when passing a direct tap located in the separation chamber [1, 3, 4].

In order to eliminate the above-described disadvantages, it is proposed to use coaxial input of a secondary swirling flow. To implement this design solution, a change in the configuration of the lower conical part of the dust collector is required, since with the preservation of the traditional design, unloading of the captured dust is difficult. Therefore, to implement the coaxial input of the secondary flow, it is proposed to use the non-coaxial lower conical part of the separation chamber (Figure 1.)

In order to increase the capture efficiency, it is proposed to create a vacuum in the volume of the dust hopper (10) [4]. For this purpose, an ejector unit (13) is designed. Regulation of the vacuum in the in the hopper area is carried out by supplying air to the ejector from the atmosphere, through the mixing nozzle (12), equipped with a regulating damper (6). The use of this design solution allows increasing the range of the effective operation of the dust collector in the presence of changes in the flow rate of the gas being purified [5,8,9]. The air is taken out from the volume of the dust hopper (10) by means of a nozzle equipped with cone-shaped confuser that allows reducing the amount of dust particles entering the secondary input by reducing the velocity in the inlet section of the nozzle.

To create a twist in the branch pipe of the secondary flow, a cochlear twister is used, characterized by less aerodynamic losses and greater uniformity of the swirling flow compared to the tangential flow traditionally used in the VI dust collectors series [1-4]. This solution allows combining the positive features of the dust collectors of the CSF and VI series, and also greatly facilitating the maintenance of the secondary input. The internal arrangement of the cochlear twister in the CSF dust collectors significantly degrades the aerodynamic characteristics of the separation chamber. In addition, the cochlear twister is much more then tangential, prone to the formation of dust deposits, eventually leading to a reduction in the cross-sections, a decrease in the efficiency of the flow swirling, and as a consequence to a decrease in the overall efficiency of the dust collector on counter-swirling flows. The above becomes particularly relevant when the nozzle axis of the swirling flow is located vertically.

Also on the intensity of deposits formation in the volume of the cochlear twister has the adhesive ability of dust particles contained in the gas being purified. Maintenance of the spinner located in the separation chamber requires a complete stop of the aspiration system, as well as the dismantling and disassembly of the dust collector, which entails significant material and time costs. Such disadvantages are deprived in dust collector of the VI series with an external location of the tangential twist, but the latter loses to the cochlear in the intensity of twisting and uniformity of the velocity field [8-10], which negatively affects the efficiency of a secondary swirling flow use. The proposed design allows combining high performance with easy maintenance and regulation.
Figure 1. Dust collector CSF with coaxial input of secondary flow. 1 - inlet air pipe; 2 - upper tangential input; 3 - separation chamber; 4 - non-coaxial bottom of the separation chamber; 5 - a branch pipe of the caught dust; 6 - regulating damper; 7 - an insert; 8 - a branch pipe of the cleared gas; 9 - clean air duct; 10 – dust hopper; 11 - secondary input of the flow; 12 - mixing nozzle; 13 – ejector unit; 14 - cochlear twister for secondary input.

The increased intensity of the flow twist, created by the secondary branch pipe, which makes it possible to increase the overall intensity of the flow swirling in the separation chamber, also reduces the amount of dust particles entering the branch pipe of the purified stream. This effect is especially displayed in finely dispersed particles, whose trajectories, unlike large particles, practically coincide with the trajectory of the gas flow, in view of the prevalence of aerodynamic forces over mass ones [3, 8]. An increase in the intensity of the secondary flow twisting allows better miscibility of the secondary and primary streams, thereby increasing the probability of fine dispersed particles entering the near-wall flow zone where the process of interaction with the walls of the separation chamber occurs, which leads to an increase in separation efficiency.

4. Experimental studies

Experimental studies were carried out to obtain data on the parameters of the wall flow in the dust collector on counter-twisted flows under study. An analysis of the experimental results of determining the circumferential and axial components of the gas flow velocities in the near-wall zone of the separation chamber allows to make an assumption about the self-similarity of the kinematic structure of the flow in the near-wall zone in regard to the initial value of the twist flux intensity \( \Phi_0 \).[1, 3]. The obtained curves are monotonically decreasing dependences of the form:

\[
\frac{\tan(\phi)}{\tan(\phi)_0} = 0.902(h/D)^{0.129} \tag{1}
\]

\[
\frac{U_t}{U_{t0}} = 0.88(h/D)^{0.183} \tag{2}
\]

To describe the movement of a dust particle in a swirling flow, it is most convenient to use a cylindrical coordinate system. In the radial direction, the particle is affected by the centrifugal force \( F_\mu \), and the radial projection of the resistance to flow around the gas flow \( F_\mu \). To determine the latter, the hypothesis was used about the absence of a radial component of the gas flow velocity in the near-wall zone of a weakly and moderately swirled flow. In this way:

\[
m \frac{d^2r}{dt^2} = m \left( \frac{d\phi}{dt} \right)^2 r + \left( \frac{dr}{dt} \right)^2 \frac{\rho \lambda_\mu \pi d^2}{8} \tag{3}
\]

The projection of forces on the movable tangent axis \( \tau \) consists of the projection of the resistance force over the flow \( F_\mu \) and Coriolis force. Replacing the angular velocity by linear on the moving axis:

\[
m \frac{d^2\tau}{dt^2} = \left( \frac{d\tau}{dt} - U_\tau \right)^2 \frac{\rho \lambda_\mu \pi d^2}{8} - m \frac{2 \, dr \, d\tau}{r \, dt \, dt} \tag{4}
\]

The projection of forces on the vertical (longitudinal) axis consists of the gravitational force \( F_m \) and the vertical projection of the resistance force over the particles by the gas flow \( F_\mu \).
To simplify the obtained equations, characterizing the projection of forces on the longitudinal and movable tangential axis, it is assumed that the circumferential and longitudinal velocity components coincide with the corresponding projections of the gas flow velocity. This assumption is based on the results of visual observation allowing to state that particles with a particle size of up to 180 microns in the near-wall region practically move along the trajectory of the swirling gas flow, due to the insignificance of the masses and inertia forces in comparison with aerodynamic forces. Then the equations describing the motion of the particle take the form:

\[
m \frac{d^2 y}{dt^2} = \left( F_y + P \right) = \left( \frac{dy}{dt} - U_x \right)^2 \frac{\rho \lambda_m \pi d^2}{8} - mg
\]

(5)

Using the ratio (1) and (2), we have:

\[
m \frac{d^2 r}{dt^2} = m r \left( \frac{d\phi}{dt} \right)^2 r + \left( \frac{dr}{dt} \right)^2 \frac{\rho \lambda_m \pi d^2}{8} ;
\]

\[
\frac{d\phi}{dt} = \frac{0.88 U \tau_0}{R} x^{-0.183} \frac{dx}{dt} = 0.794 U \tau_0 x^{-0.312}.
\]

(6)

Numerical experiments were carried out to assess the effect on the capture efficiency of the twist intensity of the CSF apparatus created by the upper input. In the numerical integration of the obtained system, the following initial conditions are accepted:

- the starting point is the point located at the lower boundary of the tangential input, closest to the center of the cross section of the separation chamber \( x = 0, r = 0.6 R \) (width of the tangential branch pipe is assumed to be \( 0.4 R \));
- the tangential component of the particle velocity \( \frac{dr}{dt} = U_{\tau_0} \), and the initial value of the angular velocity, respectively \( \frac{d\phi}{dt} = U_{\tau_0}/R \);
- the value of the vertical (longitudinal) component of the particle velocity at the entrance to the separation chamber, according to the assumptions made during the formulation of equations, is equal to the initial value of the vertical component of the gas flow velocity;
- the radial component of the particle velocity in the inlet section of the separation chamber, based on the same assumptions, is equal to that component of the air flow velocity, i.e. \( \frac{dr}{dt} = 0 \).

A sufficient condition for making a conclusion about separation of a dust particle is the radial coordinate value equal to the radius of the separation chamber \( r = R \). At the same time, the value of the angular coordinate \( \phi \) has no practical value. The size of the dust particle \( d_p \) and the initial parameter of the swirling flow intensity \( \Phi_0 \) are taken as the variables.

The calculations show that for all combinations of variable parameters, the dust collector of the proposed design demonstrates high efficiency values of dust particles capture compared to the CSF dust collectors of traditional design [2, 3, 7].

5. Results of experimental studies

Experimental studies have been carried out for experimental efficiency verification of the dust collector on counter-swirling flows with coaxial secondary insertion of the proposed design. The purpose of the research is to compare the efficiency of the dust collector with the coaxial input of a secondary swirling flow with the efficiency of the dust collectors of the VI series, while capturing fine dispersed dust of quartz sand released during the production of ceramic building materials.
The ceramic dust used in the experimental studies was selected from the existing technological equipment and granulated by the sieve method. For testing samples were selected with the content of fine dispersed fraction \( \text{PM}_{10} \) approximately corresponding to the values 5, 10, 15, 20, 25, 30, 35 %. Because of practical difficulties with the exact selection or modeling of the dispersed dust composition, measurements were taken with samples of a \( \text{PM}_{10} \) fraction with content of 4.4, 11.2, 15.3, 19.2, 26.9, 34.2 %, which is close to given values, and allows obtaining the required outcomes. The results of comparative experimental studies are presented in Table 1.

| Quantity of dust particles of \( \text{PM}_{10} \) fraction in purified gas, % | Efficiency of dust collector on counter swirling flows CSF, % | Efficiency of dust collector on counter-twisted flows with coaxial input of a secondary flow, % |
|-------------------------------------------------|-----------------|-----------------|
| \( \eta_{\text{overall}} \) | \( \eta_{\text{PM}_{10}} \) | \( \eta_{\text{overall}} \) | \( \eta_{\text{PM}_{10}} \) |
| 4.4 | 91.3 | 16.02 | 94.11 | 17.09 |
| 11.2 | 75.7 | 11.23 | 79.7 | 14.04 |
| 15.3 | 66.8 | 9.77 | 73.8 | 12.93 |
| 19.2 | 57.4 | 8.18 | 66.8 | 12.27 |
| 26.9 | 50.2 | 5.23 | 57.4 | 11.16 |
| 34.2 | 41.3 | 2.28 | 52.5 | 8.56 |

Figure 2 shows the results of the experimental determination of the overall capture efficiency of the dust collectors under study. As follows from the results, efficiency of both dust collectors significantly decreases with increasing fraction proportions of fine dispersed dust particles. At the same time, the efficiency of the dust collector with the coaxial input of the secondary swirling flow with increasing fraction of the \( \text{PM}_{10} \) decreases less intensively, and in all cases exceeds the similar value obtained for the dust collector on the counter-swirled flows of the VI series. A particularly significant difference in the capture efficiency is observed with a fraction of the \( \text{PM}_{10} \) in the captured dust of more than 30% (41.3% and 52.5%, respectively).

Figure 3 shows similar dependencies separately characterizing the capture efficiency of the dust particle of the \( \text{PM}_{10} \) fraction for the dust collectors under consideration. As in the previous case, a dust collector with a coaxial introduction of a secondary swirling flow is characterized by the greatest value of separation efficiency, and its advantage also increases with an increase in the proportion of small fractions (8.56% against 2.28% with a \( \text{PM}_{10} \) fraction of 34.2%). The latter, in addition to the above described reduction in the entrainment of fine particles into the branch pipe of the purified flow, due to their low inertia, is also presumably attributed to the more intensive interaction with the particles of large fractions observed due to the increased intensity of the secondary flow twist in the dust collector of the proposed design, which causes increased turbulence.

This effect allows more complete use of the advantages that the presence of a secondary swirling flow gives, while the fraction of the flow rate supplied to the secondary input \( (L_w/L) \) can obviously be increased.
Figure 2. Results of the experimental determination of the capture efficiency of quartz dust particles with different contents of the PM$_{10}$ fraction by dust collectors on counter-twisted flows: 1 - dust collector with a coaxial input of a secondary swirling flow; 2 - dust collector of VI series on the counter-twisted flows.

Figure 3. Results of the experimental determination of the capture efficiency of quartz dust particles with dimension $d_p < 10 \, \mu m$ by dust collectors on counter swirling flows: 1 - dust collector with a coaxial input of a secondary swirling flow; 2 - dust collector of VI series on the counter-twisted flows.

Figure 4 shows the dependence of the capture efficiency of the dust collector on the counter swirling flows from the fraction of the flow rate supplied to the secondary input.
Figure 4. Dependence of the capture efficiency of the dust collectors on the counter swirling flows from flow rate supplied to the secondary input $\eta_{\text{overall}} (L_n / L)$: 1 - dust collector with a coaxial input of a secondary swirling flow; 2 - dust collector of VI series on the counter-twisted flows.

Unlike the dust collector of the VI series, which achieves the maximum meanings of the dust collection efficiency at the fraction values of the flow rate given to the secondary input $L_n / L = 0.28 \ldots 0.35$, the dust collector with the coaxial input of the secondary swirling flow reaches the maximum efficiency in the range of values $L_n / L = 0.35 \ldots 0.45$. It should be noted that the above results were obtained on samples of fine-dispersed quartz dust, characterized by a median diameter of $d_{50} = 46 \mu m$. At the same time, the maximum efficiency of the proposed dust collector was $\eta_{\text{overall}} = 94.2\%$, which is much larger than the analogous value for the dust collector of the VI series ($\eta_{\text{overall}} = 90.08\%$).

Thus, the advantage in the efficiency of the dust collector with coaxial input of the secondary flow in front of the CSF dust collectors of the traditional design is particularly expressed while capturing fine dispersed dust particles, which makes it possible to recommend the developed construction for use in order to reduce dust emissions in the presence of increased environmental and hygienic requirements.

6. Conclusions
1. Traditionally used inertial dust collectors often do not provide increased requirements for the quality of cleaning fine dispersed dust emissions of construction industry enterprises.
2. In recent years, in the construction industry as a dust-collecting means for dry cleaning, vortex dust collectors on counter-swirling flows (CSF) have been widely used characterized by constructive simplicity and operational reliability, and with higher efficiency of cleaning dust emissions compared to cyclonic,
3. A common design disadvantage of dust collectors on counter-twisted flows of CSF and VI series is the location of the branch pipe of the secondary swirling flow in the volume of the separation chamber, which causes significant distortion of the swirling flow structure in the near-wall area of the lower part of the separation chamber.
4. The design of a dust collector with a coaxial secondary input of a swirling flow taken from a bunker zone by using an ejector thrust actuator, with an admixture of the external flow is proposed.
5. The dust collector of the proposed design exceeds dust collectors of the CSF type in operational reliability and ease of maintenance due to the external location of the secondary flow swirl, and has a higher efficiency of using a secondary swirling flow in comparison with the dust collectors of the VI series.

6. In the course of laboratory tests it was established that the efficiency of the dust collector of the proposed scheme in capturing quartz sand particles is higher than the efficiency of dust collectors on counter-swirling flows of traditional design.

7. The efficiency advantage of the dust collector with coaxial input of the secondary flow in front of the CSF dust collectors of the traditional design is especially pronounced when capturing fine dust particles, which allows recommending the developed design for use in order to reduce dust emissions in the presence of increased environmental and hygienic requirements.

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