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Numerical and experimental studies of gas cleaning in multi-cyclone elements with filter inserts

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Abstract. As a result of the tightening of standards for the content of suspended particles with a particle size of less than 10 μm in the atmospheric air, the development of production structures in the urban environment often becomes closely linked to the problem of deep cleaning of heterogeneous emissions, that requires, at a minimum, two-stage cleaning. In this paper, we consider the effectiveness of using a multi-cyclone apparatus for such purposes, the elements of which combine both stages of purification. A bench test of such an element, which is a cyclone filter with a diameter of 250 mm on the basis of a serial cyclone TsN-11, was carried out. A numerical model of the multi-cyclone has been investigated, which has made it possible to establish the optimal arrangement of the cyclone elements with respect to the trajectories of the streams of trapped particles.

1. Introduction

Recently, regulations on the content of suspended particles in air with dimensions less than 10 μm have been tightened. Accordingly, the requirements for cleaning of heterogeneous emissions from highly dispersed components were increasing. One-step processing of technological emissions cannot provide the required degree of cleaning at acceptable energy costs. In order to efficiently processing production emissions containing of the $\text{PM}_{2.5}$, PM_{10} classes particles, a multi-stage purification system is needed with cleaning devices that optimally take into account the physicochemical properties of all emission components, both pollutants and its neutral part [1]. In this paper, the results of a study of the apparatus combining the stages of coarse and final cleaning of heterogeneous emissions with PM_{10} and $\text{PM}_{2.5}$ classes are presented. The efficiency of the multi-cyclones can be calculated by methods based on theoretical and experimental data [2]. Now, quite complete and reliable data on the efficiency of the multi-cyclones have been obtained in studies carried out both with natural (physical) and on numerical models [3, 4]. However, they relate only to the studied devices of a specific size and design, and the study of innovative concepts must be carried out fully.

2. Methods

2.1. The bench test of the multi-cyclonic filter element

The scheme of the experimental stand is shown in Fig. 1. Passage of dusty air through the cyclone 7 was provided by a fan 14. Chamotte dust passed through the measuring manifold 1 into the air duct 2 with a diameter of 140 mm. The dusty flow through the duct 2 through the inlet 6 of the cyclone 7 go



into the ring space between its body and the exhaust pipe 8. The airflow at the inlet to the cyclone was measured with a bellmouth inlet 1 with an internal diameter of 140 mm and a micromanometer 3. The air flow rate in the ductwork varied in three modes, with the minimum open (first), intermediate (second) and fully open (third) throttle valve positions 15. To find the resistance of the cyclone, the pressure loss ΔP was measured by a micro-manometer 9 at points 5 and 10. The inlet velocity in the cyclone was measured prior to dusting by a thermal anemometer 19 (Model Testo 425) installed in the round access port 4. Because of the rotational motion of the flow, the particles of large and medium sizes clash with the inner wall of the cyclone and slid into the hopper 17 that has the hermetic shutter 16. On screw downward trajectory of the flow, fine dust fractions were deposited on the fabric filter 13. Then the flow turned in front of the hopper and return along an ascending screw path through the exhaust pipe 8. The flow velocity inside the cyclone element was measured with the Testo 425 thermo-anemometer. Measurements were made at two levels along the height of the element. The upper level was located 40 mm below the top of the cylindrical part, the lower one - directly under the exhaust pipe. The measuring points were along the diameter of the cyclone element. The scheme of their arrangement, is shown in Fig. 2.

Samples of the filter material were weighed before and after the test. In addition, after the experiment, tissue samples cut out from the beginning, middle and the end of filter to determine the countable concentration of the particles deposited. Its value was obtained by direct counting of particles on samples under a MIN-8 microscope with 400 times magnification, on which all settled particles with dimensions from 0,25 μm and higher were clearly visible [5]. The determination of a countable number of $\text{PM}_{2,5}$, PM_{10} classes particles is necessary to reliable compare the intensity of their settling from the flow with filter under different regimes.

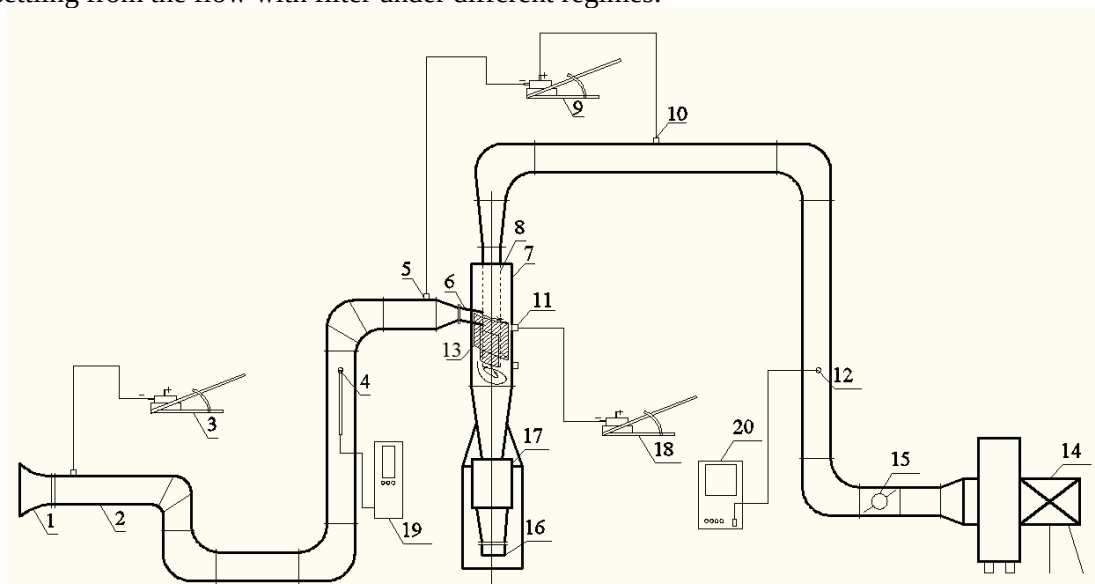


Figure 1. An experimental test bench for testing a filter element made of a standard cyclone TsN-11 with a diameter of 200 mm: 1 – bellmouth inlet, 2 – duct, 3,9,18 – micro-manometers, 4,5,10,11,12 – ports of access, 6 – input pipe, 7 – cyclone, 8 – exhaust pipe, 13 – fabric filter, 14 – fan, 15 – throttle valve, 16 – hermetic shutter, 17 – hopper, 19 – thermo-anemometer, 20 – impactor.

In this paper, a laboratory microscope MIN-8 with additional illumination was used to study opaque objects in reflected light. A digital camera (resolution 12 megapixels, a lens with an aperture of F/1.8 absorbs 50% more light to increase the contrast and improve the quality of the pictures in poor light conditions) was installed on the inclined attachment of the microscope, after which have been achieved the focusing with a microscope. To create a clear image of the dusty surface of the

filter, illumination was arranged on the right and on top in addition to the usual illumination of the stage.

In addition to bench tests, by the methods of computational hydrodynamics, the tangential components of velocities and the static pressures in several cross sections of the cyclone were calculated [6, 7]. The obtained results of numerical simulation are confirmed by results of empirical tests and are comparable with the results of external researchers, presented, for example, in [8, 9, 10].

2.2. The choice of the location of filtering cyclone elements in a multi-cyclone on the basis of numerical studies of the motion of a dispersed flow

Since the work is aimed to increasing the efficiency of cleaning the dispersed flow with the particle classes PM_{10} , $PM_{2.5}$, that is, dust of medium size and fine, including sub-micron dust, when choosing the arrangement of cyclone elements, it is necessary, as far as possible, individually to take into account the particle trajectories in flow. Previously, using the Computational Fluid Dynamics (CFD) method with the RANS (Reynolds-Averaged Navier-Stokes equation) turbulence model, a 2-d model of the serial CB-11 multi-cyclone was created, consisting of 11 cyclone elements with a diameter of 245 mm and a semi-tangential gas inlet. Two versions of the battery cyclone model, differing in the arrangement of the cyclone elements, are constructed (Figs 5, 6). At the Gambit preprocessor created an unstructured finite element mesh based on triangular elements. It allows more accurately reflect the geometry of region, although for three-dimensional numerical studies of channels with an obstacle, a structured grid that requires a smaller computational resource would be preferable. Before the problem solving beginning, the following boundary conditions were established: "Velocity Inlet" - uniform distribution of the velocity at the inlet of the channel (0.5 m/s); "Pressure Outlet" - atmospheric pressure at the outlet of the channel; "Wall" is the boundary condition for the walls. The formulation of the boundary conditions had the following singularity. The impermeable surfaces of the cyclone elements perform a trapping function for particles, and the walls of the cyclone body carry a function of their bouncing. Therefore, the "Wall" condition for adjusting the boundary conditions of a discrete phase model was created for both - obstructions and channel walls.

3. Results and Discussion

Results of bench tests of a filtering cyclone element

Figure 2 shows the results of measurements of the flow velocity inside the cyclone at the positions of the throttle valve 15 at the lower point V1, V2, V3 and in the upper point V4. It can be seen that the flow velocity at the cyclone center under the exhaust pipe (at distances of about 0.12 m) is 21-25 m/s for all regimes. The results of the tests also showed that the velocity in the upper part of the cyclone decreases to 17.5 m/s, and asymmetry of the velocity diagrams is observed throughout the whole height of the exhaust pipe that has the boundaries 0.06–0.14 m. This indicates the preservation of the flow precession in the exhaust pipe after passing the filter and serves as an indirect confirmation of the qualitative conservation of the hydraulic flow regime in the cyclone element after the installation of the filter insert.

Figure 3 shows the results of measuring the flow pressure inside the cyclone at various concentrations of supplied dust.

The results show that the vacuum inside the cyclone with a fully open throttle valve with supply 0.145 and 0.141 kg of dust under the ring space (distances from 0.01 to 0.04 and 0.16 to 0.19 m) is in the range of 400-600 Pa, and the pressure diagram under the exhaust pipe (distances from 0.04 to 0.16 m) is also asymmetric.

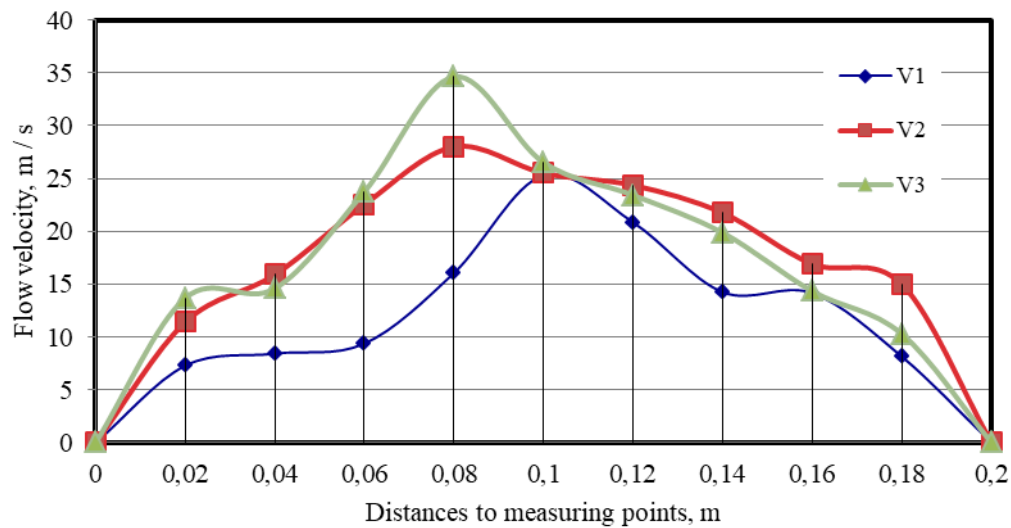


Figure 2. The velocities of not dusty air flow inside the cyclone under the exhaust pipe, V1, V2, V3, m / s in the first, second and third positions of the throttle valve 15, respectively.

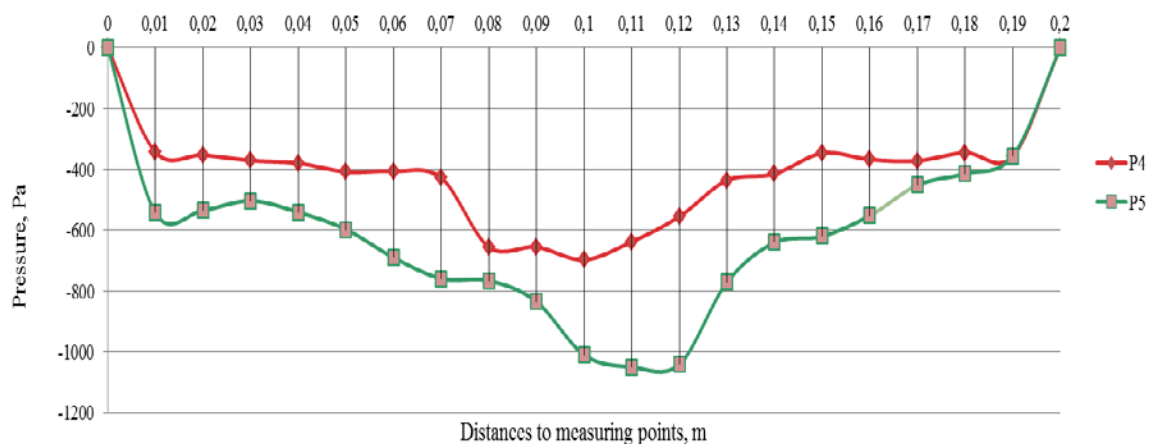


Figure 3. Underpressure P4 and P5, Pa, at the flow inside the cyclone in its lower part at the fully open throttle valve, with supply 0.145 and 0.141 kg of dust, respectively.

3.1. Numerical studies of the motion of a dispersed flow in a multi-cyclone

Numerical calculations of this multi-cyclone construction carried out by the statistical two-parameter model of turbulence $k-\varepsilon$, whose main advantage is the availability of a computational resource for problems close to real conditions. The inlet velocity of dusty gas flow into the multi-cyclone is assumed to be 4 m / s. In Fig. 4, Fig. 5 as an example, the velocities and static pressures in the horizontal section of the battery cyclone are presented. Calculations showed that pressure peaks occur on the frontal parts of the elements, not only in the first, but also in a subsequent rows. This allows to optimize the arrangement of the tangential inlets of the cyclonic elements.

The highest velocities are observed between the cyclonic elements, which is explained by the narrowing of the flow between them.

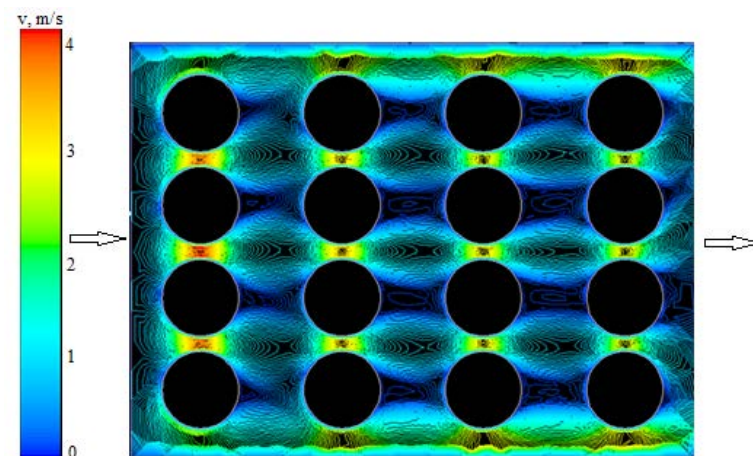


Figure 4. The velocity diagrams in the first model of the multi-cyclone.

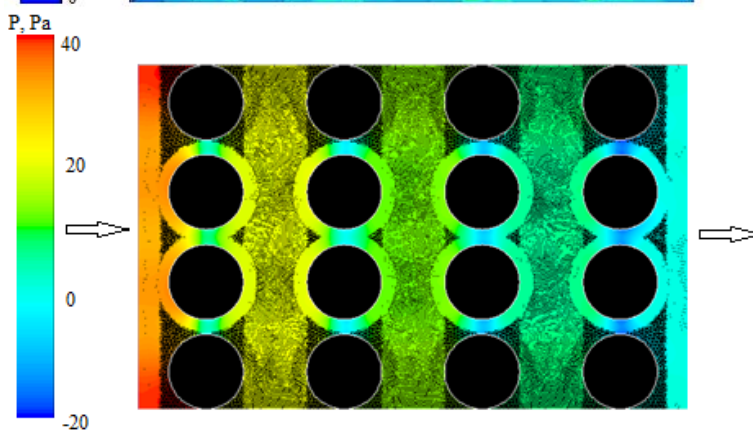


Figure 5. Distribution of static pressure in the second model of the multi-cyclone.

The results of numerical studies show that in the working space of second model between the elements, both the values of the velocity and the pressure are higher, although the flow rate characteristics at the inlet of the elements body are the same for both models. This is because the flow in the second model passes only in the spaces between the cyclone elements. In the first model, a significant part of the flow passes in the zone near the walls of multi-cyclone body that creating less resistance than the areas between the elements. Calculations clearly show that these zones represent local resistance such as one-sided sudden contraction and sudden expansion. The created numerical model of multi-cyclone allowed to estimate the influence of various factors on the efficiency of dust trapping in cyclones.

The results of the investigations made possible to arrange the inlet branches of the cyclone elements in the multi-cyclone, according to the first and second models, taking into account the hydraulic resistance of the apparatus. Then solved the problem of finding the most advantageous location of the elements inlets, taking into account the particle trajectories in the apparatus. A 2d-model of a multi-cyclone is constructed. An example of a geometric model of part of the multi-cyclone with dimensions of 1325x445 mm with 4 cyclonic elements with a diameter of 245 mm is shown in Fig 6. The number of cells of the grid is more than 150 thousand. According to the previous models (Fig. 4, 5) it could be seen that the elements of the multi-cyclone for the incoming flow represent an array of obstacles. A numerical experiment was carried out with the injection of particles with size ranging from 5 to 45 μm into the air flow in front of such an array. The problem of the turbulent flow motion equations closure solving by including the $k-\varepsilon$ model. The flow with the particles reached a velocity of 0.5 m / s to the obstacles and flowed around them. At the same time, part of the particles, together with air, escaped from the channel, but some part of particles was kept on the obstacles. On the basis of fraction of the total mass flow of particles passing through the channel, the penetration and the degree of precipitation are determined, and also the trajectories of

particle motion are detected. The study was carried out under standard conditions $T = 20^{\circ}\text{C}$, $P = 101325 \text{ Pa}$. The density and dynamic viscosity of the flow are assumed to be constant: $\rho = 1.205 \text{ kg/m}^3$, $\eta = 18.1 \cdot 10^{-6} \text{ Pa} \cdot \text{s}$. The developed numerical model of the multi-cyclone made it possible to evaluate the influence of various factors on its hydrodynamic characteristics and to find the location of the cyclonic element inlets that best correspond to the trajectories of the particle flows in the multi-cyclone body.

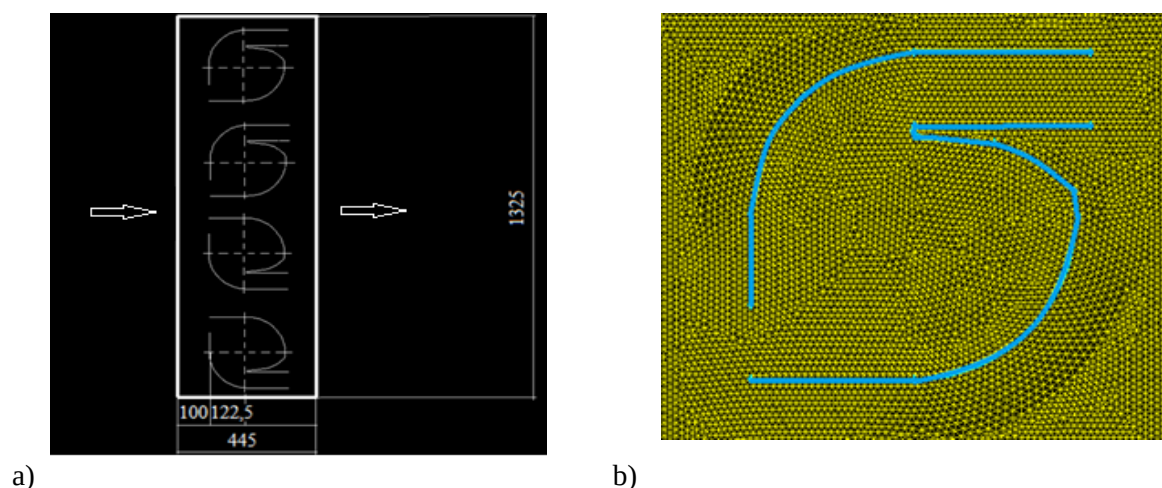


Figure 6. Geometric model of a part of a multi-cyclone body with a configuration of cyclone elements: a - a calculation model; b - an example of a calculated unstructured finite element mesh with triangular cells around one of the cyclone elements.

4. Conclusion

Thus, the experimental study carried out showed the effectiveness of the multi-cyclone cell with a tangential inlet and a filter insert. In a numerical study, the hydrodynamic characteristics of dispersed flows in a multi-cyclone body were obtained and the best scheme for locating cyclone elements with the optimum localization of their inlets was determined.

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