THERMAL ELECTRIC POWER STATIONS

DEVELOPMENT AND INTRODUCTION OF NEW DESIGNS FOR GAS-DUST FLOW MIXING DISTRIBUTION SYSTEMS AT THERMAL POWER PLANTS

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Translated from *Élektricheskie Stantsii*, No. 7, July 2008, pp. 10 – 23.

The successful introduction and setup of new designs for dust separators in Russian and foreign 200 – 800 MW coal-fired power production units is described. Results from mathematical and physical modelling of these designs, as well as data on their operation in test stands, are presented. Recommendations are given for the most suitable equipment and configurations of new dust distribution systems in dust preparation systems.

Keywords: dust-gas flow mixing distribution systems, introduction and setup, design models, test stand studies, mechanism for motion of stable dust layers, equipment recommendations.

Operating experience and industrial research show that the operational efficiency and reliability of furnace systems, the explosion safety and operational reliability of dust preparation, the reliability and operating lifetime of heating surfaces, and the amount of nitrogen oxide emissions depend on the degree of uniformity of the distribution of fuel and air over the burners in a furnace. Failure to meet the required fuel-air ratio in the burners leads to a deterioration in ignition stability, reduced fuel burnup, and increased yield of toxic combustion products [1 – 4]. Elevated concentrations of dust in the dust ducts can lead to dust deposits in the ducts or even to blockage of individual lines, which increases the explosion hazard for the system and reduces the productivity of the dust system [5 – 7]. Nonuniform heating in different burners causes greater distortions in the temperature over the cross section and height and may make the flare stretch into the upper part of the furnace and cause a rise in the temperature at the furnace outlet; this sharply reduces the service lifetime of the heating surfaces and causes slag buildup on them [1, 3, 8, 9].

During operation of dust preparation systems this nonuniformity can be extensive (up to 100%) owing to different fuel dust feed rates at various outlets from the system: three-way distribution feeds, turns, separators, etc. Even with a uniform distribution over the outlets for the transport air, the dust can fall into one or several outlets as it is extruded toward the channel walls [9]. If the dust system includes dust ducts with greatly differing lengths and configurations, as is typical of most coal-fired thermal power plants with high-power energy production units, an additional nonuniformity is imposed on the distribution of air over the outlets.

It should be noted that efforts to introduce new technologies and equipment for fuel burning may not yield the expected theoretical effect, if the specified distribution of fuel feed rate over the burners is not ensured. These problems are especially pressing in connection with the tasks now facing the national power generation system of enhancing the steam parameters (which requires the elimination of temperature distortions at steam superheater surfaces) and meeting modern ecological standards (through use of stepwise combustion and the strict need to maintain specified air excesses in burners).

In order to avoid the negative effects owing to nonuniform feed of dust over the burners, special equipment — dust-gas flow distributors (dust separators) — has been introduced around the world. Until recently, insufficient attention has been devoted to the question of ensuring uniform fuel feed over the burners in the Russian energy power generation system. A large number of operating boiler units have not been equipped with devices for enhancing the uniformity of fuel feed over the burners or have been equipped with only the simplest, low-efficiency dust distributors. At the same

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1570-145X/08/4205-0281

time, in accordance with buyer requirements, boiler systems intended for export are equipped with Russian made dust distributors that exceed, in both their size and their engineering parameters, many of their foreign equivalents. A dust separator is a measure that costs little, but in many cases it greatly enhances the operating efficiency of a boiler system. A rational scheme for dust feed over the burners also is very important.

Several characteristics of dust preparation systems are currently used for comparative estimates of the uniformity of the distribution of gas-dust fuel over dust ducts and burners:

distribution nonuniformity (in percent) [1, 9, 10]

$$\Delta g = 100(g_{i\,\max} - g_{i\,\min}), \quad (1)$$

where $g_i = G_i \Big/ \sum_{j=1}^{n} G_j$ is the absolute dust feed rate in the i-th dust duct, G_i is the absolute dust feed rate over all the dust ducts, and n is the number of dust ducts;

maximum nonuniformity of the distribution (in percent) [11, 12]

$$\Delta g_{\max} = 100(g_{i\,\max} - g_{i\,\min})/g_{\text{avg}}, \quad (2)$$

where $g_{\text{avg}} = \sum_{j=1}^{n} G_j n$;

root mean square deviation in the relative dust feed rate over the outlets (for a small number n, in percent)

$$\sigma_n = 100\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(g_i - g_{\text{avg}})^2}; \quad (3)$$

maximum relative deviation in the dust distribution over the outlets (in percent) [13]

$$\delta g_{\max} = 100(|g_i - g_{\text{avg}}|_{\max})/g_{\text{avg}}. \quad (4)$$

Analysis and practical experience indicate that, of these indices, the degree of nonuniformity in the distribution of the fuel over the dust ducts, Δg (1), provides the most accurate characterization. For example, when all the dust falls into one of the dust ducts, i.e., the case of maximum possible nonuniformity of the distribution, $\Delta g = 100\%$, which is consistent with the physical significance of the phenomenon. At the same time, it is easy to shown that then $\Delta g_{\max} = 100n$; so that, $\delta g_{\max} = 100(n - 1)$, i.e., always $\geq 100\%$, while $\sigma_n = 100n^{-0.5}$, i.e., always less than 100%. Based on these data, we can see that Δg is the best choice for the index characterizing the nonuniformity of the fuel distribution over the burners in standards and technical recommendations [1], in which the allowable level of Δg is taken to be 20% based on the stability and economy of the fuel process. Experience shows that even in terms of the equipment operational reliability conditions for the dust system, this level of Δg is acceptable. However, when the modern specifications for boiler installations mentioned above are taken into account, it is necessary to strive for a lower level of Δg, 5 – 10%, and it is obvious that the permissible level of nonuniformity must decrease as the number of burners supplied with dust by a single mill is increased. For a comparative analysis, all the results of test stand runs and industrial trials reported in this article are reduced to the index Δg.

Two types of gas-dust flow distributors are currently in use at thermal power plants: laminar and mixing types. In *laminar dust distributors* [1, 14], which are most widely used in foreign countries and are used at a number of thermal power plants in Russia, an air mixture from different zones in the inlet section of the equipment with different concentrations are gathered into each outlet; as a result, there is a balancing of the dust flows over the outlets. Slit channels are made in sleeve, sector, and some other types of laminar dust distributors by placing barriers in the vessel, and each dust duct is joined by pipes to several channels in different parts of the cross section with different flow concentrations. In order to deliver dust over the height (with corner multistage burner siting), laminar dust distributors designed by SibVTI [1] are used in a number of thermal power plants. These distributors contain a series of sequentially mounted chambers, with slit channels formed in them by barriers that are joined by the outlets through the boxes joining them; parts of the channels are blocked out on passing to the chamber the next, higher outlet.

A common deficiency of all laminar distributors is that a large number of plates are mounted inside the vessel and are subject to wear, and are large in size and use a lot of metal. They are essentially uncontrolled and are difficult to repair. In addition, on working with sufficiently fine dust ($R_{90} < 25 – 30\%$) in dust systems with centrifugal separators and extended dust ducts with bends (as happens in most coal-fired thermal power plants), the efficiency of these dust distributors is found to decrease. To a great extent, this phenomenon follows from the enormous forces leading to sticking (adhesion) of fine (below 50 – 100 μm) dust fractions with a high specific surface area to the channel walls and to sticking of the particles to one another (cohesion forces), so they are slowed down sharply as they move along the walls. As a result, in the wall region there is an enhanced concentration of dust and a dust layer consisting of fine particles bound by the strong adhesion forces develops and moves as a unified whole. Very detailed studies [10, 15] have shown this by direct measurements: the highest concentration of dust occurs at a distance of less than 0.05 channel diameters from the wall (3 – 4 times higher than on axis) and the finest fractions move within this region. It has been shown [10] that in horizontal segments, this process is stable over a length of 90 – 100 diameters of the dust duct or more, and when bends are present, it becomes significantly stronger. Formation of layers of this sort (dust clumps) can lead to a significant reduction in the uniformity of the dust distribution in laminar dust distributors when a dust clump enters one or more of the outlets along the channel wall or an inner separator plate. Similar effects can also occur at the outlet of a centrifugal separator, where the flow is extruded to the walls owing to the centrifugal forces.

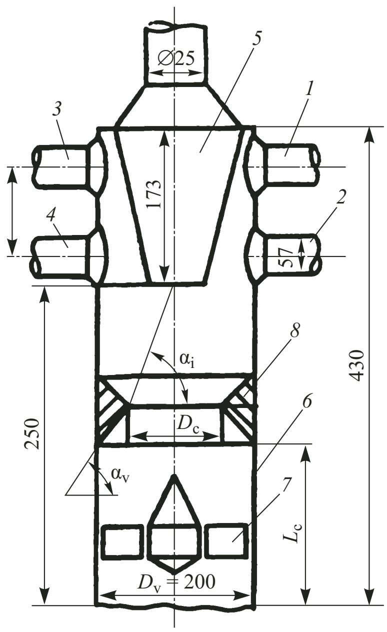

Fig. 1. Layout of the model of a separator-concentrator with a diffuser-nozzle constriction: *1* – *4*, outlets for the highly concentrated flow; *5*, outlet for low-dust flow (waste outlet); *6*, vessel; *7*, axial blade swirler; *8*, constriction.

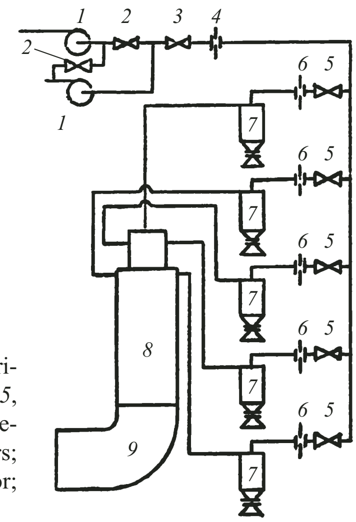

Fig. 2. Scheme for the experimental test stand: *1*, fans; *2*, *3*, *5*, regulator valves; *4*, *6*, measurement devices; *7*, dust extractors; *8*, model separator-concentrator; *9*, inlet dust duct.

In mixing-type dust distributors, which are mainly employed with moderate and fine grinding of the fuel, uniformity of the air mixture feed is achieved by balancing the concentration of the dust though mixing in the cross section prior to the outlets; this leads to significantly more compact equipment and better mass and size characteristics for distributors of this type. The standards and technical recommendations [1] list designs for operationally tested diffuser distributors with a conical housing, diffuser dust distributors with a constriction, and dust distributors with a constriction and a deflecting plate mounted along the axis of the housing. However, experience has shown that these designs do not provide a highly uniform distribution when fine dust is used, while dust distributors with a deflector plate have very high drag (1500 – 2000 Pa), so that they are not in use anywhere [14].

Our analysis and studies show that the low efficiency of these dust distributors is, to a great extent, caused by the fact that their designs do not take into account the stability of the dust layer which forms near the wall and, although it enters the flow after extrusion and constriction away from the wall, is basically not destroyed within the volume (is not scattered by the gas even when the latter has a speed of 30 – 40 m/sec), but shifts to another part of the channel wall. There is only a slight removal of the constricted layer as a whole (or, possibly, a slight expansion of it). This process shows up extremely clearly during modelling of a separator-dust concentrator (Fig. 1) for a P-57R boiler at the Ékibastuz GRÉS-2 (state regional electric power plant) on a test stand (Fig. 2) [11] during operation with fine dust. As opposed to the standard configuration [12], instead of a single outlet for the high concentration mixture, in this dust concentrator there are four main outlets for the highly concentrated mixture on the cylindrical housing, mounted above the axial conical pipe for exhaust of the incompletely milled dust waste. This dust concentrator is positioned after a 90° bend in the dust duct. During studies of this design, no measures (changing the angle of the swirler blades, the flow velocity, inlet position for the dust, etc.) capable of providing a satisfactory uniformity of the dust feed through the main outlets (Δg was 40 – 50%) were found because the layer of dust which formed at the walls fell into one or more of the outlets.

Installing a conical diffuser-nozzle constriction immediately above the blades (of the swirler) for pushing the flow away from the walls was essentially ineffective (Fig. 3). When this constriction was shifted along the axis of the housing toward the waste outlet, at a certain distance from it a sharp reduction in the nonuniformity of the feed was observed, followed by an equally sharp rise as the constriction was moved closer to the outlet duct (Fig. 3*a*). This variation suggests that, as it moves into the volume from the nozzle surface of the constriction, the direction motion of the dust layer changes insignificantly, while the dust layer is not scattered much by the gas and moves mainly as a whole until it again strikes the wall. In fact, this variation in the nonuniformity of the dust distribution with the angle of inclination α_i of the line joining the inner edge of the constriction to the center of the inlet cross section of the waste exhaust shows that the minimum of Δg is attained in the region $\alpha_i \approx \alpha_v$, where α_v is the angle of inclination of the generatrix of the surface of the constriction nozzle (Fig. 3*b*), i.e., partial scattering and destruction of the dust layer occurs during a collision with an obstacle placed perpendicular to its flow direction, i.e., the edges of the wall of the waste duct of the dust concentrator (taking into account some removal of the layer by the flow). When the constriction is low ($\alpha_v < \alpha_i$), the layer of dust moves mainly under the waste duct to the opposite side of the housing, while when it is positioned higher ($\alpha_v \geq \alpha_i$), the layer strikes the outer surface of the conical exhaust

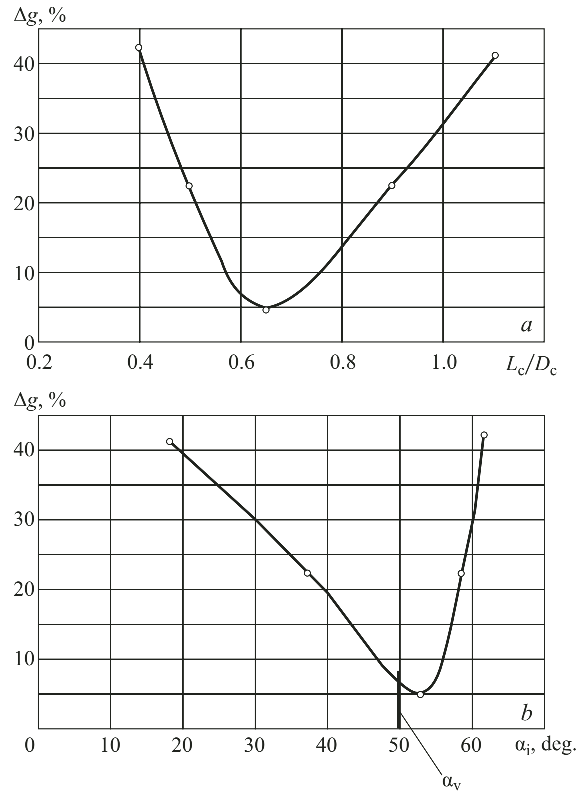

Fig. 3. The nonuniformity index for the dust distribution of the separator-concentrator (Fig. 1) over the outlets as a function (*a*) of the ratio of the distance between the cross section of the constriction and the inlet cross section of the waste pipe to the diameter of the constriction and (*b*) of the angle of inclination of the line joining the inner edge of the constriction to the center of the inlet cross section of the waste outlet.

duct and moves along it into the upper primary outlets. (This was confirmed by the size distribution of trapped dust.) This mechanism was also confirmed by industrial studies of dust distributors in the second stage of the Novosibirsk TÉTs-4 heat and electric power plant (see below).

These results show that in order to obtain a highly uniform distribution of the fuel dust, it is necessary to ensure destruction of the dust layer within the volume of the dust distributor with minimal expenditure of energy. In addition, given today's rigorous environmental requirements and the impossibility of predicting the initial distributions of the concentration and of the dust layer at the inlet to an industrial system, a design for a dust distributor must include the possibility of controlling and optimizing the dust feed distribution over the outlets during startup and repair work. Based on a large set of scientific and design engineering studies, including mathematical modelling, analysis of model samples, and industrial development of the designs, dust-gas distributors which meet these specifications have been developed and introduced by NPO TsKTI together with boiler factories, research and setup organizations (UralVTI, SibKOTÉS, Sibtekhénergo, and others), and repair services for thermal power plants. At present, essentially all the boiler units of large coal-fired power generating units manufactured by Russian industry since the 1990's (in Russia and China) include dust distributors and separator-concentrators employing this design. In addition, dust distributors of this type, based on the designs of NPO TsKTI, are expected to be installed in most of the new coal-fired boiler units in Russia which are projected or being built.

All the model tests were based on the well established classical theory of similarity for dust distributor equipment in dust preparation systems [12, 16]. According to that theory, for geometrically similar installations and relatively fine dust ($R_{90} < 50\%$), a necessary and sufficient condition for transfer of laboratory data to an industrial scale is that the model and field setups must satisfy the following conditions:

$$\mathrm{St} = (\delta^2 W_o \rho_2)/(\mu D) = \mathrm{idem};$$

$$\mathrm{Fr} = W_o^2/(Dg) > 8.5;\ \ \mu_o = \mathrm{idem}, \tag{5}$$

where St is the Stokes number, Fr is the Froude number, ρ_2 and μ are the density of the dust and viscosity of the gas, W_o is the characteristic velocity of the gas, D is the characteristic dimension of the apparatus, μ_o is the mass concentration of dust, and g is the acceleration of gravity.

It should be noted that satisfaction of these limitations does not, in general, yield an exact quantitative agreement between the indices for the model and the industrial equipment, but long experience confirms that if the requirements (5) are met, a qualitative similarity of the processes in the model and the field equipment does result, and the specified performance (indices) can be achieved by means of fairly simple controls under specific conditions.

One of the first designs of the new type (chamber or centrifugal-counterflow [17]) developed under test stand conditions and introduced into industrial use was a dust separator with four outlets for boilers manufactured by a company (ZIO) for 500 MW power generation units at the Cixian thermal power plant (China). It is shown schematically in Fig. 4. Based on the assembly conditions, these devices were installed in dust systems with in-line mills (at $R_{90} = 20 - 25\%$) in the dust ducts after bends. Their design precludes the possibility of direct impact of the dust layer at the walls of the dust duct on the outlets because it first enters special hollow chambers, where conditions are created for destruction of the layer and the arrival of the different fractions (counter to the rising particle flow) into different zones of the cross section of the collector shell with the outlets. This ensures mixing of the solid phase and balancing of the concentration at a cross section ahead of the outlets. A splitter and an axial blade swirler were installed at the inlet to the dust distributor to remove the initial dust from the volume into these chambers and mix it with the remaining dust. The dust feed rate over the outlets is controlled by special rotatable inserts mounted in the collector shell, as well as by the angle of inclination of the swirler blades.

In order to analyze the process and optimize the design, the motion of the dust particles in the housing of the chamber dust distributor was modelled mathematically. The system of differential equations for the three dimensional motion of the particles was based on the current standard problem statement and assumptions for low concentration gas-dust flows in power generation equipment (neglecting the Moebius forces, apparent mass, interparticle interactions, etc. [10, 12, 15, 16]). The equations of motion were solved using a Runge – Kutta – Merson method on a computer. The velocity distribution of the gaseous phase was calculated using the "Fluent" program package, and the effect of the particles on the stream lines of the gas flow was ignored [15, 16]. The effect of turbulent fluctuations in the flow was also neglected, but this only favors the calculations, since turbulence facilitates mixing of the particles. Figure 5 shows some computed trajectories of dust particles of various sizes (diameters δ_p ranging from 15 to 1000 μm) entering the dust separator at different distances from the walls of its inlet pipe.

An analysis of these results indicates that, for the assumed design of the dust distributor, dust particles, including the smallest ones, can move from the region of the cross section of one of the outlet pipes into the zones of the cross section of the other outlet pipes. This provides greater uniformity of the dust distribution. Of course, in any case, the picture of the particle motions obtained from the mathematical model is extremely approximate, but it is useful for estimates and for choosing a design configuration, as subsequent studies on model samples demonstrated.

The design scheme for the dust distributor was worked out on a stand similar to the one shown in Fig. 2. The test stand runs yielded the specified indices for the dust distribution and the coefficient of aerodynamic drag of the apparatus. Since the mills at the Cixian thermal power plant were made in China, the dust system equipment was tested by the Chinese. The dust separators met all the design specifications and were accepted by the Chinese customer. From 1990 through the present, 16 of these dust separators have been used successfully at Cixian.

In the next stage of this work, a design for an improved chamber-type dust separator was created [18]. This dust separator does not have a blade swirler mounted immediately after the centrifugal separator, but works with it as a unified whole. A simpler design of this sort was possible because there is a residual rotation of the dust-gas mixture at the outlet of the centrifugal separator (after it has acquired substantial swirl from the separator blades when a sufficiently fine dust has been obtained [16]). In addition, using the energy of the rotating flow following the separator reduces the aerodynamic drag of the dust separator. A splitter is also installed on the axis to squeeze the flow in the mixing chamber. One of the first designs of this type was the dust separator at the first step for the three outlets in TPP-804 boilers manufactured by the TZK "Krasynyi kotel'shchik" firm (for the 800 MW generation units at the Suichun thermal power plant in China), whose configuration is sketched in Fig. 6. These devices were mounted behind the outlet flange of the separators for the in-line MVS-260 mills manufactured by the JSC "Tyazhmash" firm. Based on the working drawings from NPO TsKTI, 16 dust separators of this type were built and placed in commercial use by the Chinese and all the design specifications were met.

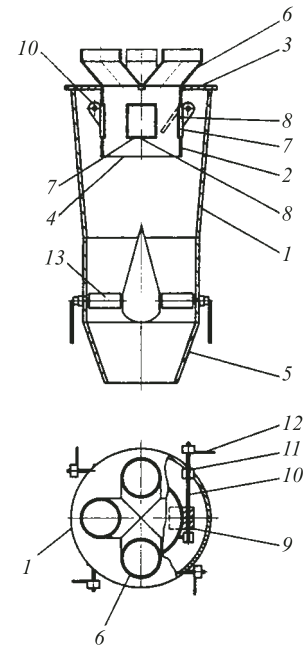

Fig. 4. Sketch of the design of the model dust separator for the Cixian thermal power plant: *1*, vessel; *2*, collector shell; *3*, lid; *4*, inlet cross section of the collector shell; *5*, inlet pipe; *6*, outlet pipes; *7*, window in the collector shell; *8*, rotatable insert; *9*, bracket; *10*, axis of insert; *11*, bushing; *12*, lever; *13*, axial blade swirler.

The dust distributor system for the boilers in the power generating units at the 800 MW Suichun thermal power plant, where each of the eight mills supplies the fuel dust for six burners in a single row of the furnace, is arranged in a two level 3 × 2 configuration. Each of the three outlets for the dust separators in the first stage (Fig. 6), mounted on the flanges of the separators of the MVS-260 mills, is connected with an 830-mm-diam dust duct to the dust separator in the second level and connected to the burners. The dust separators in the second level (three per layer) are mounted right at the walls of the furnace chamber roughly at the level of the corresponding burner level. This arrangement ensures high uniformity of the distribution, both with respect to the fuel, and with respect to the primary air. Newly designed diffuser-nozzle dust separators from the NPO TsKTI were used as separators in the second level at the two outlets; with their simple setup these yielded very high uniformity of the dust distribution (on the test stand, up to $\Delta g = 0.5 - 1\%$), essentially without affecting the distribution of air over the outlets or the amount of aerodynamic drag. When it was built, it yielded similar performance under commercial conditions (cf. data on the second stage of the dust distributor in Table 1). These devices have a constriction which directs the layer of particles away from the channel walls and a regulator system which distributes the flow of dust over the outlets at the place where it is concentrated in the center of the vessel. They are quite compact and can be repaired easily. Figure 7 shows the comparative sizes of these diffuser-nozzle dust separators and a standard laminar dust separator manufactured by the German firm EVT.

The new designs for the dust separators in the first and second levels of the Suichun thermal power plant were worked out on a test stand that fully modelled the industrial dust preparation system, including an in-line dust mill (which produced grist and dust of the required composition), a first-level dust separator mounted at its separator, dust ducts with a layout geometrically similar to the design configuration, dust separators for the second level, and dust ex-

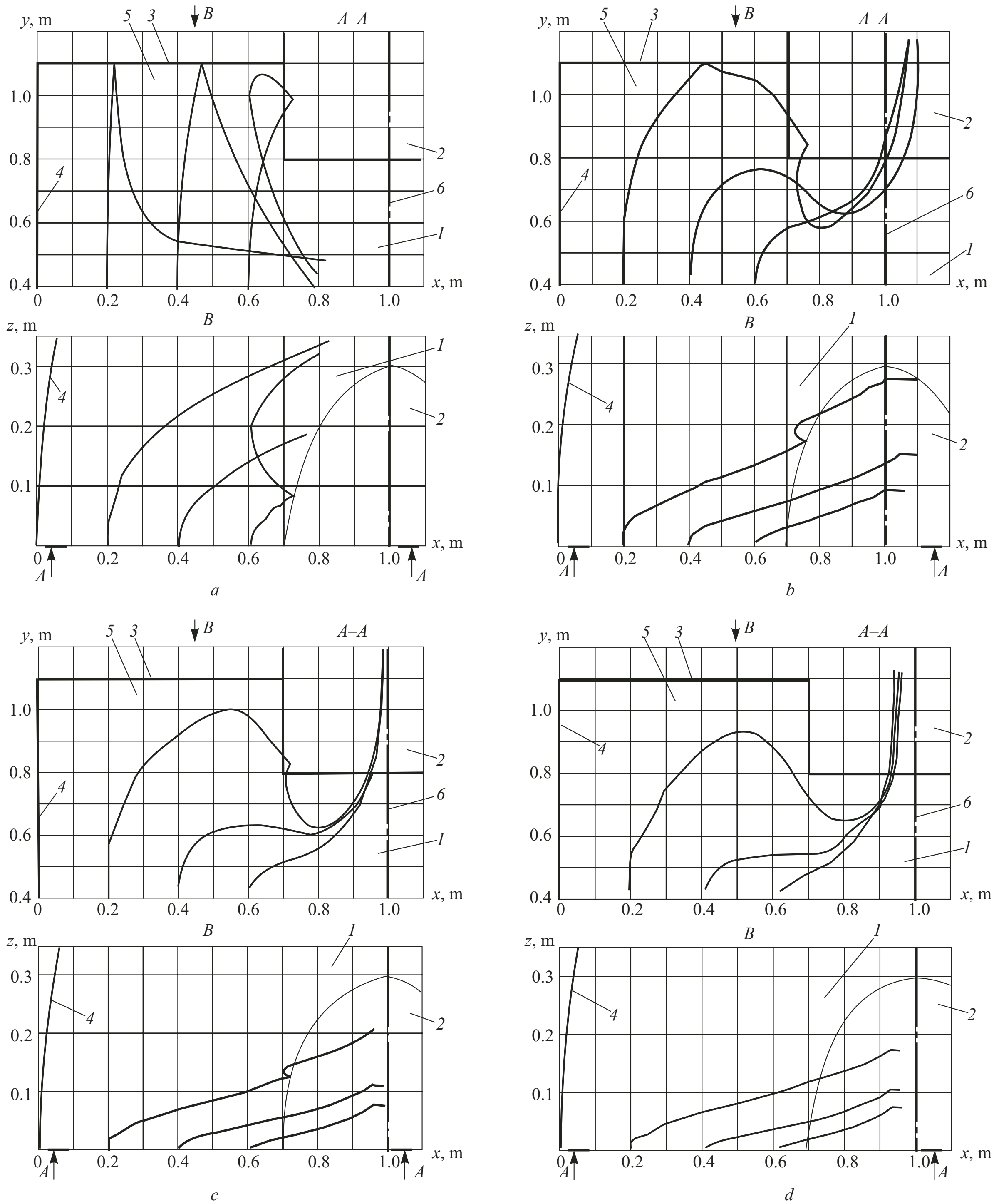

Fig. 5. Calculated trajectories of dust particles of different sizes in a chamber dust separator: (*a*) δ_p = 1000 μm, (*b*) δ_p = 200 μm, (*c*) δ_p = 90 μm, (*d*) δ_p = 15 μm; *x* and *z* are the horizontal axes and *y* is the vertical axis; the coordinate origin is at the vessel wall in a vertical plane in the inlet cross section of the dust separator; the vertical axis of symmetry of the separator corresponds to coordinates *z* = 0, *x* = 1 m; the calculated coordinates of the particle positions are indicated with a time interval of 0.004 sec; *1*, inlet cross section of the dust separator; *2*, collector shell; *3*, upper lid; *4*, wall of the cylindrical vessel; *5*, chamber between the vessel wall, collector shell, and lid; *6*, vertical axis of symmetry of the dust separator.

tractors for trapping the dust, mounted at the site of the burner structures (Fig. 8). The experiments were conducted subject to the conditions (5) by a method described elsewhere [11, 12]. Figure 9 is a plot of the nonuniformity of the dust distribution in the first level as a function of the position of the mill separator blades and angle of rotation of the inserts, obtained with the final version of the model for the distributor in the first level, whose configuration was chosen for commercial use. Figure 10 shows the nonuniformity of the dust distribution over the outlets of the distributor for the second level as a function of the location of its regulator

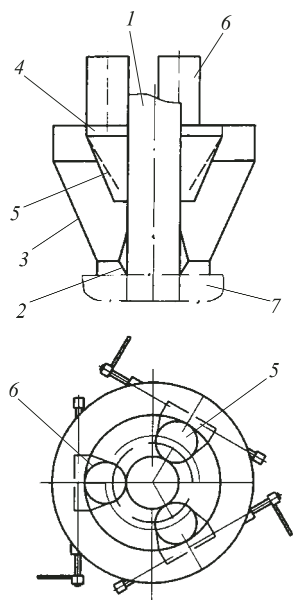

Fig. 6. Design of the model dust separator for the first stage of the Suichun thermal power plant: *1*, pipe for fuel feed to mill; *2*, splitter; *3*, vessel; *4*, collector shell; *5*, rotatable insert; *6*, outlet pipes; *7*, mill separator.

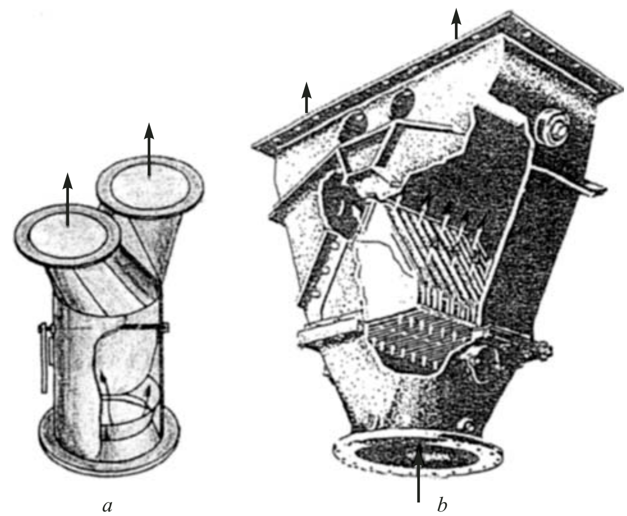

Fig. 7. Comparative dimensions of the diffuser-nozzle dust separator (*a*) and a laminar separator with two outlets from the EVT firm (*b*).

TABLE 1. Results of Test and Adjustment of the Dust Separators for the Boiler in Power Production Unit No. 6 at the Novosibirsk TÉTs-5

Dust distribution system equipment	Nonuniformity index for the dust distribution Δg, %	Nonuniformity index for the air distribution Δv, %	Angle of rotation of the regulator valves $\Delta\alpha$, deg.
Mill A (leftmost)			
Dust separator in the first stage to two outlets	5.76	0.95	21.0
Dust separator in the second stage to two outlets (left)	1.70	3.98	13.0
Dust separator in the second stage to two outlets (right)	2.36	4.06	–20.0
Dust distribution system as a whole (to four burners)	2.71	2.48	
Mill B (second from left)			
Dust separator in the first stage to two outlets	6.45	2.15	32.2
Dust separator in the second stage to two outlets (left)	3.54	0.25	30.0
Dust separator in the second stage to two outlets (right)	3.93	2.32	–24.0
Dust distribution system as a whole (to four burners)	4.52	4.38	
Mill C (center)			
Dust separator in the first stage to two outlets	0.29	3.06	8.0
Dust separator in the second stage to two outlets (left)	0.00	10.60	–10.0
Dust separator in the second stage to two outlets (right)	4.04	12.67	23.0
Dust distribution system as a whole (to four burners)	3.59	10.97	
Mill D (second from right)			
Dust separator in the first stage to two outlets	8.95	0.19	10.0
Dust separator in the second stage to two outlets (left)	0.33	6.05	25.0
Dust separator in the second stage to two outlets (right)	1.19	3.87	–5.0
Dust distribution system as a whole (to four burners)	2.97	4.33	
Mill E (rightmost)			
Dust separator in the first stage to two outlets	3.20	4.78	13.0
Dust separator in the second stage to two outlets (left)	4.05	5.16	–7.0
Dust separator in the second stage to two outlets (right)	5.51	11.09	18.0
Dust distribution system as a whole (to four burners)	4.62	6.11	

Note. A negative angle corresponds to turning the valve away from the furnace wall.

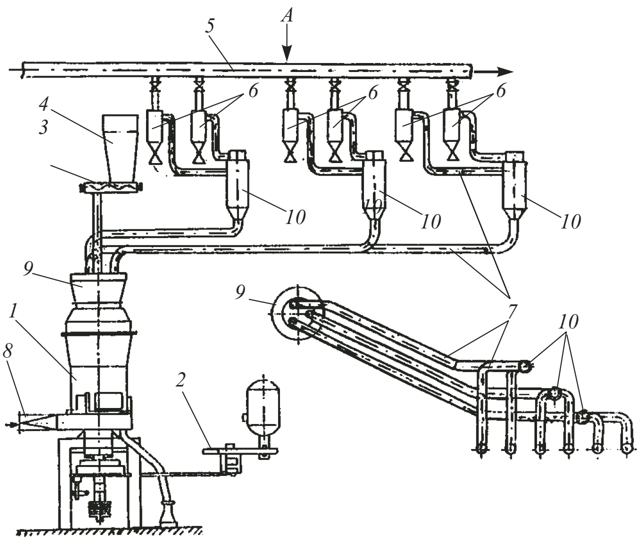

Fig. 8. Test stand for working out the design of dust separators, modelling the industrial dust preparation system (the variant for the dust system at the Suichun thermal power plant is shown): *1*, in-line mill; *2*, drive for mill; *3*, raw coal feed; *4*, raw coal bunker; *5*, dust-free air outlet; *6*, dust extractors; *7*, dust ducts with configurations geometrically similar to the project setup; *8*, air feed duct to mill; *9*, first stage dust separator; *10*, second stage dust separators.

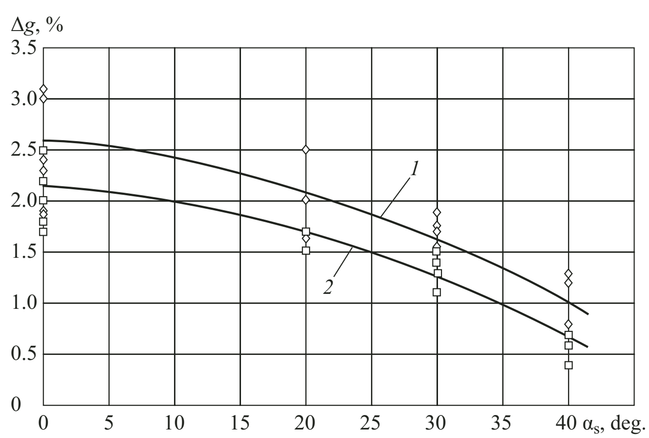

Fig. 9. The nonuniformity index of the dust distribution over the outlets of the first-stage dust separator of the Suichun thermal power plant as a function of the angle of inclination of the separator blades: *1*, with closed inserts; *2*, regulated by the inserts.

structure. At present, 16 chamber dust separators and 48 diffuser-nozzle dust separators are in use at the Suichun thermal power plant.

A chamber dust separator for four outlets for the boilers of the 300 MW Inkou (China) thermal power plant was developed and worked out on a test stand which modelled the industrial dust system (analogous to the scheme in Fig. 8). The dust distribution system for this boiler is arranged in a single layer 1×4 scheme: the dust separators are located right on the flanges of the in-line mills and provide fuel to the four burners of a single layer of the furnace. In all, six

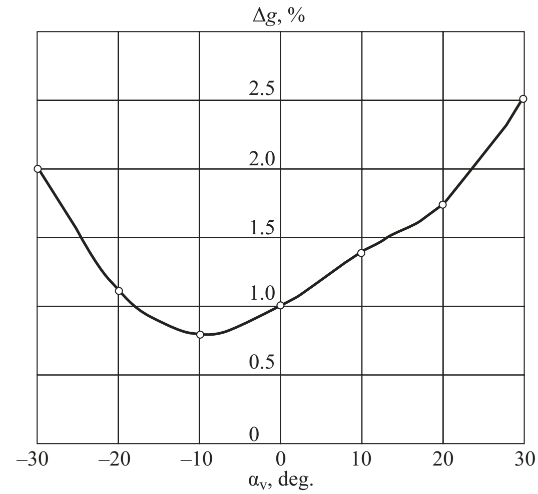

Fig. 10. The nonuniformity index of the dust distribution over the outlets of the second stage dust separator at the Suichun thermal power plant as a function of the angle of inclination of the regulator valve.

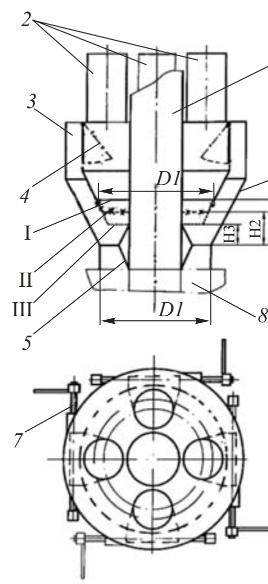

Fig. 11. A sketch of the modifications in the model dust separator for the Inkou I thermal power plant with short (I), medium (II), and large (III) conical collector shells: *1*, vessel; *2*, outlets; *3*, cylindrical part of the collector shell; *4*, rotatable inserts; *5*, splitter; *6*, fuel feed pipe for mill; *7*, axes of the inserts; *8*, mill separator.

mills and 24 burners are installed in the boiler; they are mounted in three layers of four each on the front and back walls of the furnace. Figure 11 shows some of the stages during development of the variants for this design: with short, medium, and long conical shells. In the case of the setup with a short shell (whose inlet diameter was somewhat greater than the inlet diameter of the housing), the uniformity of the distribution for low and moderate bending of the flow is poorest; this indicates that a large fraction of the dust layer near the wall falls into it (Fig. 12, curve *1*). In this variant, a significant reduction in Δg to 4 – 5% observed only at the maximum turning angle for the blades of the separator (because of the large amount of highly compressed dust arriving in the chamber and at the edge of the shell). When a medium collector shell is installed, a fairly high uniformity of the dis-

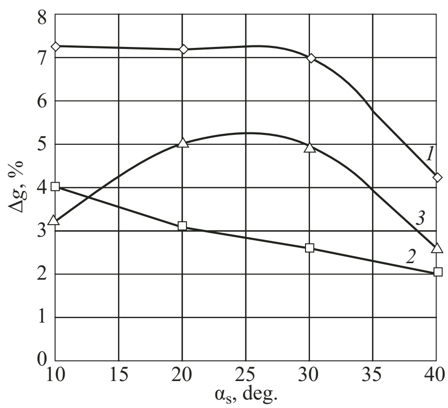

Fig. 12. The nonuniformity index for the dust distribution over the outlets of the dust separators (Fig. 11) as a function of the angle of inclination of the separator blades, α: *1*, short shell, *2*, medium shell, and *3*, large shell.

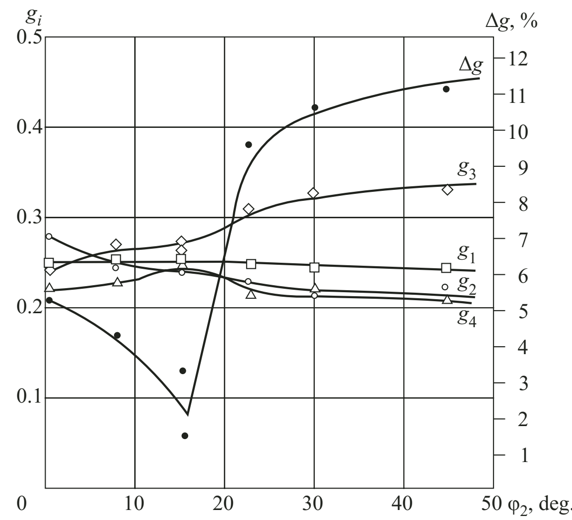

Fig. 13. The dust distribution gi over the outlets and the nonuniformity index Δg for the dust separators (Fig. 11) as functions of the angle of rotation φ_2 of the valve at the second outlet (with large shell installed).

tribution is attained, which increases smoothly as the bend of the flow is increased: Δg reaches 2 – 4% (Fig. 12, curve *2*). With the large shell (Fig. 12, curve *3*), a high uniformity is observed with a small bend, since in this case the dust layer adjacent to the walls is destroyed efficiently by the edges of the shell, as it enters the inner volume of the shell along with the peripheral streamlines of the flow (however, this configuration has a high aerodynamic drag). In the case of a moderate bend ($\alpha_s = 20 – 30°$), the nonuniformity of the distribution increases slightly (to $\Delta g \approx 5\%$), apparently because of the nearby slit in the shell, so that part of the dust layer does not reach the walls of the vessel and strikes the inner wall of the shell (a similar result is observed for $\alpha_v > \alpha_i$; see Fig. 3) with a subsequent smooth motion toward its interior volume. And only when there is a sharp bend in the flow ($\alpha_s > 30°$ does a substantial fraction of the dust layer penetrate into the chamber of the dust distributor along the vessel walls, which causes an increase in the distribution efficiency (Δg = 2 – 3%). Thus, the most efficient control by the rotatable inserts occurs when a large shell has been installed.

Figure 13 shows the amount of dust entering the outlets, g_i, and the nonuniformity index Δg as functions of the amount of coverage, φ_2, by the rotatable insert in the second outlet (into which the largest amount of dust entered for the initial position of the inserts). When φ_2 is increased to 15°, the amount of dust in this outlet decreases and the amount in the next (third) outlet in the direction of the twist. The amount of dust in the other outlets changes little. This makes it possible to reduce the nonuniformity of the distribution Δg to 2.5% (here the distribution of air over the outlets is essentially unchanged). Further covering of the valve leads to a still greater increase in the amount of dust in the third outlet, but here its feed rate into the other outlets (especially the second) is reduced. This leads to a sharp increase in the nonuniformity of the dust distribution.

Based on the test stand work, a design for the industrial sample for the Inkou thermal power plant was developed which satisfied all the technical specifications. At present 12 of these devices are successfully in use in China.

The most complete set of industrial tests and setups of chamber and diffuser-nozzle dust separators with the new design has been carried out on five dust systems for the TPE-214 boiler at power production unit No. 6 of the Novosibirsk TÉTs-5 heat and electric power plant. These boilers are equipped with five dust systems with MMT2000/2590/750K hammer mills in which Kuznetsk grade G and D coal is ground to $R_{90} = 25 – 32\%$. The furnace layout includes a tangential ignition scheme and is equipped with sets of coal burners mounted in two layers (three layers each of coal inlets of the air mixture in the lower units of the burners and two, in the upper). The dust distribution system of the boiler is arranged in a two layer scheme (2 × 2). The chamber dust separators in the first level at two outlets are mounted right on the flanges of the mill separators and connected by 630-mm-diam dust ducts to the diffuser-nozzle dust separators of the second level, where fuel is feed to the two adjacent coal burners in one layer. The dust separators in the second layer are mounted right on the side walls of the furnace chamber approximately at the level of the corresponding row — in symmetry with the burner assemblies. This configuration and the equipment for feeding the air mixture over the dust ducts are essentially completely analogous to the configuration and equipment for the dust distribution arrangement at the boiler for unit No. 5 designed by NPO TsKTI. It should be noted that the five mills are arranged in a row in front of the boiler, which means that there is a considerable difference in the length of the dust ducts for the outermost dust systems (from 55 to 20 m).

After the boiler was brought into use, tests were conducted with the original position for the regulator inserts of all the dust distributors, which indicated sufficient uniformity of the dust distribution for the schemes with tangential burn — Δg in four of the burners was less than 17.5% in each row (Δg was 2 – 20% for 18 of the dust distributors and 30 and 32% only for two of them). However, in order to enhance the economy and reliability of the equipment, as well as to meet the strict environmental standards for a startup power production unit [19] (furnace with a three-stage fuel burning scheme), efforts were undertaken by staff from the firm JSC "SibKOTÉS," with setup arranged by the firm JSC "Inzhenernyi tsentr," at the Novosibirsk TÉTs-5 heat and electric power plant to ensure high uniformity of the dust distribution over the burners using various possibilities for controlling the feed of dust over the outlets specified in the design of the dust distributors.

The work on each of the dust systems was carried out in two stages: to start, the separators in the second level were adjusted and then, in the first (after which a correction was specified, which, tests showed was unnecessary). During the adjustment process, the major operating parameters were held constant: mill output at 20 – 25 tons/h, feed rate of drying-transport agent per mill at 55 – 65 m^3/h, and the angle of inclination of the blades of the separator installed for production of dust with R_{90} = 25 – 32% (The optimum value of R_{90} was determined for each row of burners.) After adjustment, the regulating inserts were fixed in their optimum position, which was not changed during operation afterward. The results of the adjustment are listed in Table 1. The nonuniformity index Δg for the dust separators in the second stage was less than 5.5%, for the first, 8.9%, and for the dust redistribution system as a whole (for the four burners), 4.6%; that is, performance significantly better than the standard level was obtained.

The test results confirmed the validity of the major theoretical assumptions used in creating the new designs for dust separators, primarily taking into account the existence of a stable layer of fine particle dust near the walls which moves as a unified whole, even after it has been detached in a constriction within the volume of the vessel. For example, inspection revealed that no diffuser-nozzle constrictions had been installed in the dust separators in the second level of dust system "6B." As a consequence, rotating the regulator valve in the separator over its entire range essentially had no effect on Δg and only after it was installed in an extreme position (approaching contact with the vessel wall) was it possible to obtain a significant reduction in the nonuniformity of the distribution (with a simultaneous large increase in the aerodynamic drag owing to coverage of a large part of the vessel cross section). This is evidence of the existence of a dust layer near the wall which, without a constriction, would move along the separator wall mainly into one of the outlets, while placing the edge of the valve right up against this wall ensured the destruction of this layer and made sure that part of the dust moved along its surface into another outlet.

The adjustment procedure also showed that maximum balancing of dust detached in the constriction occurs when the edge of the regulator valve is located near the theoretical center of the layer along the vessel axis, as established by calculating its trajectory in the volume as a unified whole. Thus, the layer extruded into the volume is not scattered by the gas flow, despite its high velocity (over 40 m/sec), the substantial cross section of the vessel (about 70 µm), and the fine powder composition (The mass fraction of particles finer than 100 – 120 µm is over 85 – 90%; under these conditions, at distances of less than 50 mm, individual particles of this size follow the gas streamlines after they enter the flow.)

Yet another important results should be noted. In accordance with the configuration, the axes of the regulator overhanging valves of the vertically mounted dust separators in the second layer are located in a single vertical plane with the axes of the extended (up to 20 m) supply horizontal dust ducts. At the same time, the optimum inclination for the valves in the different dust separators found during the adjustment process varies from ±5 to ±25° (Table 1). This may indicate the existence of a tangential component of the velocity of the dust layer, i.e., that it moves along a helical path. It is significant that variations in the inclination of the regulator valves within these limits has little effect on the distribution of air over the outlets (no more than 10%). Within the operating range of the regulator valves, the aerodynamic drag coefficient ξ_D is essentially independent of their inclination, which is the same for all the dust separators, and (within the outlet cross sections) equals 1.15 – 1.20 in the dusty flow (which is close to the value of ξ_D obtained for model samples).

A new approach to developing chamber-type dust-gas flow distributors is represented by the in-line separator-dust concentrator mills (DPK-SM) developed for and introduced at the P-57R boiler with a two-swirl ignition scheme (developed by the JSC "SibKOTÉS" and ZIO firms [20]) at the 500 MW power generation unit No. 2 at the Ékibastuz GRÉS-2. Six dust systems for direct injection into the P-57R boiler are equipped with type MPS-2560 in-line mills in which low grade Ékibastuz coal is milled to R_{90} = 15 – 20%. Because of the elevated aeration in these mills and the requirement of a reduced fraction of primary air (in order to suppress NOx formation) it is planned to install separator-dust concentrators after their separators; these are meant to ensure removal of drying-agent particles with a low concentration of dust from the dust-gas mixture and transfer them to special waste burners. The in-line separator-dust concentrator mills should ensure distribution of the dust-gas mixture over the five outlets:

— 90 – 93% of the fuel dust and 65 – 70% of the drying-transport agent– uniformly over the four main outlets which supply fuel dust to the main flow-through burners located in three rows;

— 30 – 35% of the gases and 7 – 10% of the dust in the waste outlet, which is connected to flow-through burners located between the main burners at the height of the second row.

The dimensions of the in-line separator-dust concentrator mills were also limited by the very crowded configuration of the boiler cell in the Ékibastuz GRÉS-2, and this made the problem much more complicated. In particular, the outgoing, inclined segment of the fuel feed pipe *1* (Fig. 14) from the coal feed to the mill had to be placed inside the vessel of the in-line separator-dust concentrator mill in the collector shell between the two outlets. It should be noted that the presence of this pipe made it possible to obtain a very interesting result regarding the mechanism by which the dust-gas moves. Both the test stand studies and the industrial tests for each of the in-line separator-dust concentrator mills of the six dust systems for the boiler in unit No. 2 at the Ékibastuz GRÉS-2 showed that dust with a significantly finer composition (R_{90} = 7 – 8%) enters the outlet lying immediately behind this pipe along the direction of twist of the flow than enters the other three main outlets (R_{90} = 16 – 19%). This indicates that, on contact with the fuel feed pipe, the larger particles mostly do not remain on its convex cylindrical surface but are detached and move back into the flow (Fig. 14, curves I), while the finer fractions move along the flow into the stable wall layer and then flow out into the outlet pipe (Fig. 14, curves II). This result is in good agreement with the experimental data on dust separators with different designs described above.

The new design was worked out on a test stand that fully modelled the industrial dust system, including a type MPS in-line mill (analogous to that in Fig. 8). Given the complexity of this problem, a large set of studies was undertaken to examine 16 variants of the DPK-SM in-line separator-dust concentrator mill. Figure 14 shows the layout of the model, which yielded performance in full compliance with the specifications and was taken as a design prototype for the industrial sample. In this variant, a truncated cone whose large base overlaps the slit in the waste pipe and prevents direct arrival of dust from the inlet pipe into the waste pipe, was installed coaxially to the waste outlet. Another important modification is regulator inserts made so that they can be rotated about vertical axes (and not horizontal, as in the previous designs), which makes possible a much more efficient interaction with the dust layer near the wall, which has a substantial tangential velocity component owing to the large angle of inclination of the separator blades (the separator is set to receive fine dust with R_{90} = 12 – 18%).

In accordance with the engineering design from NPO TsKTI, the commercial in-line separator-dust concentrator mills were fabricated by ZIO and installed on six MPS-2650 mills at boiler No. 2 of the Ékibastuz GRÉS-2. After the boiler was brought into operation, staff from Sibtekhénergo, SibKOTÉS, and UralVTI carried out setup tests of the dust system, including the dust distribution systems and equipment. The in-line separator-dust concentrator mills were tested both as separator-dust concentrators and as dust separators with the waste outlet blocked. In this case, for the initial position of the inserts (i.e., without adjustment), the nonuniformity Δg of the dust distribution for the front mills

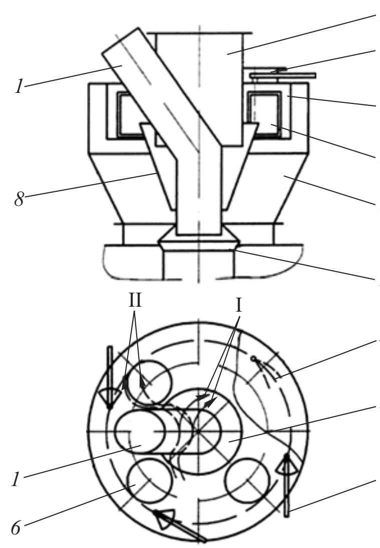

Fig. 14. Model of the separator-dust concentrator with in-line mills (DPK-SM) at power production unit No. 2 at the Ékibastuz GRÉS-2: *1*, section of the fuel feed pipe to the mill located inside the separator; *2*, splitter; *3*, vessel; *4*, collector shell; *5*, rotatable insert; *6*, outlets for the high concentration flow; *7*, levers for the inserts; *8*, shielding cone; *9*, outlet for low-dust flow (waste outlet); I, trajectories of large particles; II, trajectories of fine particles.

(Nos. 2A and 2D) was about 6.8%, and for the back and middle mills (2C, 2F, 2B, and 2E), less than 5.5%. Regulating one of the inserts makes it possible to achieve $\Delta g \sim 4.2\%$. It is important to note that the nonuniformity of the dust distribution obtained here occurs for a wide range of variation in the mill yields (30 – 70 tons/h). When the in-line separator-dust concentrator mills operate with a waste dust duct, the required performance regarding the dust and air feed rates are attained with an approximately 50% opening of the regulator blades of the outlets located after the fuel feed pipe in the mill (then $\Delta g \sim 5.0 – 8.5\%$).

After the successful trial runs with the in-line separator-dust concentrator mills at boiler No. 2 in all the dust systems of the first power generating unit at the Ékibastuz GRÉS-2, all the existing low efficiency dust separators of the old design were removed and chamber (centrifugal-counterflow) dust separators were installed.

CONCLUSIONS

1. Based on a set of scientific and technical work, including working out of models on dust system test stands and industrial studies undertaken at coal-fired 800, 500, 300, and 200 MW power generation units, new designs for regulated mixing dust-gas flow distributors — chamber (centrifugal-counterflow)and diffuser-nozzle dust separators — which offer high performance with respect to the uniformity of the fuel dust distribution over the burners, $\Delta g < 5 – 10\%$, for moderate and fine grinds ($R_{90} < 35\%$). By adjustment during startup and adjustment, Δg can be reduced to 2 – 3% if necessary.

2. Chambered dust distributors are best installed directly after the centrifugal separators of hammer and in-line mills (as was done at the Novosibirsk TÉTs-5 heat and electric power plant, the Ékibastuz GRÉS-2 state regional electric power plant, and the Suichun and Inkou thermal power plants). In this case, a blade swirler is not required at the inlet of the dust distributor because the dust-gas mixture after the separator has a residual rotation after it has been brought to rotation by the blade apparatus (in the case of a sufficiently fine dust). Using the energy of the rotating flow after the separator reduces the aerodynamic drag of the dust separator and enhances its efficiency.

3. Diffuser-nozzle regulated dust separators on two-three outlets provide (by simple adjustment at the start) extremely high uniformity of the dust distribution (up to $\Delta g = 0.5 - 1\%$) without having a significant effect on the distribution of air over the outlets and on the amount of aerodynamic drag. They are best installed as a second stage immediately at the walls of the furnace chamber roughly at the level of the corresponding row of burners (the scheme employed at the Suichun thermal power plant and the Novosibirsk TÉTs-5). This configuration ensures high uniformity, both with respect to the fuel and to the primary air, as well as savings of capital and operating costs by reducing the number of dust ducts from each mill.

4. Tests of chamber (centrifugal-counterflow) separator-concentrators of the in-line mills at unit No. 2 of the Ékibastuz GRÉS-2 showed that they supply fuel dust efficiently with a specified different concentration into the different burner structures while simultaneously providing the required level of uniformity of dust feed over the main burners (including for an extremely fine grind with $R_{90} = 12 - 20\%$). This is especially important for meeting strict modern environmental standards (including arrangements for two- and three-step combustion of the fuel), as well as for installations with above- and super-critical steam parameters (which do not permit even slight temperature distortions in the furnace).

5. The mechanism whereby fine dust moves in the form of a stable layer was confirmed experimentally, under both test stand and industrial conditions, in the region near the walls of the equipment, as well as after the flow had been extruded into the flow volume at a constriction, when the dust layer changes its direction of motion only slightly, is not scattered significantly by the gas (for flow velocities of up to 40 m/sec), and moves mainly as a unified whole until it strikes the wall again. In standard designs, failure to take this phenomenon into account may lead to the arrival of a substantial amount of dust at one or more of the outlets, which reduces the operating efficiency for fine dust. In the new designs for dust separators of the mixing type, the dust layer is destroyed in the volume and the concentration is balanced ahead of the outlets, so that the fuel distribution across the dust ducts is more uniform.

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