Experimental and calculated testing of the efficiency of cyclone filtering devices

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Abstract. The aim of the study is to identify ways to improve the efficiency, reliability of the dust collection process and improve the aerodynamic properties of cyclone apparatuses in the gas cleaning unit. The analysis of existing methods of cyclone filtration of fuel gases is carried out. Bench tests of a cyclone filter based on the serial cyclone CN-11-200 were made, and the aerodynamic characteristics of its operation were found. The efficiency of the use of multi-cyclone apparatus, the elements of which combine both stages of cleaning, are also analyzed. The problem of finding the optimal location in the apparatus of cyclone elements with semi-tangential inlet nozzles are solved. A numerical model of a multi-cyclone is created and several options for the arrangement of elements are considered. The most effective location is determined taking into account the overall hydraulic resistance of the device. The numerical model also made it possible to evaluate the influence of various factors on the dust sedimentation efficiency in the developed cleaning device.

1. Introduction

Requirements for the efficiency of dust collection processes are constantly increasing with the tightening of regulatory requirements for the purity of atmospheric air and air in the spaces of industrial and civil buildings, as well as with the advent of new technologies, the use of new materials and, therefore, with the release of new emissions [1].

Of practical interest is the combination of the dust trapping by the inertial mechanism with the filtering of the gas flow by porous walls, carried out in the same housing and implemented in the apparatus, known as filter-cyclones. They achieve two-stage dust sedimentation in one unit, facilitating the process of regeneration of the filter sleeves by high concentrations of dust. Such a gas cleaning scheme is especially adapted to local aspiration systems.

Literature analysis [3-10] showed, that the existing devices either provide a high degree of deposition of fine particles of classes PM_{10}, PM_{2.5} with high energy consumption, or have a low degree of cleaning. The cyclone filters have higher effectiveness at not high energy costs.

The cyclone filters can also be used as elements of multi-cyclones for increase fine of cleaning. The wide distribution of multi-cyclones in dust cleaning equipment due to the simplicity of their device, reliable in operation, small capital and operating costs. They are effective in the deposition of suspended particles of mid (from 10 microns) and large sizes, which is why they are used in systems as primary processing of emissions. For finishing processing, behind them it is necessary to install fine
cleaning devices. In this case, small particles are most efficiently deposited by porous filters. However, this leads to higher prices, drop reliability and complicates the cleaning system as a whole.

2. Methods

2.1. Creating of cyclone devices with filter elements

The desire to optimize the processes of dust cleaning is aimed at obtaining a harmonious ratio of the degree of trapping, hydraulic losses and energy costs of gas cleaning equipment. Therefore, it is currently important to create devices with a high degree of deposition of fine particles PM_{10} and PM_{2.5} with a low coefficient of hydraulic resistance.

One of the technical solutions we offer is a cyclone apparatus combining two stages of cleaning for efficient deposition of fine particles of classes PM_{10}, PM_{2.5} with minimal energy and material costs.

To achieve this result, bench tests of the cyclone filter were carried out, the design of which was developed by the authors based on the serial cyclone CN-11 with a diameter of 200 mm. The tests were carried out on a specially prepared dispersion material - chamotte dust with a particle size of up to 63 microns.

A sample of material for testing was taken in accordance with good laboratory practice according to GOST R 51568-99 (ISO 3310-1-90). The selected sample was subjected to sedimentation analysis in distilled water to determine the median particle diameter and dispersion. The change in the mass of crushed material deposited in the dispersion liquid was recorded on a VT-500 torsion scales.

For the sedimentation analysis, a quantity of material was taken from the sifted sample, sufficient for preparing a suspension with a volume fraction of suspension to 0.5 ... 1%. In the future, according to the results of experimental measurements on the basis of the Stokes law the particle sizes were counted:

\[
 r = \frac{9\eta \cdot H}{2(\rho_p - \rho)g \cdot \tau}
\]

where \(H\) – particle sedimentation height, \(\tau\) – settling time, \(v=H/\tau\) – sedimentation rate, \(r\) – particle radius, \(\rho_p\) – particle density, \(\rho\), \(\eta\) – density and viscosity of the dispersion medium.

The design of the cyclone filter is shown in Figure 1. The input velocity into the cyclone was measured before dusting with a thermal anemometer (Testo 425 model) installed in the round access port. The dust laden stream passes through the duct into the cyclone inlet and enters the annular space inside it between the body and the exhaust pipe. During such a flow, a number of particles due to inertia come down from curved current lines, collide with the wall of the cyclone and slip into a bunker with a hermetic shutter. The smallest fractions of dust are trapped by a fabric filter, where the deposition of dust of medium and small size along touch and inertial mechanisms. Further, the flow moves down along the helical trajectory, turns up in front of the bunker and exits along the ascending helical trajectory through the exhaust pipe. A micro manometer is installed in the round access port to find the resistance inside the cyclone.

The air flow rate at the cyclone inlet was measured using a collector with an internal diameter of 140 mm and a micro manometer. Adjustment of air flow in the network was performed with a throttle valve in five modes. In to access port of circular section 12, an impactor 20 was installed to determine the dispersed composition of dust after the cyclone-filter.
Filter material samples were weighed at the beginning and the end of the test and examined under a MIN-8 microscope with 400-fold magnification. This made it possible to determine the particle enumerable concentration of the classes PM$_{2.5}$, PM$_{10}$, which is necessary for a reliable comparison of the intensity of their sedimentation from the flow to the filter in different modes.

Based on the methods of computational hydrodynamics, a numerical simulation of the aerodynamic parameters of the cyclone filter was performed to observe all the characteristics of the flow, which can be identified in a numerical 3d model. The energy parameters of the rotating flow are comparable with the magnitude of its energy at the entrance to the apparatus.

To ensure the closure of the system in the equations of transport and dissipation of kinetic energy, the Spalart-Allmaras viscosity model is used. [11-14].

2.2. Finding the best location of the cyclone filter elements in a multi cyclone based on numerical studies of the movement of the dispersed flow

With methods of computational fluid dynamics (Computational Fluid Dynamics - CFD) using the RANS turbulence model (Reynolds-Averaged Navier-Stokes equation), was built a 2-d model of the first row of the standard multi-cyclone CN -16 [15-17]. The air flow with dust particles ranging in size from 5 to 45 microns enters at a velocity of 5 m/s, then flows around obstacles. The air with part of the total flow of particles get out of the channel, and part is held on obstacles.

Considered two models of the multi-cyclone, differing in the arrangement of cyclone elements: in the first model, the cyclone elements are located at the same distance from each other, and in the second - the middle cyclone elements are located as close to the extreme side ones as possible. The unstructured mesh based on triangular elements was created using the internal tools of the Gambit preprocessor.

Before starting to solve the problem, were established the following boundary conditions: Velocity Inlet – uniform distribution of velocity at the channel entrance; Pressure-Outlet – atmospheric pressure at the channel exit; Wall – the boundary condition of the wall.
The problem of finding the best arrangement of the inputs of the elements in the apparatus is further solved by the method of numerical modelling based on the computational fluid dynamics methods in the Fluent processor. In numerical calculations of this construction the two-parameter turbulence model $k-\varepsilon$ was adopted, which provides the solution of the problem in close to real conditions at an available computing resource.

3. Results and Discussion

The size of the fractions obtained from the sedimentation analysis is shown in figure 2. The minimum particle size of 1.09 microns, maximum – 60.94 microns, average particle size $d_{50} = 1.37$ microns.

To determine the efficiency of the separation of the weighted part of the flow in this cyclone-filter was used dimensionless parameter obtained by methods of similarity theory – the relative Reynolds number $Re_r$, [11]:

$$Re_r = \frac{U_0 \cdot \rho_p \cdot D_p^4}{c \cdot \rho_g \cdot R_s^2 \cdot \eta}$$  \(\text{(2)}\)

where: $U_0$ -initial velocity, m/s, $\rho_p$-particle density, kg/m$^3$, $D_p$-diameter of particles, m, $c$ - a numerical coefficient, which, depending on the geometric characteristics of the device, $\rho_g$-gas density, kg/m$^3$, $R_s$ -cyclone radius, m, $\eta$ - coefficient of dynamic viscosity, Pa·s.

The dimension less $Re_r$ parameter is used to determine the efficiency of inertial deposition of particles, as well as the Stokes number $St$, but unlike it, the $Re_r$ number characterizes the energy costs of the particle to move along a curved trajectory.

The diameter of the particles deposited with an efficiency of 50% under operating conditions at the top B (Figure 4) determined by the formula:

$$D_{50} = D_{50r} \sqrt{\frac{D_r}{D_p}} \left(\frac{\rho_{pr}}{\rho_p}\right) \left(\frac{\eta}{\eta_r}\right) \left(\frac{w_c}{w}\right)$$  \(\text{(3)}\)

where: $D_{50r}=3.65\cdot10^{-6}$m, $D_r=600$mm, $\rho_{pr}=1930$kg/m$^3$, $\eta_r=22.2\cdot10^{-6}$Pa·s, $w_c=3.5$ m/s respectively, the average diameter of the deposited in the cyclone particles, the diameter of the cyclone, the particle density, dynamic viscosity and velocity of the gas flow taken according to the reference data; $D_{50r}$, $D=200$ mm, $\rho_p=1990$kg/m$^3$, $\eta=17.96\cdot10^{-6}$Pa·s·s$^{-1}$, $w=11.29$ m/s - the same in the working conditions. Relative Reynolds number $Re_r$ for $D_{50r}$: $Re_r = 2.5\cdot10^9$. 

![Figure 2](image_url) The results of the sedimentation analysis: a – the dependence of the size fractions of particles from the time of deposition; b – dispersed composition of the particles.
The diameter of the particles captured at 50%, according to the formula (5), is: $D_{50}=1.039$ microns. Particle size $D_{99.18}$ was determined by the deposition parameter $x$ by the formula:

$$x = \frac{1}{\sqrt{\frac{\log^2 \sigma_n}{\sigma_p^2} + \log^2 \sigma_p}}$$

(4)

where $\sigma_n, D_{50}$ - respectively, the dispersion and diameter of the particles deposited in the apparatus by 50%. For the cleaning coefficient $f(x)=99.18\%$ the value of the deposition parameter at 99.18% $x=2.40$ [1].

The diameter of the particles captured at 99.18%, according to the formula (2), is: $D_{99.18}=14.53$ microns. Now find the value of the $Re$ for $D_{99.18}=14.53$ microns, providing almost complete precipitation of the contaminant from the release: $Re=9.55\times10^{-5}$.

Thus, the $Re$ value for particles captured almost completely (by 99.18%) in the experimental cyclone is $9.55\times10^{-5}$. Consequently, this cyclone without a filter insert provides complete deposition of particles having an inertia characteristic of motion in a curvilinear flow $Re$ above this value. As shown earlier, the size of the particles deposited in the experience on the wall of the cyclone by 50%, amounted to 1,039 microns, indicating the effectiveness of the cyclone with a filter insert, in comparison with the standard value for the CN-11 $D_{50}=3.65$ microns. Figure 3 shows the flow pattern inside the cyclone in the annular section and inside the exhaust pipe.

**Figure 3.** Flow diagram: a) in the annular part of the cyclone at the bottom of the measurements $A$ and at the top of the measurements $B$, b) inside the exhaust pipe at the top of the measurements $B$.

Figure 4 shows the distribution of axial, tangential and radial flow velocities inside the cyclone at the top point $B$. In the annular section of the cyclone, the maximum velocity was 15 m/s.

The experimental studies have shown the possibility of a constructive additions the return-flowing cyclones the filter insert on the zone where inertial dust precipitation occurs.
As can be seen from figures 5 - 6, for the incoming dispersed gas flow, the elements of the multi-cyclone as a whole are represented by an array of obstacles. On the basis of the calculation, taking into account the trajectories of solid particles of different sizes, the optimal variants of the arrangement of filtering cyclone elements are selected. The results of numerical studies show that at the second model in the working space between the elements is higher both the velocity and pressure values, although the flow characteristics at the inlet to the housing are the same for both models. This is due to the flow passing in the second model only in the intervals between the cyclone elements. In the first model, a significant part of the flow passes the area near the walls of the multi-cyclone housing, creating less resistance than the area between the elements.

Calculations clearly show that these zones represent local resistances such as unilateral sudden narrowing and sudden expansion. The created numerical model of a multi-cyclone allowed to estimate
the influence of various factors on efficiency of dust capture in cyclones, and also to create a technique of an assessment of efficiency of a dust collector.

4. Conclusion
The proposed method of equipping a return-flowing cyclones the filter inserts allow you to achieve increased throughput of the treatment apparatus while improving the quality of cleaning, which is expressed in reducing the size of the particles captured at 50 % (diameter of cutting off), from the average for the cyclones values of 5-10 microns to 0,5 microns. This improvement in the quality of cleaning does not require a significant increase in energy costs. It is one of the advantages over conventional cyclonic devices, which for reducing the diameter of cutting off requiring an increase in energy costs up to 15 % every tenth of a micrometer.

The obtained results provide an opportunity to optimize the location of the inputs of semi-continuous nozzles of cyclone elements in the multi-cyclone on the first and second models. They also make it possible to more accurately take into account the hydraulic resistance of the device in determining the most effective location of the cyclone elements.

Thus, the experimental studies have shown the feasibility of constructive additions of return-flow cyclone filter insert in the area where the inertial deposition of dust.

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