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Operational tests of an electrostatic precipitator reducing low dust emission from solid fuels combustion

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Highlights

- An electrostatic precipitator was designed and manufactured to reduce dust from low emission sources.
- A microprocessor controller with the function of monitoring device operating parameters through the LoRaWAN network was developed.
- The required dedusting efficiency was achieved with relatively low operating costs of the electrostatic precipitator.

Abstract

The article presents the continuation of the research aimed at designing, manufacturing and selecting the operating parameters of the electrostatic precipitator for household applications. The tests were carried out in the laboratory and real conditions. The object of the research was a pre-production prototype of the electrostatic precipitator installed in the flue gas duct of a single-family building. The source of exhaust gases was a coal-fired, low-temperature water heating boiler with a nominal power of 21 kW (old generation boiler-year of production: 2007). The obtained results showed that the adopted design of the electrostatic precipitator enables the reduction of dust emissions generated in the combustion of solid fuels in households at relatively low operating costs.

Keywords

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air protection, low emission, electrostatic precipitator, operating parameters.

Introduction

Significant exceedance of the standards for suspended dust concentrations from low emission sources is a significant problem. Low emission is defined as the emission of combustion products of solid, liquid or gaseous fuels into the atmosphere from sources located at a height not exceeding 40 m. Low emission is a source of many air pollutants, especially PM10 and PM2.5 [31]. The chemical composition of suspended dust PM10 and PM2.5 contains chemical components that are hazardous to health [6], which was pointed out in the recent report of the European Environment Agency [10]. Dust from solid fuel combustion contains organic compounds: polycyclic aromatic hydrocarbons, dioxins and heavy inorganic metals or their compounds [32], including particularly toxic mercury [33]. One of the significant sources of low dust and harmful gas emissions is the combustion process of low-quality coal in home furnaces or local boiler houses [3]. The source of dust is also burning biomass in stoves and fireplaces [5, 30]. Fuel combustion in outdated boilers is due to economic reasons. The reduction of dust emissions from the combustion of solid fuels by individual users is possible by replacing obsolete boilers with modern devices that meet emission standards or by equipping existing heating installations with relatively cheap, easy-to-use electrostatic precipitators. Electrostatic precipitators are commonly used in many industries [15, 21]. The leading sector of the economy that uses electrostatic

precipitators is energy. Industrial electrostatic precipitators are large-size devices [22] and their design solutions cannot be used to separate dust from low emission sources. Many design electrostatic precipitators for household use [28] have been developed, and new solutions are constantly sought. The device that generates large amounts of free ions (sonic-jet charger), presented in [18], to be used in the process of diffusive charging of dust particles deserves attention. Household electrostatic precipitators are often installed directly at the outlet of a power boiler [4, 11, 24], which is not always possible due to the cubature of the boiler room. High flue gas temperature at the boiler outlet may cause accelerated corrosion of the electrostatic precipitator. An alternative is to place a tubular electrostatic precipitator in the flue gas duct (inside the chimney) [9]. Such a design solution was adopted by the authors [16]. This electrostatic precipitator is intended mainly for older generation boilers, which are fed with fuel with lower quality parameters than the fuels used in the new generation boilers.

The elaboration of the electrostatic precipitator design was preceded by testing the properties of dust pollutants emitted by household boilers. The theoretical level of dust emissions from the combustion of solid fuels (coal and biomass) in domestic boiler houses was determined. As part of the research, analyses of the chemical composition, morphology and physicochemical properties of dust from coal combustion and biomass were carried out. Based on the research results,

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a laboratory electrostatic precipitator was developed and built, equipped with the measurement lines required by the test program.

In this electrostatic precipitator, the influence of operating parameters on the dust removal efficiency was tested. The results of laboratory tests confirmed the high efficiency of dedusting the developed electrostatic precipitator design solution. At the flow velocity of the medium through the electrostatic precipitator chamber $v=1.5$ m/s, for dust from coal combustion and biomass, the dedusting efficiency was 97.6% and 99.4%, respectively. The test results showed that for the adopted operating parameters, the concentration of suspended dust at the ESP outlet does not exceed the concentration level resulting from the EU Commission Regulation [8] (40 mg/m_N^3 for boilers with automatic fuel feeding and 60 mg/m_N^3 for boilers with manual loading). The next stage of the work was to create a prototype of the electrostatic precipitator. It was installed in the chimney channel of a single-family building, heated with the DEFRO Optima 15STD energy boiler with a power of 15 kW and subjected to operational tests.

1. Research methodology

The electrostatic precipitator's power demand results from the power consumption of the high-voltage power supply and the device's control circuits. Measurements were made with an electric energy consumption meter model EMF-1 without a load of a medium containing dust (the so-called "air measurements") and with a dust load of 500 mg/m_N^3 .

Measurement of the concentration of dust suspended in the air requires the use of special measurement techniques [29]. The most frequently used dust meters are of various designs, separating dust grains into cellulose or synthetic filters [12]. The amount and dimensions of the retained dust grains can be determined microscopically [13] or by gravimetric methods [17, 20]. Electrostatic precipitator efficiency measurements were performed with the virtual RespiCon™ impactor [23, 27]. A constant gas volume $v=30 \text{ dm}^3$ was taken from the ESP outlet with a special dosing pump (Gilian 5000) [26], maintaining a constant volumetric exhaust gas velocity ($4286 \text{ cm}^3/\text{min}$). The dedusting efficiency was determined from the ratio of dust masses retained by the impactor filters with the ESP switched on and off.

The cleaning efficiency of the collecting electrode was assessed organoleptically. Time courses of vibrations of the collecting electrode under the influence of the electromagnetic inductor were also recorded. Measurements were made with a piezoelectric acceleration sensor type KD-40 with a resonance frequency of 50 kHz and sensitivity of $Ba(125 \text{ Hz})=0.79 \text{ mV/ms}^{-2}$ connected to a Fluke 190-204/EU (Fluke) recording oscilloscope. The measurement results were analyzed in software specially developed for this purpose in the LabView environment. The program allows to read files containing the data recorded by the oscilloscope measurement, sensor calibration, and signal analysis.

2. Pre-production prototype of an ESP

The technical design and documentation of the pre-production prototype were made based on the results of operational tests of the previously prepared ESP prototype. The authors of the project were the design team of Special Machines Design Office based in Nowy Sącz. This project was under the scientific patronage of the authors. The design of the new electrostatic precipitator is similar to the previous version of the device, the description of which, along with the selection of design and electrical parameters of the discharge electrode, is included in the publication [16]. In the next version of the device, several new design solutions were used, including assembly and connectors for the high voltage supply of discharge electrode, housing for electric and electronic circuits, collecting electrode with rectangular profile 241×131 mm. An important element of the electrostatic precipitator is the system for cleaning the collecting electrode from dust deposited on it. Various technical solutions are used, e.g. mechanical,

brush systems used for cleaning the electrodes from dust [1]. The described device uses an electromagnetic inductor that forces vibrations of the collecting electrode.

A crucial element of the electrostatic precipitator is a microprocessor controller with the possibility of data transmission (electrostatic precipitator monitoring) to the LoRaWAN network, which is currently a popular communication medium [2] for smart city infrastructure devices (Smart City) [19, 25]. As part of the work, documentation was developed and then drivers dedicated to cooperation with the electrostatic precipitator were made. The electronic system of the controller consists of an ARM Cortex-M0 microcontroller, SAMD21 type (Microchip Technology) with a built-in 256kB Flash memory, 32kB RAM and a real time clock. The temperature measurement system was implemented with the use of 2 specialized Maxim Integrated ADC converters, MAX31865 dedicated to the operation of resistance sensors (e.g. PT100/PT100) and the MAX6684 system - dedicated to NTC semiconductor probes (10K/100K). Two measurement channels available in the design offer a measuring range of $-40 \div 200^\circ\text{C}$. Thanks to this, it is possible to simultaneously monitor the temperature of the chimney channel and the outside temperature. The temperature measurement channels are galvanically isolated by Analog Devices ADUM4154. The actuator consists of a set of Zettler AZ6963 electromagnetic relays with a maximum contact load of 8A/250 VAC. It controls the power supply circuit of the CX300A high voltage converter and the electromechanical actuator used to clean the collecting electrode. For data exchange between the controller and the supervisory system (coordinator), a radio transceiver of the RN2483A type (Microchip Technology) was selected, which was connected to the microcontroller via the UART serial interface. The controller was designed to work with 230VAC mains voltage. The circuit responsible for controlling the CX300A high voltage inverter provides the ability to monitor the load current in real time. The circuit responsible for measuring the current is Hall's ACS723 sensor (Allegro Microsystems), which works with the OPA344 operational amplifier (Texas Instruments). The measuring system is characterized by the possibility of adjusting the gain value of $2x \div 22x$ and the offset of the voltage signal coming from the ACS723 converter. Therefore it is possible to easily adjust the controller to measure AC currents in the range of $10\text{mA} \div 5\text{A}$. The ACS723 circuit also provides galvanic isolation for the low voltage microcontroller circuit. The prototype of the manufactured microprocessor controller is presented in Figure 1.

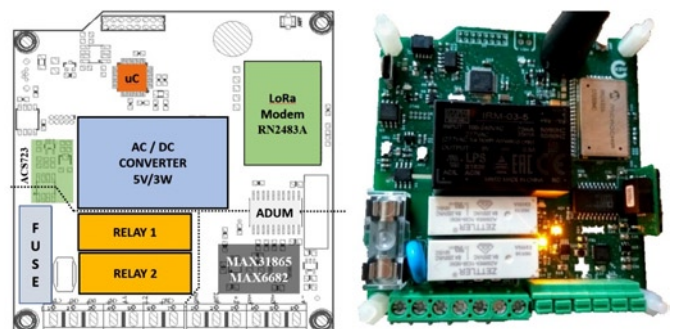


Fig. 1. A prototype of a microprocessor controller for a home electrostatic precipitator - functional and real view and devices

The microprocessor controller is responsible for the correct and safe operation of the home electrostatic precipitator. Embedded software implements the following device functions:

- configuration and saving in the controller's memory of the electrostatic precipitator's operating parameters and parameters responsible for communication with the LoRaWAN master server,
- correct switching on of the high-voltage converter supply circuits depending on the set operating temperature of the filter and the declared external temperature range,

- control of the correct operation of the high-voltage converter (real-time monitoring of the high-voltage converter current, including response to limit values defined by the installer),
- execution of time programs (e.g. collecting electrode cleaning function for the selected hour and minute in a daily cycle),
- wireless communication with an external server (cyclical report on the device status, remote device operation management and configuration of key parameters).

An important assumption for the designed device was to ensure wireless transmission of relatively small data packets over a distance of several or several kilometers without incurring costs by the end user. The common denominator of the final application was the immediate sending of information about changes in states, including information about detected problems (alarms). The current values are measured in the household electrostatic precipitator system in a relatively long time intervals. Data logging takes place at user-defined intervals (once every several minutes).

Due to the above assumptions, it was decided to use the LoRaWAN communication standard. LoRa is a definition of a physical layer that describes the modulation of a radio signal. The standard uses spread spectrum and frequency sweep modulation, which maintains the same low-power characteristics as typical FSK (frequency shift keying) modulation. The communication standard of this type was initially established at Cycleo in 2009 (Grenoble, France) to provide the ability to monitor distributed metering devices in industries such as agriculture, energy distribution, environmental protection and water supply. The advantage of LoRa modulation is a significantly increased range of communication at a distance of 2÷5 km in urban areas and 15 km in non-urban areas. All devices working in the LoRa system operate in an unlicensed frequency band known as ISM (Industrial, Scientific, Medical). In Europe, the frequency of the ISM band is 886 MHz. The second advantage of this type of communication is the lack of fees and full freedom of access. A certain downside, requiring attention to proper configuration, is the interference with other devices operating on the same bands and belonging to other users [7, 14]. The LoRaWAN standard defines the communication protocol and system architecture for a network based on the LoRa physical layer. In the structure presented in Figure 2, the following system elements can be distinguished:

- end devices that are data sources (End Node/End Point),
- data concentrators (Gateway),
- network servers,
- applications.

In the project, the data source for the supervisory system is the electrostatic precipitator controller, equipped with the RN2483 radio modem from Microchip. Data concentrators (Gateways) are responsible for communication (also bi-directional) with many end devices operating in a given area and with the network server, which must have access to the Internet. The task of network servers is to decode information collected from end devices (electrostatic precipitator drivers) and make it available to user applications. Due to the openness of the radio network, all data is encrypted with a 128-bit AES key.

The LoRaWAN communication protocol also uses two device activation mechanisms (OTAA and ABP), which differ in the way of registering keys. During the start-up of the network for several electrostatic precipitators, the RG186 (Laird Technology) hub was used, offering rich network interfaces (WiFi, LoRaWAN, Bluetooth). The IoT The Things Network (TTN <https://www.thingsnetwork.org>) server, available free of charge, was used to analyze the correctness of radio communication between devices and the data concentrator. The TTN web server working in the computing cloud, effectively receives data coming from registered drivers and transmits them to the user's applications and/or databases available on external servers. It is also possible to send an update of the configuration parameters to the selected ESP controller or to remotely

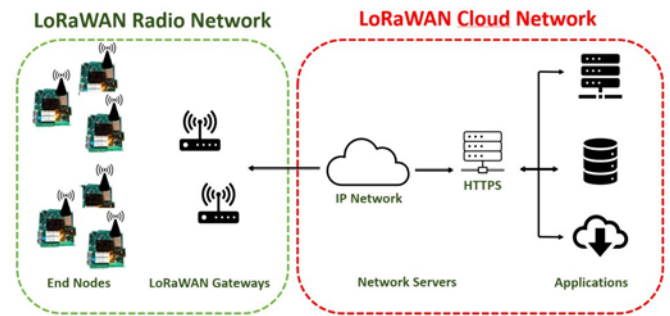


Fig.2. The architecture of a distributed sensor network, working in the LoRaWAN standard

turn off/on the device. Data flowing to the network server from the LoRa radio network operating in a defined group of devices can be monitored on an ongoing basis from the level of a web browser using the REST API technology. It is possible to freely redirect data to the target application server, configured according to the user application requirements. User application (e.g. mobile or cloud computing), depending on permissions, allows for monitoring and remote management of a selected group of devices. Available utility applications for IoT (Internet of Things) networks, available on commercial servers, offer the possibility to present the state and review historical data in the form of defined tables (Dashboards).

The design of the architecture of a distributed home electrostatic precipitator network system, prepared on the basis of the principles presented in the article, is by definition scalable. The deployment of an electrostatic precipitator network can be carried out in stages, commissioning it and modifying it during operation, which is especially important in situations where the size (scale) of the installation is not fully defined at the beginning of the work.

Based on the developed documentation, a pre-production prototype of the electrostatic precipitator was made. The view of the device during assembly and visualization are shown in Figure 3.



Fig. 3. View of the electrostatic precipitator prototype for home use

3. Research results

In the process of designing and then manufacturing the electrostatic precipitator, it is essential to know the parameters of its electrical parameters. The correctness of the selection of geometric parameters of the electrostatic precipitator was verified by determining the current-voltage characteristics of the discharge electrode. The current-voltage characteristic shows the intensity of the electric field generated by the discharge electrode. The intensity of the electric field affects the time it takes for the dust grains to obtain a charge that enables their migra-

tion and deposition on the collecting electrode. The current-voltage characteristics of the ESP prototype are shown in Figure 4.

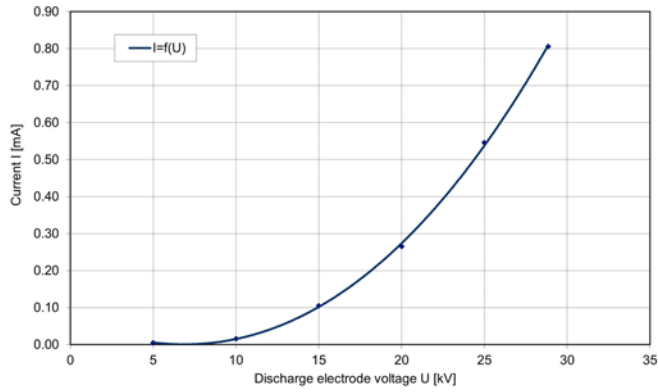


Fig. 4. Current-voltage characteristics of the discharge electrode

Based on the current-voltage characteristics, it can be concluded that the discharge electrode used shows high emissivity. The calculated initial voltage of the discharge of the electrode used in the construction is $U_0 = 7.1$ kV. It means that the electrostatic precipitator stops dust contamination with a relatively low supply voltage.

The approximate cost of operating the device is essential for the user. For this purpose, the electrical parameters of the electrostatic precipitator prototype were measured. The results of measurements without a load of a medium containing dust (the so-called: “air measurements”) are presented in Table 1.

Table 1. Results of measurements of power consumption by the prototype electrostatic precipitator without dust load

Discharge electrode voltage [kV]	Primary circuit (low voltage)				
	Voltage [V]	Frequency [Hz]	Current [mA]	Power [W]	Power factor (cos φ) [-]
10.0	226	50	130	14.0	0.47
15.0	226	50	170	19.1	0.50
20.0	225	50	250	30.2	0.51
25.0	225	50	360	45.0	0.53
28.4	225	50	440	56.1	0.54

The measurement results for the dust concentration at the ESP inlet of 500 mg/m^3 with the medium flow $v = 0.95 \text{ m/s}$ are presented in Table 2.

Table 2. Results of measurements of power consumption by the prototype electrostatic precipitator with a dust load of 500 mg/m^3

Discharge electrode voltage [kV]	Primary circuit (low voltage)				
	Voltage [V]	Frequency [Hz]	Current [mA]	Power [W]	Power factor (cos φ) [-]
10.2	224	50	130	14.2	0.48
15.1	224	50	180	19.7	0.49
20.0	224	50	260	30.5	0.50
25.0	224	50	380	46.6	0.54
28.6	224	50	490	59.3	0.55

The results of measurements of the high voltage value of the discharge electrode made without dust loading and at the dust concentration at the inlet of the ESP 500 mg/m^3 are comparable (difference $< 1\%$). This means that the power supply has a current capacity sufficient for the proper operation of the electrostatic precipitator. The diagram of changes in power consumption by the high-voltage power supply as a function of the output voltage is shown in Fig. 5.

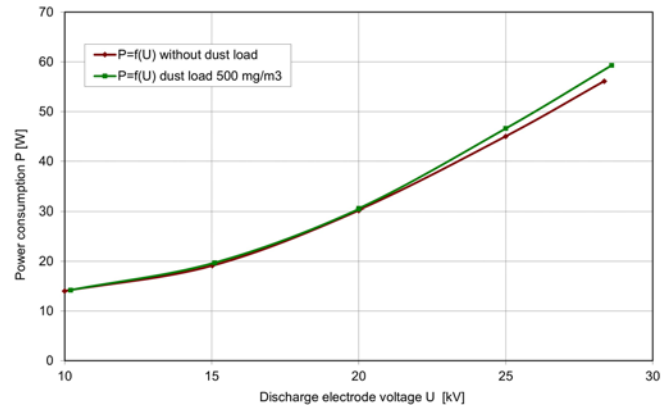


Fig. 5. Power consumption by the high-voltage power supply as a function of the output voltage

These results indicate that in the case of the ESP operating for 12 hours a day, the monthly energy consumption will be from 16.2 to 20.2 kWh.

During operational tests of the electrostatic precipitator installed in the flue gas duct, its activation temperature was set at the value of $50 \div 60^\circ\text{C}$ (30°C on the first day). The observations show that during the operation of the electrostatic precipitator at the flue gas temperature of $50 \div 60^\circ\text{C}$ there was no condensation of tar from the flue gas on its electrodes. After 15 days of operation, the presence of the so-called fluff soot. Carbon black in this form, as a loose material, is easily removed after its layer is deposited on the collecting electrode.

In March 2019, the dust removal efficiency was measured in accordance with the previously presented methodology.

The source of exhaust gases was a low-temperature water heating boiler, type POPTER DS, with a nominal power of 21 kW (boiler production year: 2007). Hard coal was burned in the boiler. The flue gas flow velocity in the chimney channel was approximately 0.7 m/s.

The first series of measurements was aimed at determining the background level of the dust concentration approx. 20 meters from the installation site of the electrostatic precipitator. The air temperature on the day of the measurements was $t = 6.6^\circ\text{C}$ and the relative humidity was $w = 29\%$. The average value of dust concentrations: $\text{PM}_{2.5} = 21 \text{ mg/m}^3$, $\text{PM}_{10} = 9 \text{ mg/m}^3$.

Another series of measurements was carried out with the electrostatic precipitator turned off, directly at its outlet. Sampling nozzle aligned parallel to the ESP outlet at its edge. Average value of dust concentrations: $\text{PM}_{2.5} = 90 \text{ mg/m}^3$, $\text{PM}_{10} = 121 \text{ mg/m}^3$ (flue gas temperature $\sim 50^\circ\text{C}$, relative humidity $w = 59.3\%$).

The measurement results showed that the ESP dedusting efficiency was 78.6% for the above flue gas parameters,

The dedusting efficiency calculated based on the measurements carried out on a real object is lower by approx. 20% than that obtained in laboratory conditions in a tubular electrostatic precipitator with a diameter of 150 mm. The lower dedusting efficiency of the

prototype ESP is due to the different geometry of the collecting electrode (asymmetry), the lower emissivity of the discharge electrode (larger radius of the emission blade ends), and exhaust gas composition (higher humidity and soot content in the exhaust gas).

The work of the cleaning system of the collecting electrode from the dust deposited on its surface was carried out by analyzing the amplitude and time course of the vibrations of the collecting electrode with the excitation caused by the electromagnetic inductor. The analysis of the measurement results showed that the acceleration values at the collecting electrode were $300\div 360\text{ m/s}^2$ (approx. $30\div 37\text{ g}$). The maximum vibration amplitude of the collecting electrode occurs at a frequency of approx. 440 Hz. The acceleration value is sufficient to remove dust from the surface of the collecting electrode.

4. Conclusions

The pre-production prototype of the electrostatic precipitator for domestic use was designed and built using the operating experience of previously developed dedusting devices. The first was a laboratory electrostatic precipitator. The next prototype was tested in a laboratory and in real conditions in a single-family building, heated with a 15 kW boiler.

The operational experience gained enabled the preparation of the design and technical documentation of the electrostatic precipitator, which, after minor modifications, can be put into serial production. The device is equipped with a microprocessor controller with the possibility of data transmission (electrostatic precipitator monitoring) to the LoRaWAN network. This enables remote supervision of the device, control of its operating parameters, and periodic cleaning programs for the collecting electrode. The driver, in the event of a failure or incorrect operation of the device, sends real-time information on errors (alarms, e.g. in the event of self-ignition of soot), which is important for the safety of users.

The analysis of the electrostatic precipitator structure shows that its mechanical elements, mainly made of stainless or acid-resistant steel, should be very durable. The most type discharge electrode is also very durable. Electrical equipment is the component of lower durability and reliability. Therefore, the developed solution adopts a modular structure of electrical circuits (controller and high voltage power supply), which enables their easy and quick replacement in the event of failure.

The results of the tests of the electrostatic precipitator in laboratory conditions and installed in the chimney indicate that the electrostatic precipitator fulfills the task of reducing dust emissions from solid fuel

combustion. The high emissivity of the discharge electrode used in the electrostatic precipitator affects the efficiency of dedusting and the energy efficiency of the device. The selection of the discharge voltage of the discharge electrode (preferably: $20\div 22\text{ kV DC}$) depends on the geometrical dimensions of the collecting electrode. Higher voltages favor the formation of spark-overs, and the energy consumption of the dedusting process increases. For larger cross-sections of the chimney channels, instead of increasing the supply voltage of the discharge electrode, its length should be increased while maintaining the pitch of the emission elements. Increasing the length of the electrodes (larger settling surface on the collecting electrode) and the number of emission blades will compensate for the lower value of the electric field strength in the electrostatic precipitator chamber.

The cost of operating the device is crucial for the user. The results of the measurements of the power demand confirm that low energy consumption by the dedusting device was achieved thanks to the adopted design of the electrostatic precipitator and the appropriate selection of the high voltage power supply. The power consumption of the device operating at the nominal voltage of the discharge electrode is relatively low (below 50 Wh).

The collecting electrode cleaning system used in the electrostatic precipitator works properly by forcing its vibrations through the electromagnetic element. The measurement results confirmed the correctness of the structure and selection of the element forcing the vibrations of the collecting electrode. The microprocessor electrostatic precipitator controller allows the user to set the date and time of starting the collecting electrode cleaning procedure in order to reduce the nuisance for the device users by starting the ESP cleaning procedure during the day.

The analysis of the design solution of the pre-production electrostatic precipitator for home applications indicates the possibility of further improving its functionality, among others, by reducing the weight of the device. Stainless steel sheets with a thickness of $1\div 5\text{ mm}$ were used to build the prototype. In serial production, most of the elements can be made using typical, plasma-welded gas-tight pipes made of acid-resistant sheet metal with a thickness of $0.6\div 0.8\text{ mm}$ with diameters adapted to the cross-sections of chimney channels.

The results of the operational tests confirmed that the adopted design of the electrostatic precipitator makes it possible to reduce the emission of dust emitted during the combustion of solid fuels in households at relatively low operating costs.

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