IMPROVING ENERGY AND ENVIRONMENTAL EFFICIENCY OF FLUE GAS CLEANING AT THERMAL POWER PLANTS

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Abstract. The aim of the work is to improve cyclone and filter dust collectors by increasing the efficiency of fine particle deposition classes PM₁₀, PM₂,₅ as well as reducing energy and material costs. The analysis of existing methods of cyclonic filtration of industrial dispersed emissions is carried out. The laboratory tests of the cyclone filter, made by modernization of the cyclone CN-11-200, were performed, the aerodynamic characteristics of its operation were found. The calculated determination of the efficiency of suspension deposition from multiphase flow in the separator using a dimensionless Re criterion is performed, derived from the Navier-Stokes single-phase flow equations of motion and the particle motion equation based on Newton's law. A numerically studied the aerodynamic parameters of the cyclone on the basis of computational fluid dynamics methods. For mathematical modeling of turbulence we used the DES model

1. Analysis of ways to improve the efficiency of separation in devices that implement the principle of cyclon filtration

In present time the problem of increase in power and environmental efficiency of cleaning of flue gases and emissions of coal dust preparation systems of power plants and the systems of preparation of gas on thermal power plants with gas generation. is very relevant, and is regulated in Russia by requirements of the Federal law No. 261-FZ from 11/23/2009 (an edition from 7/29/2017) "About energy saving and about increase in power efficiency and about introduction of amendments to separate acts of the Russian Federation" and also requirements for control of emission of greenhouse gases (e.g., the order of the Ministry of Natural Resources and Environmental Protection of the Russian Federation No. 330 from 6/29/2017 "About the approval of methodical instructions on quantitative scoping of indirect power emissions of greenhouse gases", etc.).

Now at the production facilities for dust deposition is widely used cyclone dust collectors, which is explained by the advantage of a number of their technical and economic indicators in comparison with other dust separators. It is the simplicity of design and manufacture, high capacity per unit mass of equipment, small operating costs, the possibility of dust capture in dry form, maintaining the required fractional cleaning efficiency in case the flow of the solid phase increasing, the reliability of work at a sufficiently high temperature. In the world, the search for ways to improve cyclonic devices in the direction of increasing the degree of deposition of suspended particles and reducing the energy intensity of cyclonic processing is intensively conducted. The authors of [1] presented HL-cyclone of
high performance (Hochleistungszyklon). It differs from the standard classic cyclones that it has the cross-cutting Central (axial) "guiding" pipe, strongly narrowed inlet pipe of dusty gas, significantly shortened conical part of the cyclone, connect with into the hopper. According to the authors of the development, the structural addition in the form of a Central pipe located along the HL-cyclone axis (Fig.1), provides high-performance operation of the device of this design. According to the authors [2], in the classical standard cyclones without a Central guide tube, the transition from laminar to turbulent flow occurs inside the exhaust pipe of the device. As a result, the core of the vortex flow in the apparatus becomes unstable, which causes great losses of pressure and energy, apparently, to rebuild the structure of the flow, which consists in the destruction of the organized rotational motion of the flow with the formation of small vortices of stochastic nature. According to [3], this in turn causes high losses (up to 90% of the total pressure loss) due to energy dissipation in the flow. The authors [4] conclude that the role of the Central ("guiding") pipe on the axis of the cyclone is to stabilize the rotating flow, and to shift the transition from laminar to turbulent regime in the region of higher Reynolds numbers. In this case, the static pressure loss is reduced, and the degree of separation is improved due to the increase of the dynamic pressure.

At the same time, the data of the authors [1] show that the tests of this cyclone design were carried out at loads 1.5...2 times lower than the optimal for the classical standard cyclones of this size. Therefore, the tested modes may not correspond to the conditions of industrial operation of the devices, and the efficiency achieved in the experiments may not be confirmed in real conditions.

A cyclone filter [5] can be used to clean up industrial emissions, including those contaminated with particularly hazardous suspensions, and if necessary, for fine cleaning of emissions (Fig.2).
Fig. 2. The cyclone filter (Patent No. 2361678 RF) [5]: 1-inlet, 2-body, 3-conical bottom, 4-exhaust tube, 5-cylindricity frame, 6-dense filtering material, 7-thin filter fabric, 8-purge fittings, 9-pin element 10 to the upper end, 11-retaining elements of the connector

The technical problem of intensification of cyclonic processing and increasing the degree of deposition of fine particles is solved here by increasing the velocity of the dispersed flow while taking measures to prevent abrasive wear internal surfaces of the apparatus. The device allows to reduce the resource intensity, but energy costs increase in proportion to the speed increase.

Analysis of many other existing cyclone filtration devices for industrial particulate emissions (e.g., [6, 7, 8, 9]) it also showed that the devices with a high degree of deposition of PM$_{10}$ and PM$_{2.5}$ particles are both material- and energy-intensive. Devices with low resistance, and therefore not energy-intensive, have a low degree of deposition of particles of these classes.

2. Cyclone filter unit to improve the energy and environmental efficiency of cleaning

For the purpose of good cleanup of gases from the suspended particles of the classes PM$_{10}$, PM$_{2.5}$ without increase in energy consumption at sedimentation of a suspended matter the advanced design of a cyclone filter is offered. The achievement of high extent of cleaning of a fine suspension is necessary at gas power plant for ensuring reliable operation of units of gas-turbine installations (GT) of steam-gas cycles, and at coal power plant – for increase in energy efficiency of operation of gas-cleaning devices. So, for example, increase in efficiency of trapping of the weighed part from a stream of natural gas in the point of gas preparation (PPG) of power plant leads to decrease in wear of cylinder walls of piston compressors or the surfaces of screws and cases of a complex configuration (which accuracy of processing is 10 microns) the screw compressors of the booster compressor stations (BCS). And placing a highly effective precipitators at the gas pipeline before GT (after the safety locking valve) for increase in extent of sedimentation of products of internal corrosion of pipelines and prevention of their penetration in GT for goal of reduce abrasive wear of turbines is provided by special articles of federal norms and rules of Russia of industrial safety "Safety rule of networks of gas distribution and gas consumption" (items 93, 94).

The proposed design of the cyclone filter can also be used in coal-fired power plants to improve the degree of cleanup of atmospheric emissions of dust preparation systems from coal dust and flue gas fromPM$_{10}$, PM$_{2.5}$ fine particle ash. By data [10], in flying ashes of power plants the average content of such particles about 30%, and in emissions of coal and slate dust can reach 35%. The offered cyclone filter (fig. 3) with a tangential inlet combines two steps of cleaning. Tests have shown that it provides rather high efficiency of cleaning of the emissions containing particles of the classes PM$_{10}$ and PM$_{2.5}$.
at acceptable power expenses and low abrasive wear. To increase the efficiency of sedimentation of fine particles with a minimum of energy and material costs cyclone has an additional device – the insertion of a fabric filter.

![Fig. 3. Scheme of a design of a cyclone filter: 1 - entrance branch pipe; 2 - case; 3 - bunker; 4 - exhaust pipe; 5 - filtering material; 6 - metal framework; 7 - a purge fitting; 8 - details of fixture of a removable end face; 9 – bunker lock](image)

Laboratory tests of a cyclone filter are carried out on the basis of the serial CN-11 cyclone with a diameter of 200 mm. Tests were carried out on specially prepared disperse material – aluminous (chamotte) dust with a size of particles up to 63 microns. Test of material for tests selected according to good laboratory practice and classified on a sieve in accordance with GOST P 51568-99 (ISO 3310-1-90). Radiuses of particles by results of the sedimentation analysis of fractional structure have turned out from 1,23 microns to 31,51 microns; therefore, the largest diameter of particles of dust by results of the sedimentation analysis corresponds to the sieve cell size. The disperse composition of dust in emissions after a cyclone filter was defined using an impactor. Based on the analysis of the dispersed composition of the flow, the median particle size $d_{50}$ was 1,6 $\mu$m.

The carried out experimental studies confirmed the expediency of constructive addition of the return-flow cyclones with a filter insert in the zone where inertial dust deposition occurs. At the same time, in order to refine the design, a number of studies were performed using the computational methods. To determine the efficiency of separation of the suspended part of the flow in this cyclone filter, the dimensionless criterion $Re$ [11] was used:

$$Re = \frac{U_0 \rho_p D_p^2}{\eta \rho_g R_2^2 c}$$

(1)

where: $U_0$ – initial velocity, m/s, $\rho_p$ – density of particles, kg/m$^3$, $D_p$ – diameter of particles, m, $c$ – the coefficient depending on the swirling device, $\rho_g$ – density of gas, kg/m$^3$, $R_2$ – the radius of a cyclone, m, $\eta$ – coefficient of dynamic viscosity, Pa·s.

The $Re$ parameter is received as a result of use of two standard methods of the theory of similarity (the analysis of dimensions and scaling), with reduction of system of the equations consisting of Navier-Stokes equations for flow movement and Newton's law for the movement of a particle to a dimensionless form. Calculations have shown that to degrees of sedimentation of particles in a cyclone
there correspond strictly definite values of numbers Re. So, at a speed of 5.0 m/s the number Re=2.4·10⁻³ to be compared to degree of sedimentation of 99%, and degree of sedimentation of 50% corresponded to Re=4.65·10⁻⁸. The carried out researches have shown that calculations on the basis of Re lead to the results close to the experience values of the sedimentations degree. At the same time the Re parameter allows to set the regimes of inertial separation of various sizes particles from any flow with curvilinear streamlines, i.e. from streams both in cyclones, and in the porous media.

Also numerical modeling of aerodynamic parameters of cyclone filter operation using the Computational Fluid Dynamics (CFD) methods has been performed. Today there is a set of works on CFD modeling of streams in cyclones, e.g., [12,13,14]. However only individual characteristics of a stream in concrete modifications of cyclones were, as a rule, observed. Therefore numerical researches of a 3D model of a stream in the developed cyclone filter design have been carried out. The accepted Detached Eddy Simulation (DES) model is "hybrid", based on sharing Reynolds Averaged Navier-Stokes (RANS) equations and Large Eddy Simulation (LES). It combines strengths of these two methods, namely, high precision of statistical models in the field of an interface and acceptable computing expenses of RANS and universality of LES in detachable areas of a stream.

The additional reserve of energy saving when using of the offered way of dust removal consists in optimization of details in communications. It is known that degree of sedimentation of the weighted particles from a heterogeneous stream correlates with the size of the power expenses which are directly related with sedimentation processes. In a construction of the presented cyclone filter those is processes of sedimentation of a suspension on surfaces of a filtering insert and an internal wall of a cyclone. Energy losses on local resistances arising at the movement of a dusty stream in shaped details before a cyclone and at entrance to a cyclone those aren't, but they are inevitable in use the device. Numerical and experimental studies of authors of works [15,16,17,18] have shown that losses may decrease by inserts which outlines can be also found using computer modeling of flows in connecting elements by the CFD methods.

Thus, the offered design of a cyclone filter allows to reach increase capacity of clearing devices with improvement of quality of clearing of gas which is expressed in reduction of the size of the particles caught for 50% (cutoff diameter) from averages for usual cyclones of 5-10 microns up to 1,6 microns.

The specified improvement of quality of cleaning doesn't demand essential increase in expense of energy. It is one of the main advantages over the usual cyclones at which for decrease cutoff diameter to 0,1 microns (since 2-3 microns) it is required to increase energy expenses to 15%.

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