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The contribution of individual heat sources to air pollution in Siberian cities and its reduction by household electrostatic precipitators

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Abstract. The aim of the study is to justify the feasibility of using household electrostatic precipitators (ESPs) to reduce particulate emissions from individual heat sources (IHS) in Siberian cities, using Ulan-Ude as a case study. The object of the study is particulate emissions from private coal- and wood-fired boilers and furnaces. Methodology includes field measurements of flue gas dust content (aspiration method, thermoanemometry), Deutsch formula calculations, laboratory ESP modelling with fly ash, and particle size distribution analysis. Average IHS flue gas dust concentration is 1.0 ± 0.2 g/m³ at a flow rate of 260 ± 70 m³/h; equipping 50% of coal-fired boilers with ESPs (99% efficiency) would reduce particulate emissions by 3000–4000 t/year. The developed two-zone ESP with power consumption of ~315 W and dimensions of 1.4×0.45×0.7 m can be integrated into the chimney of a private house instead of a standard section.

Keywords: atmospheric emissions, fly ash, atmospheric pollution, electrostatic precipitator, Deutsch formula, corona discharge, Ulan-Ude

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Вклад источников индивидуального теплоснабжения в загрязнение воздуха городов Сибири и его снижение бытовыми электрофильтрами

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Аннотация. Цель исследования — обоснование целесообразности применения бытовых электрофильтров для снижения выбросов твердых частиц от индивидуальных источников теплоснабжения (ИИТ) в городах Сибири на примере Улан-Удэ. Объект исследования — выбросы твердых загрязняющих веществ от частных котельных и печей, работающих на угле и дровах. Методология включает натурные измерения запыленности дымовых газов (аспирационный метод, термоанемометрия), расчет по формуле Дейча, лабораторное моделирование электрофильтра с золовым уносом и анализ гранулометрического состава. Средняя запыленность дыма ИИТ составляет 1,0 ± 0,2 г/м³ при расходе 260 ± 70 м³/ч; оснащение 50 % угольных котельных электрофильтрами с эффективностью 99 % позволит снизить выбросы твердых частиц на 3000–4000 т/год. Разработанный двухзонный электрофильтр с потребляемой мощностью ~315 Вт и габаритами 1,4×0,45×0,7 м может быть интегрирован в дымоход частного дома взамен стандартной секции.

Ключевые слова: выбросы в атмосферу, золовый унос, загрязнение атмосферы, электрофильтр, формула Дейча, коронный разряд, Улан-Удэ

Вклад авторов. *Калашников С.В.* — концептуализация. *Номоев А.В.* — ресурсы, получение финансирования. *Чимытов Т.А.* — создание черновика рукописи. *Южаков И.А.* — проведение исследования. *Самбуу М.* — проведение исследования, верификация данных. *Цырен-Очир С.-Э.* — формальный анализ. Все авторы ознакомлены с окончательной версией статьи и одобрили ее.

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Introduction

It hardly deserves a separate mention that the human need for clean air to breathe is paramount. There are 39 cities in the Siberian (SFD) and the Far Eastern Federal District (FEFD), with more than 7 times higher than the integrated index of atmospheric air pollution according to data from Rosgidromet for 2024[1] [1]. In industrial cities, large industrial enterprises are usually the main sources of air pollution. In many cities with no connection to the natural gas pipeline, exceeding permissible concentrations of pollutants is due to the significant contribution of individual heat sources (hereinafter — IHS) operating on coal or wood. 12 regions of Siberia and the Far East have no natural gas pipeline at all, in 3 regions less than 20% of the population are connected to gas, and in 7 sub-regions less than 10% [2]. The highest rate of gasification in these districts — 27.1% in the Tyumen region.

At the same time, the share of individual housing construction (IHC) in the total housing introduction for the Siberian Federal District in 2023 is on average 61.3% [3], for the Far Eastern Federal District — 56%. In recent years, there has been an increasing trend in the share of IHC, most of which is introduced in cities and their agglomerations, increasing emissions into the atmosphere.

Significant exceedance of air pollution standards is observed in many cities of Siberia and the Far East: Bratsk, Krasnoyarsk, Novokuznetsk, Norilsk, Omsk, Irkutsk, Chita, Gusinoozersk, Selenginsk, Ulan-Ude, Kyzyl, Abakan, Chernogorsk, Barnaul and others. It is also typical for cities of other countries, such as Ulan-Bator.

Let us consider the case of Ulan-Ude, a city with one of the highest levels of air pollution in the FEFD, and which is characterized by a wide range of reasons for this situation. In Ulan-Ude there are, according to various data, from 37 [4] to more

[1] *Review of the state and pollution of the environment in the Russian Federation for 2024*. Moscow: Rosgidromet; 2025. Available from: https://www.meteorf.gov.ru/upload/iblock/88f/%D0%9E%D0%B1%D0%B7%D0%BE%D1%80%20%D0%B7%D0%B0%202024%20%D0%B3%D0%BE%D0%B4_300625.pdf?ysclid=mrachsi2wd806640418 (accessed: 05.11.2025).

than 45 (in the agglomeration — 67) thousand IHC, which are heated mostly by wood and coal, since the Republic of Buryatia has no gasification. At the same time, it is expected that the number of households will increase in the near future. In addition to industrial facilities, the city has 144 municipal and departmental boiler rooms and about 2,900 small coal boilers at warehouses, production, and commercial facilities [5]. This leads to well-known problems with air pollution during the winter period and deteriorating health of residents.

In 2024, Ulan-Ude recorded a concentration of benzene(a)pyrene exceeding the MPC by up to 38.8 times, formaldehyde 3.7 times, suspended solids 2.4 times, finely dispersed suspended particulates up to 10 μm and up to 2.5 μm 1.4 times (each), phenol 1.3 times, ozone 1.2 times [2] [6]. Ulan-Ude is among the ten cities in Russia with the highest level of atmospheric air pollution.

To a considerable extent, the unfavorable state of atmospheric air in the city is due to the presence of a large number of private households with heating coal and firewood, from which the smoke does not pass high into the atmosphere, and as a result of temperature inversion falls over the ground. Being decentralized sources, this category is the most difficult in terms of its environmental reform. Any measures in this direction are very costly either for the city budget (organization of district heating, modernization of electricity grids), or for private households themselves (switch to electric heating, liquefied gas, fuel briquettes, etc.).

In general, the high gas contamination due to the expansion of IHC is non-intrusive for Ulan-Ude and primarily caused by the lack of gas infrastructure, so the study is not limited to the selected city, although it was developed on its example [7].

It is assumed that the development, construction and use of specialized electrostatic precipitators in private boiler houses will lead to a significant reduction of polluting emissions in some cities of Siberia.

The aim of the study is to analyze IHS operating modes, sketch a model of an electrostatic precipitator for them, and analyze the technical-economic feasibility of their application.

Study of the total contribution of individual heat sources (IHS) to air pollution

According to the data of the “Institute for Design, Ecology and Hygiene” LLC, which, at the request of the Ministry of Nature of the Republic of Buryatia, carried out an ecological study of air pollution in Ulan-Ude, the predominant sources of

[2] State report “On the state and protection of the environment of the Republic of Buryatia in 2023”. Ministry of Natural Resources of the Republic of Buryatia, 2023. Available from: https://egov-buryatia.ru/mpr/files/%D0%93%D0%94%202023.pdf (accessed: 24.01.2025).

polluting emissions are industrial facilities (about 40%), individual sources of heat (about 55%) and transport (no more than 5%) [8]. Similar data were obtained by researchers of BIP SO RAS [4; 9]. In other cities with a high IHC and no backbone gas, the emissions ratio will certainly be different, but the IHS share will be significant in any case. Growing private sector — residential quarters consisting of houses with autonomous small coal boilers and wood-burning stoves — is the main source of air pollution in several dozen cities of Siberia and the Far East.

The main air pollutants in Ulan-Ude are solids, sulphur dioxide and carbon monoxide, which together account for 86–88% [5; 7]. It can be assumed that coal-fired IHSs emit no less particulate matter into the air in terms of ratio than municipal boilers, but in a larger absolute value. To assess the dustiness of smoke gases from private boiler houses, the authors of the work carried out a measurement of ten IHS units equipped with solid-fuel boilers: ZOTA "Cuba" (25 kW, on coal), KO 40GK (20 kW, on coal), "Siberia-GEFEST" KW 15 TE (15 kW, on coal), Wirt Smart+ (15 and 25 kW, on coal), Pixel (8 kW, on firewood) and with two, manufactured by private enterprises (with a capacity of about 20 kW, on coal and on firewood).

Measurements were made by the aspirational method. Smoke was taken from the boiler exhaust pipe by an aspirator for a period of $t = 5$ minutes, and the mass difference of the filter before and after sampling was used to determine the mass of solid particles in the ozone. The smoke consumption of boilers was calculated by measuring the diameter of its drainpipe and the flow rate with a tachometer. Using the data obtained, smoke dust was calculated.

According to the results of measurements and calculations for December 2024, with an average outdoor air temperature of −18.7°C, the average dust from IHS was 1 0.2 g/m^3, and the average smoke flow rate — 260 70 m^3/h. According to the study [3] in Ulan-Ude, the share of houses with IHS in the form of stoves is 77.7% and 22.3% — in the form of boilers. Based on the total number of houses, which is 45 thousand, it appears that about 10 thousand of them are equipped with boilers. The heating season lasts 7.8 months, assuming at least 4 months. (2880 h) of which the boilers are operating in a mode close to that defined in December, and that they are on average close to our sample by performance, so for one year they are released into the air 10 000 × 2880 h × 260 m^3/h ≈ 7,5 billion m^3 of fume, containing 7,5 billion m^3 × 1 g/m^3 ≈ 7500 t particulate matter of carcinogenic substances. The calculation may be overstated, but in any case it is thousands of tons of ash from IHS alone equipped with solid fuel boilers that are released and precipitated in the city and suburbs. In addition, according to the authors [4], the private sector emits about 48.6 thousand tons of pollutants per year (this includes gaseous substances), so our estimate seems quite realistic.

Analysis of methods for reducing emissions from HIS

It is possible to solve the IHS air pollution problem when using smokeless fuel, switching to electric heating or gas heating, when transferring loads from small boiler rooms to thermal power plants. These activities are costly projects with long lead times. In order to reduce emissions from large boiler houses, the federal "Clean Air" programme under the national "Environmental Welfare" project is currently carrying out activities in a number of cities, including an increase in the share of electric vehicles, closing or equipping municipal boiler houses with electrostatic precipitators, etc. However, the substantial share of emissions, as shown above, is produced by IHC, and to reduce this share it is most often proposed to switch to electric heating, which requires high investment. However, given the high cost of electricity in many regions, a full transition from heating of IHC to electric heating seems quite optimistic — many homeowners are certain to continue using solid fuel.

An alternative may be to equip the IHS with affordable smoke purification devices. Contaminated gas can be cleaned in various ways: mechanically, in the field of force, by dry and wet means, etc. Mechanical cleaning (filtration) creates high flow resistance and high replacement element costs. The most common means of cleaning in a field of force include cycles that use inertial forces to remove particles from the flow, and electrostatic precipitators that act on pre-charged particles of an electric field contaminant. Cyclones have a high resistance, require high flow speeds and can only work with smokestacks, which are most often absent in small boiler rooms. The electric filter is devoid of such shortcomings, but at the same time it is complicated and expensive, requiring a source of electricity supply.

These methods remove only solid particles from the smoke, but they also have a smog effect on the city; moreover, these particles adsorb many dangerous carcinogens such as benzpine. Therefore, cleaning smoke from soot particles is very non-toxic, especially since it is technically easier to do than cleaning smoke from harmful gases.

Thus, the most advanced and applicable for domestic conditions that does not require major changes in private boiler houses is a cleaning system using a small electrostatic precipitator. The amount of smoke emitted by a private boiler room is small, it should be expected that the household electrostatic precipitator must have low dimensions, low power consumption and cost.

Electrostatic precipitators are available from manufacturers or for use in kitchen, communal or industrial premises (Table). The first have a low capacity (up to 4000 m^3/h) [9], are designed for indoor installation and are combined with other types of filters. Such units do not have automatic cleaning systems and storage of collected dust, therefore require periodic washing. Industrial electrostatic precipitators are characterized by high throughput (70–430kt m^3/h), very large dimensions, cost, energy consumption and mass — a class of aggregates that goes beyond the scope of the topic.

Russian and some foreign manufacturers of electrostatic precipitators, their performance and purpose

<table>
<tr><th>Manufacturer</th><th>Productivity, m³/h</th><th>Gas temperature, °C</th><th>Purpose</th></tr>
<tr><td>LLC NPP Yatagan</td><td>1000–4000</td><td>10–200</td><td rowspan="3">For industrial or domestic kitchen cooking</td></tr>
<tr><td>LLC “Plant Ecostrada”</td><td>3000</td><td>no data</td></tr>
<tr><td>Pro-welding LLC</td><td>1000–4000</td><td>no data</td></tr>
<tr><td>Fingo-complex LLC</td><td>50000–2000000</td><td>10–425</td><td rowspan="2">For industrial or domestic kitchen cooking</td></tr>
<tr><td>HC “Condor Eco”</td><td>14000–300000</td><td>up to 330</td></tr>
<tr><td>BotonAir (China)</td><td>до 30000</td><td>no data</td><td>For industrial food preparation in the kitchen, and some types of industrial production</td></tr>
<tr><td>Dürr Systems (Germany)</td><td>до 1000000</td><td>no data</td><td rowspan="2">Dedusting gases in various industries</td></tr>
<tr><td>F.L. Smidth Airtech (Denmark)</td><td>50000–2000000</td><td>no data</td></tr>
</table>

Source: compiled by S.V. Kalashnikov, A.V. Nomoev.

However, extensive research in recent years has confirmed the technical feasibility and effectiveness of micro-electric filters for small boiler houses. In particular, [10] presents the results of field tests of compact electrostatic precipitator in real residential homes: with stable operation of the boiler, the cleaning rate reaches 90%, and with long use by users — 70–82%, which allows significantly reducing the concentration of PM2.5 and PM10.

Electrostatic precipitator are poorly represented in the market as ready-made technical solutions for IHS. Given the need to clean flue gases, it makes sense to assess both the efficiency and economic feasibility of mass use of targeted electric filters for IHS size.

Calculation and experimental verification of an household electrostatic precipitator

The purification of gases from suspended solid or liquid particles in electrostatic precipitator is carried out under the action of electrical forces, for which an electrical charge is communicated to the particles. Charged particles are removed from the purified gas stream as a result of an electric field and precipitated on collecting electrodes.

In most applications, these steps can be performed in one work chamber [11]. In single-zone electrostatic precipitator, a series of discharge wires (collecting electrodes) are arranged between the parallel collecting electrodes — plates forming the gas channel. The electrodes are connected to a high voltage source. The thin electrode produces a crown discharge, electrons move to positively charged collecting electrodes, on the path of sitting dust particles and charging them. As a result, the electric field dust is removed from the flow and settles on plates that are cleaned by mechanical action, resulting in particles of sedimented dust falling into bunkers located at the bottom of the filter.

The degree of gas purification by the electrostatic precipitator is calculated according to Deutsch's formula [11; 12]

$$\eta = 1 - \exp\left(-\frac{\omega L}{dv}\right), \quad (1)$$

where L — length of the precipitated part of the electrostatic precipitator, m; v — flue gas flow rate, m/s; ω — average particle speed over electrostatic precipitator, m/s; d — the distance between the corona and collecting electrode, м. By setting this d, v and ω, you can calculate the length of precipitator.

The cleaning rate for industrial electrostatic precipitators is 98–99% [13], which is quite high. It is advisable to set the precipitator of the IHS value $\eta = 0{,}99$.

The shorter the distance between the corona and collecting electrode d, the higher the other equal electrostatic precipitator retention, but this is limited by the electrical strength of the discharge interval and at a normal supply voltage of 50 kV it shall not be less than 100 mm [11; 13].

The gas movement speed in electrostatic precipitator does not exceed 1–1.5 m/s. With increasing speed, the cross-sectional dimension of the precipitator decreases, but its length increases, which is completely undesirable for our purposes, so we limit ourselves to low speed, equal to 0.3 m/s. The cross-sectional area of the active part of the master filter S equals the primary Q with the line v, so that the cross-sectional area of the active part of the electrostatic precipitator for a performance of 300 m^3/h (satisfying most IHSs) must be capital $S = 0{,}28$ m^2.

For reasons of easy installation on boilers or stoves, and to reduce the number of electrodes, insulators and cleaning system elements, it is preferable to make electrostatic precipitators high but with a limited width. Therefore, it is best to choose the width of the active part equal to 0.42 m and, correspondingly, the section area height equal to 0.67 m.

Knowing the average velocity of particles across the omega precipitator can also set the length of the collecting part of the main precipitator L, however, the calculation of particle drift speed is based on empirically derived patterns and gives a greater error, therefore it was decided to determine the speed on a natural model of an electrostatic precipitator.

The laboratory electrostatic precipitator includes one gas passage. Filter design is modular, with the active part length of each module being 0.96 m and the height 0.76 m (Figure 1). The measurements were made using one module with a distance of 100 mm between the collecting electrodes and the ends of the corona electrodes. The machine is equipped with a diffuser with a gas distribution device and a convector, at the outlet of which a tangential fan is installed.

Figure 1. Laboratory electrostatic precipitator with the collecting electrode removed
Source: the photo was taken by S.V. Kalashnikov.

Through the precipitator the air of room temperature with a flow rate of 150–200 m^3/h was pumped, it was injected with fly ash taken from the cyclone cleaners of municipal boiler houses (operating on typical coal variety for the region, burning it in clusters, that is, just as in IHS boilers). The analysis of the granulometric composition of the fly ash from these sources showed its overall identity, i.e. it can be concluded that on average the ash by particle size formed in different furnaces is almost identical (Figure 2). The dust content in the air was maintained in the range of 1–5 g/m^3. The inlet and outlet dust of the air was measured by optical sensors for which gas was selected by piton tubes. Sensors allow the determination of mass content in two particle sizes: 0.3–2.5 and 2.5–10 μm.

To calculate the transverse particle velocity, a measurement of the dust capture rate was performed on the precipitator layout as a function of the distance from which the gas was sampled. Received input curves (ζ_{in}) and output (ζ_{out}) gas dust from time of experiment is used to calculate the degree of capture by an electrostatic precipitator according to formula $\eta = 1 - \zeta_{out} / \zeta_{in}$. The deposition rate at 0.2 m is about 75%, dust capture at 0.9 m — 99% (Figure 3).

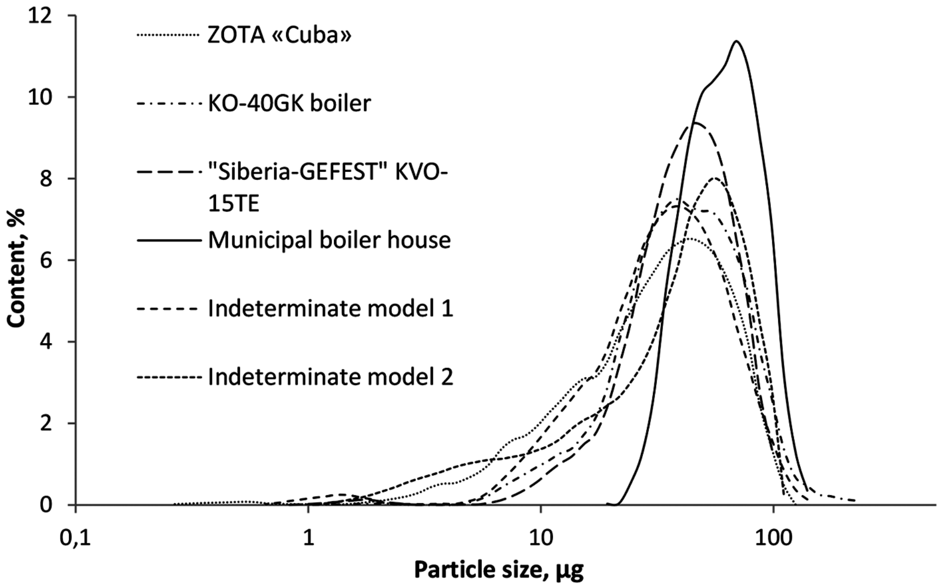

Figure 2. Granulometric composition of fly ash from various emission sources

Source: compiled by S.V. Kalashnikov.

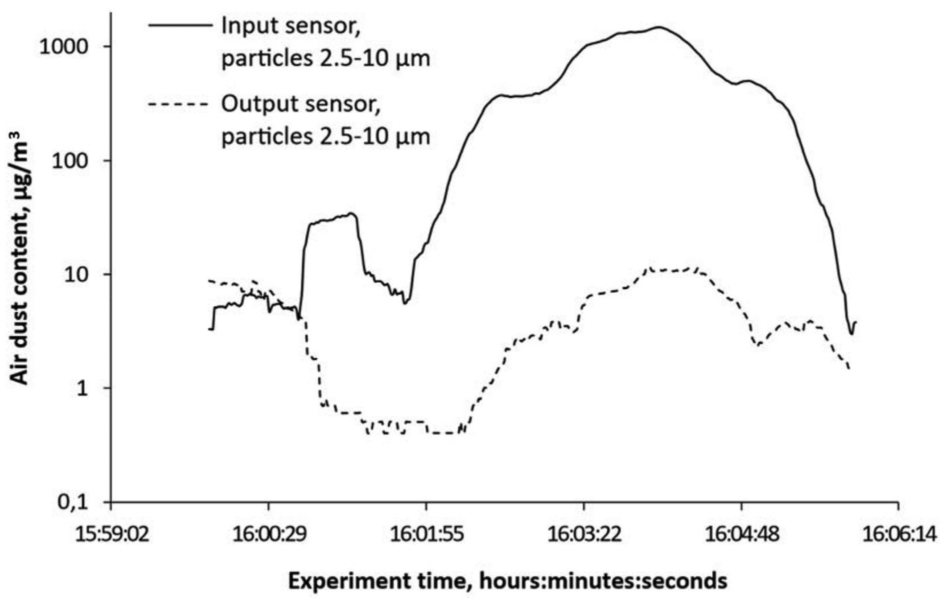

Figure 3. Data on dust content at the filter inlet and at a distance of 0.9 m from it.
The ratio of the instantaneous outlet and inlet dust content gives a capture efficiency of 99%

Source: compiled by S.V. Kalashnikov.

Based on the known length of the electrostatic precipitator layout and the degree of dust deposition, the average particle drift rate was calculated according to formula (1):

$$\omega = -\frac{dv\ln(1-\eta)}{L} = 0{,}16 \text{ м/с}. \qquad (2)$$

The drift rate of particles, however, depends on the distance between the electrodes and the voltage on them, as well as on the size of the particles, since the charge they acquire is proportional to their radius. However, for practical calculation with the constant granulocrometric content of fly ash, the presented method of determining omega is quite sufficient and can be applied to calculate the precipitator length with other originally set parameters.

Thus, to clean 300 m^3/h of smoke from solids an electrostatic precipitator with dimensions about 0.45 0.7 m and active part length about 0.9 m (together with diffuser and confer about 1.3–1.4 m) is needed. At the recommended distance between the adjacent corona electrodes 0.1 m [14], they will require 9 pcs. The width of the active part of such a filter would require two gas passages with interelectrode distances of 100 mm, so that the total number of electrodes is 18 with each about 0.7 m in length, i.e. their total length would be 12.6 m.

The linear current density during experimental deposition was 0.5 mA/m. Thus, the current consumed by the electrostatic precipitator under development will be about 12.6 m × 0.5 mA/m = 6.3 mA. This gives the capacity consumed by precipitator core P equals 315 W, which is quite moderate (with an average value of electricity cost in Russia of 4.72 P/kWh, the cost of energy consumed per month would be about 1070 Rub.).

The IHSs have an unstable operating mode characterized, among other things, by a wide range of smoke flow and its dusting. Adjustment of the power parameters of the single-zone electric filter considered in order to save electricity has a strong influence on the dust capture rate. This is because the dust loading function and the removal function are assigned to the same field. In all single-zone electrostatic precipitator an electrodynamic field is created, the transfer of charges between the electrodes causes relatively high energy consumption. Reducing the current of this field, even with low flow dusting, causes a sharp decrease in the drift rate of particles as a result of a reduction in their charge. At the same time, the main charge of dust particles is carried out at the entrance to the electric filter, so that the presence of an electrodynamic field in most of the volume of the electrostatic precipitator is excessive.

Dual electrostatic precipitators have separate fields for charging particles and for deposition. Accordingly, it is possible to regulate particle charge and deposition separately. The ionizer, limited in area of electrodes, has relatively low energy consumption with high charge rates of particles. The extended collector can only have an electrostatic field requiring little energy. Essentially, the energy of a collectingfield is spent only on drifting particles in it. The less dusty the flow, the less energy consumed.

Thus, the energy input is automatically adjusted in the two-zone electrostatic precipitator. The introduction of dust detectors or granulometric dust composition also makes it possible to carry out and regulate the activity intensity of the ionizer in order to reasonably reduce its energy consumption and ozone emission.

The charged dust in the crown discharge, which flies with smoke, is deposited on the collecting electrodes (Figure 4). There is a finite dust thickness at which the electrostatic precipitator can still continue to work stably. How quickly this layer thickness is reached depends on the dusting of incoming smoke. Thus, at a dusting of 1 g/m^3, given the area of two settling electrodes of our electrostatic precipitators (1.34 m^2) and the bulk density of gold oxide (0.7 g/cm^3), the layer will be about 0.65 mm thick in one hour of operation. The ultimate thickness of a layer that begins to emit a positive charge from a collecting electrode with its negative charge can be considered to be about 5 mm thick [15]. This layer at the specified dusting will be reached in about 8 hours of filter operation. Thus, the apparatus can either be periodically cleaned by hand or have an automatic cleaning system with dust collection in the bunker by shaking collecting electrodes.

Figure 4. Photograph of the structure of precipitated dust in a laboratory electrostatic precipitator

Source: the photo was taken by S.V. Kalashnikov.

Conclusion

Based on the calculation, it was found that even with a smoke cleaning degree of 99% by electrostatic precipitator, its dimensions would be quite permissible for installation in private boiler houses, for instance, instead of one standard section of air flue. It has been shown that about 10,000 private small boiler houses in Ulan-

Ude emit up to 7.5 thousand tons of particulate matter into the air. If electrostatic precipitator were installed at least 50% in private boiler houses, the amount of particulate matter emitted could be reduced by at least 3,000–4,000 tonnes per year with the required level of capture. To understand how much this is, consider the following information: 1,000 tons of ash at a bulk density of 700 kg/m^3 and with complete precipitation will cover the city area 350 km^2 with layer of 4 mm.

It should be considered that wood-burning furnaces emit less particulate matter and carcinogens such as benzpine, so, despite their large share in the city (77%), coal boilers are considered to provide the lion's share of solid emissions. Emissions of fine particulate matter in 2023 exceeded MAC by 4.7 times [3] [6], that means that measures to use electrostatic precipitator in small boiler houses can bring this important factor of air quality to normal.

However, equipping even 5,000 private boiler houses with electrostatic precipitators is difficult because it leads to additional household costs and probably only possible if local governments take the initiative. Let's try to calculate the approximate cost of the electrostatic precipitator considered in the project. The most expensed item is a power supply with output voltage 50 kV and current up to 7 mA. To manufacture the filter housing and collecting electrodes, about 4.2 m^2 of stainless-steel sheet is required, as well as metalloprofiles, methases and insulators. Metalworking, energy, assembly, enterprise profit, overhead production costs including workers' wages — a major category of costs that is difficult enough to calculate at this stage. However, the analysis showed that the cost of an electrostatic precipitator mass-produced at one of the enterprises already specializing in similar products could not exceed 50% of the value of a solid fuel boiler, which is expensive but quite permissible for the sake of clean air.

Such an electrostatic precipitator can be developed, for example, at OJSC "Ulan-Uden Instrument Engineering Production Association", which has just developed the production of electrostatic precipitators developed by IFM CO RAS for small municipal boiler houses with a smoke capacity of 10–30 thousand m^3/h.

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