Experimental and numerical studies in elaboration the multi-cyclone with filter cells to processing of flue-gases of coal-fired and incineration power plants

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Abstract. Currently, in various industries for both sanitary and technological treatment of heterogeneous flows, as a rule, several devices are used that consistently provide the coarse and fine stages of gas clean up. For example, to prevent the penetration of mechanical (solid and liquid) impurities to the measurement instruments, regulation, control and automation at compressor stations of gas transmission systems the gas cleaning units are setup. They consist of two types of apparatus - cyclone dust collectors and filters. Similar gas cleaning devices are at booster compressor stations of TPPs. In this paper, we consider the effectiveness of using a multi-cyclone apparatus for such purposes, the elements of which combine both stages of cleanup. The problem of finding the optimal arrangement in the apparatus of cyclone elements with tangential inlet branch pipe is solved. A numerical model of the multi-cyclone is created and several variants of the arrangement of elements are considered. The most effective arrangement was determined taking into account the total hydraulic resistance of the apparatus and the trajectories of the motion of suspended particles.

Introduction
Coal-fire and incineration thermal power plants are the main source of air pollution with fly ash. Reduction of local concentrations of suspended solids to permissible levels can be achieved by installing efficient ash collectors. For ash trapping at the primary stage currently used the multi-cyclones, the louver-type separators, fly-ash scrubbers and on the final stage as a rule, electrostatic precipitators [1]. However, with the transition to coal-fired generation not less than 99.5% cleanup will be required. An even deeper cleanup is needed even now to the flue gases of the incineration power plants [2, 3] which are difficult to achieve in electrostatic precipitators. Therefore, it is necessary created energy-efficient and low-resource devices with filtration in a porous medium.

Figure 1. Examples of cells disposition in the battery cyclones with a tangential inlet: a - BCU-M [4], b - BC 2-7x (5 + 3) [5], c - CB 56 [6]
Now in the technique of dust cleaning, battery cyclones are widespread due to the simplicity of the design, reliability in operation, and low investments. However, multi-cyclones efficiently precipitate suspended particles only of medium size (from 10 μm) and larger. For smaller sizes of particles it is necessary the filtering apparatus for fine cleaning. In our paper, the problems of creating a multi-cyclone combining both stages of cleanup are considered.

The cyclone battery can be composed of cyclonic cells of various types. Taking into account the fact that the task of this work is to clean fine dust, and its adhesiveness is much higher than that of medium-sized dust, a type of return-flow cyclone elements with a tangential air supply was taken for further studies.

Figure 1 shows the arrangement of elements with a tangential inlet in the serially produced in Russia battery cyclones. It can be seen that the methods of orienting the inlet openings of the elements in different designs can be very different, while the direction of movement of the cleaned flow inside the body of apparatus is the same. This indicates that in the design of these devices, any circumstances are taken into account, except the particle trajectory in the flow of cleaned flue gases. For example, Figure 2a shows that the elements of the first line of the BCU-M multi-cyclone will be less loaded with dust, and their resistance during operation will be lower than in the following rows, which will worsen the overall cleaning degree. In the disposition of the elements as shown in Figures 2b, 2c, there remain gaps between the rows. In addition, in version b, the front rows overlap the movement of the streams to the inlets of the rear row elements. Such factors may not be of great importance for the operation of conventional multi-cyclones that process flows with a median dust diameter of 10-15 μm or more. Developing of multi-cyclones with filter elements which should target to provide a very high cleaning degree (99.5% or higher), the unsuccessful positioning of elements inlets can significantly increase the penetration of particles across the filter and nullify the efficiency of created devices.

**Methods**

Creating a filter cell for the multi-cyclone. A filter cell for the multi-cyclone was created. An experimental sample of the element of a multi-cyclone filter apparatus was made. A test bench was developed and assembled for its testing (Figure 2a). The diameter of the cyclone body d = 0.1 m, the diameter of the exhaust pipe d = 0.065 m. The scheme of test bench is shown in Figure 2b, the results presented in Table 1.

![Figure 2. Photo (a) and scheme (b) of the test bench for the filter cyclonic element of the multi-cyclone: 1 - the cyclone filter element; 2 - fabric filter; 3 - container with dust (not visible in the photo); 4 - a supercharger (not shown in the photo); 5- U-shaped manometers; 6-cartridge with a grid; 7- Petryanov's fabric.](image-url)
As a supercharger 4, a vacuum cleaner was used with a measuring manifold at the inlet. Air through an outlet nozzle of the vac at a pressure of about 200 Pa was supplied to container 3 with dust (talc with a median particle diameter of 10 μm and spread of 3.5). The dust particle sizes were determined in advance by sedimentation in distilled water. The mass of the dust container was determined on the analytical balance at the beginning and the end of a series of experiments with the same flow rate. Dusty flow from the container entered tangentially into the cyclone filter element 1. On the filter 2 (lavsan fabric) the dust deposited due of inertia and contact effects. The flow entered in the exhaust tube of the cyclone, where it passed through the cartridge with the Petryanov's fabric 7 and the metal grid 6, and then it removed from the system. Filters 2, 7 and grid 6 were weighed at the beginning and at the end of the test. Then, from the beginning, the middle, and the end of the filter fabric 2, samples were cut out to compare the sedimentation efficiency by the number concentration (per unit volume) of trapped particles, which determined by studying the samples under a microscope.

First, the flow rate characteristic of the filtering cyclone element was obtained; it is the dependence of its resistance on the flow rate of the emissions. When performing calibration, the flow through the element varied from a minimum of 0.001 m³/s to a maximum of 0.011 m³/s. The flow rates were calculated from the flow velocity \( w \) and the area \( S \) of the nozzle inlet \( d = 0.025 \) m in diameter. The flow velocity \( w \) was determined from the underpressure value measured by the micro-manometer at the collector, \( \Delta P \) Pa, as \( w = \left( \frac{2 \Delta P}{\rho} \right)^{1/2} \), where the air density \( \rho \) was taken at its room temperature, which was 22-24 °C. The experiment was conducted with four combinations of flow rate (velocities) and the amount of dust in the container: with a minimum mass of dust at a minimum velocity; with a maximum dust mass at minimum velocity; with a minimum dust mass at maximum velocity; with a maximum dust mass at maximum velocity. Dust samples of the filter material were examined with a MIN-8 microscope with a 400-fold magnification. The growth of dusty sample's mass was determined on an analytical balance capable of weighing to the nearest 0.1 mg.

Detect the best location of the filtering cyclonic elements in the multi-cyclone on the basis of numerical studies of the dispersed flow motion. Since the investigation is aimed at increasing the efficiency of the dispersion flow purification with a class of suspended particles PM10, PM2.5, i.e. with size's less than 10 microns, when choosing the location of the cyclone elements, it is necessary to take into account the particle traces in the flow. The problem of finding the best location of the elements inlets of the apparatus is solved further by numerical simulation based on Computational Fluid Dynamics (CFD) methods. The RANS (Reynolds-Averaged Navier-Stokes equation) model of turbulence is used. The problem of closure of governing equations is solved with the k-\( \varepsilon \) model. A 2d-model of a battery cyclone was constructed. The developed numerical model of the multi-cyclone made it possible to evaluate the influence of various factors on its hydrodynamic characteristics. In order to optimize the arrangement of the elements in the multi-cyclone body and to evaluate the efficiency of the dust collector, a numerical experiment was performed with the injection of particles into the gas flow.

**Figure 3.** Geometric models of a part of the multi-cyclone bodies: a - with the staggered arrangement of cyclone elements, b - with the in-line arrangement; c is an example of a computational triangular unstructured finite element grid around one of the cyclone cells.
It can be seen from Figure 1 that for the incoming dispersed gas flow, the cells of the battery cyclone are the array of an obstacles. This constructional feature of the multi-cyclone is used in study to efficiently arranging of its filtering cyclonic elements, with taking into account the trajectories of the motion of solid particles of various sizes. Figure 3 shows an example of a geometric model of a part of the multi-cyclone body with dimensions of 1500x500 mm, with the staggered and with the in-line arrangement of obstacles - a group of 9 cylindrical elements with a diameter of 115 mm and with a spacing of 140 mm. The air flow with dust particles with dimensions from 5 to 45 μm enters the channel with velocity 0.5 m/s, and then flows around the obstacles. One part of the total mass of particles, together with air, leaves the channel, and the rest is held on obstacles. The study is carried out under standard conditions close to previous tests: \( T = 20 ^\circ C, P = 101325 \text{ Pa} \); density and dynamic viscosity of the flow are assumed to be constant: \( \rho = 1,205 \text{ kg/m}^3, \eta = 18.1 \cdot 10^{-6} \text{ Pa} \cdot \text{s} \).

An unstructured finite element mesh based on triangular elements was created with the help of internal Gambit preprocessor tools. Here it was used because of the advantage that with its help the geometry of the region is better displayed, although a structured grid would be preferable for three-dimensional numerical studies of obstacle channels, since it requires a smaller computational resource [7]. Structured grids for studying a two-phase solid-gas system were proposed, for example, in [8], for a model with the simplest configuration for generating grids, a single spherical domain whose center coincides with the center of a spherical particle.

Before the beginning of the solution of the problem, the following boundary conditions were established: “Velocity Inlet” - uniform velocity distribution at the entrance to the channel (0.5 m / s); “Pressure Outlet” - atmospheric pressure at the exit from the channel; “Wall” is the boundary condition on the walls. The formulation of the boundary conditions had the following singularity. Impenetrable surfaces of cyclone elements performed the function of trapping particles, and the walls of the multi-cyclone bodies - the function of their reflection. Therefore, the condition "Wall" has been created as the boundary conditions of the whole discrete phase model, both for obstacles and for channel walls.

After exporting the finite element mesh in the ANSYS®Fluent software, the quality and scaling of the finite element mesh was verified (to ensure the correctness of the solution, it is necessary that the geometric dimensions of the model correspond to a scale of 1:1). When setting up the solution of the task, the parameters of continuous and discrete phases are set. For calculations, a solver type "Based Pressure" with an "Implicit" solution scheme of the "Unsteady" task was chosen. The initial conditions for the particles are as follows: for the particle injection surface, the entrance surface of the Velocity Inlet is accepted, the type of distribution of the dispersed phase in terms of particle sizes, is taken in accordance with the Rosin-Rammler equation, with the number of fractions (Number of Diameters) 10, and with the dispersion parameter (Spread Parameter) 2.5. The material is industrial dust with a density of 2000 kg / m³.

Results and Discussion

Experimental study of the filter cyclonic cell of the multi-cyclone. Experimental data obtained in the experiments are given in Table 1.

Tests of the filtering cyclone element sample's showed that about 75% of the dust is trapped on the filtering insert from lavsan, 20% settles on the walls. And about 5% is retained by the exit filter from Petryanov's fabric, wherein the dust, leaves a spiral trace on the surface. This indicates a fairly intense swirl of the flow in the exhaust pipe, which is the case conventional cyclones without filter inserts, as well as shown the presence of low-frequency precession of the core of a swirling flow, typical for the return-flow cyclones. Consequently, in the investigated cyclone with a constructive addition of fabric lavsan filter the nature pattern of the flow is preserved, which makes it possible to recommend its use as cyclonic cells for the multi-cyclones.

Detect the best location of the filtering cyclonic elements in the multi-cyclone on the basis of numerical studies of the motion of a dispersed flow. Figure 4 shows the results of a numerical calculation of a continuous phase flow inside a channel with filter cyclonic elements located in a
staggered (Figure 4a) and in-line (Figure 4a) configuration. They show that the flow velocity reaches a maximum value of 1.8 m / s in the zones between the cyclone elements. Minimum velocities of 0.2 m / s are located in areas with increased resistance - near the walls of the channel and obstacle surfaces, as well as in the frontal and shadow areas of the obstacles. The flow characteristics in both multi-cyclone bodies by the velocity minima and maxima practically coincide, which also indicates the coincidence of the maxima and minima of the static pressures.

Table 1. Experimental data

| Measured object            | \( m_0, \times 10^{-3} \) kg | \( m_b, \times 10^{-3} \) kg | \( m_c, \times 10^{-3} \) kg | \( Q_{air}, \times 10^{-3} \) m³/s | \( Q_{dust}, \times 10^{-3} \) kg/s | \( C, \times 10^{-3} \) kg/m³ |
|---------------------------|-------------------------------|-------------------------------|-------------------------------|----------------------------------|----------------------------------|-------------------------------|
| Container with dust       | 26.607                        | 26.42                         | 1.113                         | 0.155                            | 0.14                             |
| Filter fabric             | 4.137                         | 4.245                         | 1.113                         | 0.09                             | 0.08                             |
| Petryanov's fabric        | 0.662                         | 0.681                         | 1.113                         | 0.015                            | 0.014                            |
| Container with dust       | 27.911                        | 27.602                        | 1.113                         | 0.128                            | 0.115                            |
| Filter fabric             | 2.998                         | 3.208                         | 1.113                         | 0.087                            | 0.078                            |
| Petryanov's fabric        | 0.607                         | 0.649                         | 1.113                         | 0.017                            | 0.015                            |
| Container with dust       | 25.635                        | 25.488                        | 11.3                          | 0.245                            | 0.22                             |
| Filter fabric             | 4.328                         | 4.448                         | 11.3                          | 0.2                              | 0.0179                           |
| Petryanov's fabric        | 0.649                         | 0.676                         | 11.3                          | 0.045                            | 0.004                            |
| Container with dust       | 41.276                        | 40.978                        | 11.3                          | 0.414                            | 0.0372                           |
| Filter fabric             | 4.341                         | 4.426                         | 11.3                          | 0.118                            | 0.106                            |
| Petryanov's fabric        | 0.666                         | 0.723                         | 11.3                          | 0.079                            | 0.0071                           |

Designations: \( m_0 \) – original mass of the container; \( m_b, m_c \) – the initial and final masses of the measured objects; \( m_{dust}, Q_{air} \) – mass of dust and air flow, fed into the filtering cyclone element; \( Q_{dust}, C \) – mass loading and concentration of particles.

Figure 4. Air velocity distribution in the channel with the staggered (a) and the in-line (b) cyclone element locations and near the obstacles

Figure 5 presents the numerical results of calculating the trajectories of the discrete phase (industrial dust) within a channel with the staggered and the in-line arrangement of cyclone elements.
Figure 5. Results of calculation of particle trajectories in a channel: a - with the staggered arrangement of cyclonic elements; b - with the in-line arrangement of cyclonic elements; the particles color changes deep blue to red corresponded by particle sizes from 5 to 45 microns.

The results of numerical studies allowed to find out that the places of the settling of dust particles on cyclone elements do not coincide with the location of cyclonic element inlets in the serially produced multi-cyclones. You can also make a choice in favor of the effectiveness of the staggered arrangement cells, while the mass-produced multi-cyclones have a generally the in-line arrangement.

Conclusion
Thus, carried out experimental study showed the efficiency of the multi-cyclone cell with tangential inlet and the filter insert. With the numerical study obtained the hydrodynamic characteristics of disperse flows in the multi-cyclone body, and was determined the best scheme for placing its cyclonic elements with the localization of their entrances.

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