SOLUTION TO THE PROBLEM OF PRECIPITATION OF HIGH-RESISTIVITY ASHES BY ELECTROSTATIC PRECIPITATORS

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The innovative and highly effective Russian electrostatic precipitators of the ÉGAV type were created in order to solve problems associated with the reduction of ash emissions at coal power plants. The new electrostatic precipitators ensured an increase in precipitation effectiveness to 99.87% in the same overall housing sizes along with a reduction in emissions up to 16 times, with actual emissions ranging from 12.6 to 119 mg/m^3 (under standard conditions). The technical solutions for intensifying electrostatic precipitation realised in ÉGAV precipitators increase particle drift velocity to the precipitating electrode by 65%. The application of the ÉGAV type electrostatic precipitators for removing high-resistivity ashes from flue gases led to the required reduction of emissions during the modernization of the acting electrostatic precipitators. The cost of reconstructing the gas-cleaning unit with the application of innovative electrostatic precipitators turned to be less than with the use of a combined electrostatic precipitator or a bag filter. The new electrical cleaning technology also formed a scientific basis for the innovative development of other promising gas-cleaning technologies.

Keywords: electrostatic precipitator; high-resistivity ash; drift velocity; ash emissions.

One of the priority tasks associated with the ecological situation in Russia involves the removal of the solid ash particles from flue gases. To a certain degree, the success of the national Ecology project as part of the Pure Air and Implementation of the Best Available Technologies (BAT) federal projects depends on the solution of this problem.

According to ITS BAT 38-2017 [1], around 600 power units using coal as the basic fuel are applied in Russia. For the last 10 – 15 years, the proportion of gross emissions produced by combined heat and power (CHP) plants was reduced by only 30%, demonstrating the need for reconstruction work in up to 95% of CHP cleaning units. In this case, up to 70% of ash emissions are generated by large coal power plants. Thus, e.g., the Reftinskaya SDPP (State District Power Plant) emits more than 70 thousand tonnes of high-resistivity ash per year, accounting for around 12% of all CHP emissions.

The range of recorded ash emissions during the combustion of solid fuel (Table 1) shows that, for the flue gas cleaning units exploited from 2001, the actual level of the ash emissions is 150 – 400 mg/m^3 (under standard conditions). An increased level of emissions is allowed for units commissioned between 1981 and 2000. According to GOST R 50831–95 [2], this indicates the acting emission requirements (Table 1) for the currently operating gas-cleaning units (GCU) utilized in the heat-power engineering to be unimplemented or implemented at the critical level.

In European countries, the emission norm directive of 2010/75/ES requires the filtration effectiveness at electrical stations to be ensured with a residual dust content of 10 – 20 mg/m^3 (under the standard conditions). This is lower than the actual level of CHP emissions in Russia by more than 10 times.

According to the recommendations published in GOST R 54204–2010 [3] regarding the application of advanced technologies for the removal of dust from flue gases at large CHP burning hard and ligneous coal, the dust emission level for both projected and currently operating enterprises is established within the limits of 5 – 30 mg/m^3 (under standard conditions) with a cleaning effectiveness of 99.5 – 99.95% and 99.95 – 99.99% for electrostatic and bag filters, respectively. Therefore, in terms of advanced technologies, electrostatic and bag filters are recommended.

For the cleaning of large volumes of flue gases, however, electrostatic precipitators are most widely used in Russian heat-power engineering.

Under such conditions, the use of contemporary and innovative Russian electrostatic precipitators of the ÉGAV

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type is expedient for cleaning of flue gases due to conformity with BAT and GOST requirements.

At the present time, the ÉGAV Russian electrical cleaning technology is at a high stage of development, leading to the production of new highly effective Russian electrostatic precipitators. The technology is based on the results of scientific research, experimental design and technological works according to the following directions [4 – 10]:

the intensification of the electrical cleaning processes:

— reduced ignition voltage technology for corona discharge is developed ensuring an increase in the tension of the electric field;

— technology for the equalization of electric field and corona current over the surface of the precipitating electrode is developed providing an increase in breakdown voltage values;

— pulse corona discharge technology in the interelectrode space is developed with the aim of increasing the limiting charge due to greater instantaneous intensity at the front of the space charge pulsations;

— the expediency of an increase in the interelectrode distance with the retention of cleaning effectiveness and reduction in the specific metal content is substantiated;

the design and production of the electrostatic precipitator construction elements created for realizing technologies aimed at intensifying electrical cleaning:

— the design of the new elements of corona electrodes is substantiated with the created technology for their production;

— the design of new precipitating electrode elements is substantiated with the created technology for their production;

— principles and technology for the manufacture of the electrostatic precipitators with a height of up to 18 m are developed;

— the optimum design of interelectrode space ensuring the maximum breakdown voltages is developed;

— the corona electrode frame is developed to reduce the semi-active zones by the height of electrode, the increased effectiveness of the dust removal under rapping, and, correspondingly, the service life under repeated impact loads;

— the optimum design parameters of the electrostatic precipitator (number of fields and interelectrode spaces, the electrode height, and interelectrode distance) are substantiated providing the maximum service life of the unit [8];

the advancement of processes improving electrical cleaning:

— principles are developed and an effective electrode rapping system is created;

— principles and designs of electrostatic precipitator units are developed along with servicing regulations allowing the operating electrostatic precipitators to retain cleaning effectiveness under prolonged operation [9, 10];

— a calculation procedure of the gas distribution system is developed with design solutions for an increase in the effectiveness of electrostatic precipitator;

— a method of calculating the rapping mode of electrode systems according to the electric fields of electrostatic precipitator is developed. The application of calculation results ensures the electrostatic precipitator operated in the increased power supply modes and the long service life of mechanical designs.

A constant increase in the technical level of electrostatic precipitators of the ÉGAV type allowed outstanding problems to be solved leading to a considerable reduction in CHP emissions. Table 2 represents the results of tests regarding the effectiveness of the electrostatic precipitators made by the ÉGAV technology during the reconstruction and new construction of GCU.

According to the analysis of data presented in Table 2, the following conclusions can be drawn:

TABLE 1. Technical Level and Requirement for the Ash Emissions at Russian CHPs, Recommendations Regarding the Application of Advanced Cleaning Technologies

Regulating document	Boilers of the thermal output, MW		
	50 – 100	100 – 300	over 300
[1], actual emission range (O_2 = 6%), mg/m^3, for GCU commissioned:			
before 1981	1500 – 2000	1400 – 2000	1300 – 2000
before 2000	600 – 1300	400 – 1300	300 – 1400
since 2001	250 – 450	200 – 400	150 – 350
[2], emission requirements for GCU commissioned before 31.12.2001 (since 01.01.2001), mg/m^3	150 – 500 (150 – 250)	100 – 400 (50 – 150)	
[3], recommendations regarding the application of BAT for cleaning flue gases at large CHPs burning coals:			
the dust emission level for enterprises, mg/m^3:			
projected	5 – 20	5 – 20	5 – 10
operating	5 – 30	5 – 25	5 – 20
cleaning effectiveness for the enterprises burning coals, %:			
hard and ligneous	≥99.5% (electrostatic precipitator), ≥99.95% (bag filter)		
ligneous, low-calorie	≥99.95% (electrostatic precipitator), ≥99.99% (bag filter)		

Notes. (1) GCU are gas-cleaning units; (2) emission values are provided for the standard conditions.

— the effectiveness of cleaning flue gases in heat-power engineering achieved by the ÉGAV electrostatic precipitators ensures, in the same overall sizes, the reduction in the emissions by 7 – 16 times with respect to previously-used technologies;

— the cleaning effectiveness comprises the value of 99.52 – 99.87%, therefore meeting the BAT recommendations (99.5% and higher);

— the proposed type of electrostatic precipitator ensures output dust content at the level of 12.6 mg/m^3 (under standard conditions), demonstrating the possibility of decreasing the influence of semi-active zones using the design solutions;

— the level of emissions ranges from 12.6 to 119 mg/m^3 (under standard conditions). In order to guarantee missions of 5 – 30 mg/m^3, an increase in the overall sizes of the units is proposed in addition to the electrical cleaning technologies. The positive experience of development and introduction of electrostatic ash precipitator for the flue gas volume of more than 2, 000, 000 m^3/h (Table 2, pos. 6) allowed problems associated with an increase in the active volume of units to be solved.

Results of the conducted investigations into an increase in the effectiveness of electrostatic precipitators and their practical introduction into industrial gas-cleaning units (Table 2) resulted in measures being carried aimed at reducing ash emissions with high (>10^8 $\Omega \cdot$ m) specific electrical resistivity (RES). In heat-power engineering, high-RES ashes are formed during the combustion of Ekibastuz and Kuznetsk coals.

Previously, it was proposed to solve the problem of high-RES coal ash removal from flue gases by increasing the retention time of gases in the active region of the electrostatic precipitator [11]. For this, it is recommended that the height of electrode systems be increased to 18 m, with the number of fields reaching the value of 5 – 7. Thus, according to the results of the data evaluation in [11, Table 3], an increase in the retention time by 1.39 times leads to a reduction in the emissions by 8 times (from 400 to 50 mg/m^3). Under an increase in retention time, the cost of the unit and its equipment increases almost proportionally. Consequently, the proposed design method for the highly-effective removal of high-resistivity ashes from flue gases will require a considerable increase in expenditures and cannot always be realized under the conditions of limited space for installing an electrostatic precipitator both during reconstruction of existing GCUs and when constructing new units. Moreover, the cost of such electrostatic precipitators is higher by 1.38 times than the cost of the combined electrostatic precipitator and by 1.23 times higher than the cost of bag filters [11, Table 4].

In this connection, taking into account the effectiveness of cleaning in the lamellar electrostatic precipitator to depend both on gas retention time and on the drift velocity of particles according to the formula (variant of the Deutsch – White formula [12]):

$$\eta = 1 - \exp(-w t_{\text{ret}}/h_0), \tag{1}$$

where η is the cleaning effectiveness; w is the drift velocity of particles to the precipitating electrode; t_{ret} is the gas retention time in the active region; h_0 is the distance between the corona and precipitating electrodes, a further increase in the effectiveness of electrostatic precipitator can be accomplished by intensifying the process of electrical cleaning and increasing drift velocity.

Table 3 contains the basic technical solutions for reducing emissions in CHP flue gas cleaning by increasing the drift velocity in the electrostatic precipitator.

Data analysis of Table 3 demonstrates the new (protected by Russian Federation patents) technical solutions for the separate and assembly units of electrostatic precipitators to ensure the decrease in emissions by 1.5 – 2.2 times. In addition, an increase in the active volume of the electrostatic precipitator (Table 3, pos. 5) provides, in addition to the technical solutions for individual units, a decrease in emissions by 1.9 – 2.6 times, which is necessary for electrostatic precipitators when collecting ash with a high specific electrical resistivity (Table 4).

According to the data analysis of Table 4, the following conclusions can be drawn:

— the efficiency of the flue gas cleaning from high-RES ash obtained by ÉGAV electrostatic precipitators ensures a

TABLE 2. Gas Cleaning Effectiveness by the ÉGAV Electrostatic Precipitators in Heat-Power Engineering

No.	Object of reconstruction or construction	Inter-electrode space, mm	Gas volume, m^3/h	Efficiency, %/residual dust content, g/m^3		Reduction in the emissions, times
				before the reconstruction	after the reconstruction	
1	Omsk CHPP-5 (reconstruction in the same overall sizes)	350	612,000	97.9/1.47	99.83/0.119 (2009)	12.35
2	Novosibirsk CHPP-4 (reconstruction with an increase in the overall sizes)	400	850,000	98.0/0.420	99.83/0.024 (2015)	11.76
3	Krasnokamenskaya CHPP (reconstruction in the same overall sizes)	400	256,000	97.9/0.150	99.70/0.037 (2014)	7.00
4	Krasnoyarsk CHPP-4 (new construction)	460	340,000	99.56/0.05	99.7/0.041 (2012)	1.47
5	“KrasMash” Boiler (new construction)	400	520,000	98.7/0.052	99.52/0.0126 (2011)	2.71
6	“Vung Ang” CHP, Vietnam (new construction)	400	2,120,000	99.68/0.120	99.87/0.087 (2014)	2.46
7	Novo-Irkutsk CHPP (reconstruction in the same overall sizes)	400	808,000	97.9/0.378	99.87/0.022 (2015)	16.15

Note. Values of residual dust content are provided for the standard conditions.

decrease in emissions up to 12.35 times in relation to the previously used electrostatic precipitators of EGA type (EGB, EGBM, EGB1M, etc.);

— the proposed type of electrostatic precipitator (ÉGAV) should be promoted for practical solutions aimed at achieving a residual dust content at the level of 24 mg/m^3 for the ash of Kuznetsk coals and not more than 150 mg/m^3 (under normal conditions) for the ash of Ekibastuz coals;

— electrostatic precipitators of the ÉGAV type meet the requirements of customers in reduced emissions when precipitating ash generated during the combustion of Ekibastuz and Kuznetsk coals, even during the reconstruction of existing electrostatic precipitators. An even greater effect on reducing emissions can be obtained as part of the development and new construction of the GCU.

Based on the results of industrial tests of electrostatic precipitators (Table 4, pos. 5), the drift velocity was estimated using formula (1) with the following comparison of this velocity to that calculated by the same formula using the data of [11, Table3]. Comparison of the drift velocities showed that, due to the intensification of electrical cleaning processes (Table 3), the drift velocity of particles to the precipitating electrode increased by 1.65 times, which is commensurate with the decrease by the same amount in the dimensions of the electrostatic precipitators proposed according to [11, Table 3] for ensuring the required residual dust content when precipitating high-resistivity ash. The cost of

TABLE 3. Main Technical Solutions for an Increase in the Effectiveness of CHP Electrostatic Precipitators

No.	Technical solution	Realization, patent, the year of the introduction of the technical solution	Effectiveness parameters of the electrostatic precipitator	
			drift velocity increase, %	reduction in the emissions, times
1	Reduction in the ignition voltage of the corona discharge	Production of the corona electrode element with a minimum curvature radius, RU2448779 [13], since 2012	Up to 20	2.2
2	Increase in the breakdown voltage	New technology for the production of precipitating electrode elements for preventing end breakup, RU2377071 [14], since 2009	Up to 10	1.5
		Optimum arrangement of electrode system elements with the guarantee of a minimum distance to the profile plane side of the precipitating electrode element, RU2655691 [15], since 2018	Up to 10	1.5
3	Reduction in the semi-active zones	Production of corona electrodes with a minimum number of link-up points of separate frames by height, RU2694661 [16], since 2019	Up to 12.5	1.64
4	Pulse mode of power supply of the electrostatic precipitator	For electrostatic precipitators collecting high-RES ashes, since 2019	Up to 10	1.5
5	Increase of the active volume of electrostatic precipitator “in the plan” for the precipitating high-RES ashes	Designs are implemented with an increase in the active height of electrodes by 25% (from 12 to 15 m), RU2377071 [14], since 2013	—	2.6
		Designs are implemented with an increase in active field length to 16.6% (from 3.84 to 4.48 m), RU2211094 [17] since 2003 and RU2694661 [16] since 2019	—	1.9

TABLE 4. Test results of ÉGAV electrostatic precipitators utilized for removal of ashes from flue gases during the combustion of Ekibastuz and Kuznetsk coals

No.	CHP	Boiler		N_0, mm	Design gas volume per one electrostatic precipitator, m^3/h (gas temperature, °C)	Efficiency, %/residual dust content, g/m^3		Reduction in the emissions, times	
		Power, MW	Coal			before the reconstruction (according to the project)	maximum result after reconstruction (year of testing)	after the reconstruction	according to the project
1	Omsk CHPP-5 (block st. No. 3)	150	Ekibastuz	350	419,000 (137.0)	97.9/1.47 (99.5/0.350)	99.83/0.119 (2009)	12.35	2.94
2	Novosibirsk CHPP-4 (block st. No. 11)	300	Kuznetsk	400	510,000 (148.5)	98.0/0.420 (99.76/0.05)	99.83/0.024 (2015)	11.76	2.1
3	“Vung Ang” CHP, Vietnam	660	Similar to Kuznetsk	400	1,056,000 (137.0)	New construction (99.68/0.120)	99.87/0.087 (2014)	New construction	2.46
4	Reftinskaya SDPP (block st. No. 1)	300	Ekibastuz	400	349 200 (up to 150)	97.80/1.200 (99.59/0.250)	99.62/0.234 (2018)	5.79	1.07
5	Reftinskaya SDPP (block st. No. 9)	500	Ekibastuz	400	Project — 941,000 (up to 190), actual — 1,174,560 (167.1)	98.60/0.854 (99.75/0.150)	99.79/0.135 (2018)	6.67	1.11

the electrostatic precipitator is also commensurably reduced by 1.65 times, thus becoming cheaper than the combined electrostatic precipitator and bag filter [11, Table 4]).

The proposed design solutions for new electrostatic precipitators are interchangeable with units of the EGA type (EGB, EGBM, EGB1M) developed before 2001. At the same time, for obtaining the required residual dust content, no additional area is required "in plan" and the height of the electrode systems can be limited to 12 – 15 m.

The experience of the reconstruction of existing electrostatic precipitators, both by increasing the unit height and developing a new housing in place of the two previous electrostatic precipitators, supports the conclusion concerning the necessity of evaluating efficiency and taking measures not only for replacing the internal equipment of the electrostatic precipitators, but also for the distribution of the dust and gas flow over the cross section of the electrostatic precipitator at the inlet and outlet, as well as on increasing the efficiency and reliability of dust rapping devices due to the increased amount of dust entering the bunker. Consequently, when implementing new electrostatic precipitators, a thorough analysis of the processes providing effective cleaning in an electrostatic precipitator should be conducted at the level of the gas cleaning unit as a whole.

Thus, in order to reduce CHP emissions up to 10 times or more, it is are sufficient that new, effective, and proven technical solutions be applied implemented in the design of ÉGAV-type electrostatic precipitators. During the reconstruction of CHP GCU using new electrostatic precipitators, the existing housings (if necessary, with an increase in height and refinement of gas distribution) and foundations (if necessary, with reinforcement) are retained, with the consequent capital costs for reconstruction being significantly less than under the application of a combined electrostatic precipitator or bag filter.

The positive results of the application of the new electrical cleaning technology implemented in ÉGAV electrostatic precipitators became the scientific basis for the creation of new cleaning methods (RU 2619701 [18]) and a new promising class of gas cleaning equipment. Thus, for gas cleaning from the dust difficult to be collected by electrostatic precipitators, the design of a combined electrostatic precipitator (or hybrid filter) was developed, consisting of two cleaning stages: the first represented by an electrostatic precipitator in the volume of one field with a cleaning efficiency of up to 90%, and the second including a bag filter also in the volume of one field of the electrostatic precipitator. The result is a synergistic effect from the merger of two cleaning technologies with an industrial unit offering high cleaning efficiency combined with compactness and low operation cost (RU 2419478 [19]). In addition, on the basis of the development of electrical cleaning technology, prospects have emerged and research work has been carried out for creating an integrated air cleaning device for air cleaning of gas turbine plants based on an electrostatic precipitator (RU 2644004 [20] and RU 2651391 [21]) instead of fine filters. The advantages of this technical solution include the reduction of operating costs due to a decrease in hydraulic resistance, an increase in the efficiency of air purification, reliability during operation, and, as a consequence, reduced losses in the turbine efficiency, power generation and capacity of gas turbine plants.

CONCLUSIONS

1. During the present study, the solution of problems related to a reduction in ash emissions during the operation of coal plants up to 10 times or more is shown to be possible under the application of Russian-designed ÉGAV high-performance electrostatic precipitators developed on the basis of a complex of research, development, and technological work.

2. According to the results of industrial implementation of ÉGAV-type electrostatic precipitators in heat power engineering during the reconstruction and new construction of the GCU, a 16-fold decrease in emissions in the same dimensions of the housing was demonstrated. At the same time, cleaning efficiency is ensured at the level of 99.52 – 99.87%, with emissions ranging from 12.6 to 119 mg/m^3 (under normal conditions) to meet the requirements of BAT and GOST. Additionally, with an increase in the size of the electrostatic precipitator, a stable achievement of the level required by European standards is possible (<20 mg/m^3).

3. Technical solutions on the intensification of the electrostatic precipitation realised in ÉGAV precipitators are shown to provide an increase in particle drift velocity to the precipitating electrode to a value of 65%.

4. The advantages of using a new ÉGAV electrostatic precipitator for solving the problem of cleaning flue gases from high-resistivity ash have been demonstrated. The required cleaning efficiency is provided during the reconstruction of operating GCUs. In addition, the cost of the electrostatic precipitator appears to be less as compared with the combined electrostatic precipitator or bag filter.

5. The created novel electrical cleaning technology is shown to form the scientific basis for the innovative development of promising gas-cleaning equipment.

REFERENCES

1. *ITS NTD 38–2017. Combustion of Fuel in Large Plants for the Purpose of Power Generation: Information and Technical Guide to the Best Available Technologies* [in Russian], Bureau of NTD, Moscow (2017).
2. *GOST R 50831–95. Boiler Units. Thermal Mechanical Equipment. General Technical Requirements* [in Russian], IPK Izd. Standartov, Moscow (1996).
3. *GOST R 54204–2010. Resource Saving. Black and Ligneous Coals. Best Available Technologies of Combustion* [in Russian], Standartinform, Moscow (2011).
4. L. V. Chekalov, *Scientific Foundations for Creating a New Generation of Electric Gas Cleaning Equipment. Author's Abstract of Doctoral Thesis* [in Russian], Moscow (2007).

5. L. V. Chekalov, “Analysis of the electrostatic precipitator operation at a high concentration of a finely dispersed phase,” *Khim. Neftegaz. Mashinostr.*, No. 3, 27 – 30 (2016).
6. L. V. Chekalov, V. A. Guzaev, M. E. Smirnov, I. P. Vereshchagin, S. I. Khrenov, K. A. Smagin, and E. M. Timofeev, “New Russian electrostatic precipitators and modernization of existing electrostatic precipitators for increasing the efficiency of ash collection,” in: *Proc. Int. Sci.-Pract. Conf.* “*Coal Eco-2016*”, pp. 139 – 147 (2016).
7. L. V. Chekalov, M. E. Smirnov, and V. A. Guzaev, “A new generation of electrostatic precipitators and a solution to the problem of collecting high-resistivity ash,” in: *Proc. Int. Sci.-Pract. Conf.* “*Ecology in Energy*”, pp. 50 – 56 (2019).
8. V. A. Guzaev, “The influence of the mechanical equipment durability on the efficiency of electrostatic precipitators,” *Khim. Neftegaz. Mashinostr.*, No. 7, 29 – 31 (2014).
9. *V. A. Guzaev, Status and Prospects for Increasing the Reliability of Electrostatic Filters. Overview Information. Series KhM-14. Industrial and Sanitary Gas Treatment* [in Russian], TsINTI-khimneftemash, Moscow (1991).
10. V. A. Guzaev, “The main directions of increasing the durability of electrostatic precipitators,” *Khim. Neftegaz. Mashinostr.*, No. 11, 46 – 48 (2013).
11. I. P. Vereshchagin, P. S. Platonov, G. I. Subbotina, et al., “Flue gas cleaning from coal ash by high electrical resistivity,” *Élektr. Stantsii*, No. 10, 28 – 33 (2010).
12. L. V. Chekalov (ed.), *Ecotechnics. Protection of Atmospheric Air from Dust, Aerosols, and Fog Emissions* [in Russian], Rus’, Yaroslavl’ (2004).
13. RF Pat. No. 2448779, L. V. Chekalov, M. E. Smirnov, and Yu. I. Sanaev, “Corona electrode,” publ. 04/27/2012, *Byull. Otkryt. Izobret.*, No. 12 (2012).
14. RF Pat. No. 2377071, L. V. Chekalov and S. A. Shaposhnik, “Manufacturing method for collecting electrode elements of electrostatic filter,” publ. 12/27/2009, *Byull. Otkryt. Izobret.*, No. 36 (2009).
15. RF Pat. No. 2655691, L. V. Chekalov, V. A. Guzaev, and M. A. Kopanskov, “Electrostatic precipitator,” publ. 05/29/2018, *Byull. Otkryt. Izobret.*, No. 16 (2018).
16. RF Pat. No. 2694661, L. V. Chekalov, V. A. Guzaev, and M. E. Smirnov, “Electrostatic precipitator,” publ. 07/16/2019, *Byull. Otkryt. Izobret.*, No. 20 (2019).
17. RF Pat. No. 2211094, L. V. Chekalov and V. A. Guzaev, “Electrostatic precipitator,” publ. 08/27/2003, *Byull. Otkryt. Izobret.*, No. 24 (2003).
18. RF Pat. No. 2619701, L. V. Chekalov and V. A. Guzaev, “Gas cleaning method,” publ. 05/17/2017, *Byull. Otkryt. Izobret.*, No. 14 (2017).
19. RF Pat. No. 2419478, L. V. Chekalov and Yu. I. Sanaev, “Combined electrostatic precipitator,” publ. 05/27/2011, *Byull. Otkryt. Izobret.*, No. 15 (2011).
20. RF Pat. No. 2644004, L. V. Chekalov, “Air cleaning gas turbine unit,” publ. 02/06/2018, *Byull. Otkryt. Izobret.*, No. 4 (2018).
21. RF Pat. No. 2651391, L. V. Chekalov and Yu. I. Sanaev, “Air treatment device for gas turbine installations,” publ. 04/19/2018, *Byull. Otkryt. Izobret.*, No. 11 (2018).