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Bolesław KARWAT
Ryszard MACHNIK
Jerzy NIEDŹWIEDZKI
Magdalena NOGAJ

SELECTING OPERATING PARAMETERS OF AN ELECTROSTATIC PRECIPITATOR DECREASING EMISSION OF SOLID FUELS FLY ASHES

DOBÓR PARAMETRÓW EKSPLOATACYJNYCH ELEKTROFILTRU OBNIŻAJĄCEGO NISKĄ EMISJĘ PYŁÓW POCHODZĄCYCH ZE SPALANIA PALIW STAŁYCH*

The article presents the results of research aimed at developing the construction of an ESP (electrostatic precipitator), as well as the performance and selection of operating parameters of the ESP for household applications. The object of the experiment was the ESP prototype, designed and made by the authors, assigned to be placed in a gas pass of a detached house. A simulation of dustiness caused by burning solid fuels has been done. The experiment has been carried out for two different degrees of dust concentration at the ESP inlet, by controlling the given voltage. The results proved that the proposed constructional solution of the ESP significantly limits low emission PM2.5 and PM10 dust emitted during the process of burning solid fuels: coal and/or biomass in boilers and fireplaces used in households or in small local boiler houses.

Keywords: *air protection, low emission, PM10 and PM 2.5 dust, electrostatic precipitator, operating parameters.*

W artykule przedstawiono wyniki badań, mających na celu opracowanie konstrukcji, wykonanie oraz dobór parametrów eksploatacyjnych elektrofiltru do zastosowań w gospodarstwach domowych. Obiektem badań był opracowany i wykonany przez autorów prototyp elektrofiltru przeznaczony do montażu w kanale spalinowym budynku jednorodzinnego. Istotnym problemem jest dobór odpowiedniej elektrody ulotowej. Zasymulowano zapylenie powstające na skutek spalania paliw stałych. Badania przeprowadzono dla dwóch różnych stężeń pyłów na wlocie do elektrofiltru, regulując podawane napięcie. Uzyskane wyniki wykazały, że przyjęte rozwiązanie konstrukcyjne elektrofiltru umożliwia znaczne ograniczenie niskiej emisji pyłów PM2,5 i PM10 emitowanych w procesach spalania paliw stałych: węgla kamiennego i/lub biomasy w kotłach lub kominkach stosowanych w gospodarstwach domowych lub małych kotłowniach lokalnych.

Słowa kluczowe: *ochrona powietrza, niska emisja, pyły PM10 i PM2,5, elektrofiltr, parametry eksploatacyjne.*

1. Introduction

Suspended dust pollution in the air seems to be a crucial problem widely influencing on the environment and the society heath due to lead, cadmium, nickel and arsenide compounds migration, together with toxic dust. One of the sources of air pollution is dust produced during burning solid, liquid and gas fuels emitted to the atmosphere. Another reason of air pollution is dust occurring as exhaust gases as a consequence of using vehicles, burning diesel fuel in spontaneous ignition engines and abrasion of mechanical elements e.g. braking systems [4, 5]. Sources placed on height lower than 40 metres are called low emission ones. Low emission is the source of many kinds of pollution, among others PM10 and PM2.5 dusts. Those fractions contain, among others: polycyclic aromatic hydrocarbons, dioxins and heavy metals or their compounds [20]. The problem of exceeding air purity standards with suspended dust coming from low emission sources affects both big urban agglomerations and small towns (including heath resorts).

In towns with poor natural ventilation, resulting from geographical features or land development limiting natural ventilation ducts of building areas, low emission is the main factor causing smog.

The air pollution problem has been a subject of analyses carried out by European Environment Agency (EEA) for many years [8]. Their reports indicate for Poland as one of leading countries facing problems especially with suspended dust, occurring mainly by solid fuel combustion. The highest number of days with exceeded standards of PM10 fraction is observed in Bulgaria.

Examinations carried out as a part of international project Aphecom in cooperation with European Thematic Centre on Air and Climate Change (ETC/ACC) showed that increase in morbidity caused by air pollution with PM10 and PM2.5 dust generates additional costs of medical care by 31 billion € in the countries which are members of UE [3, 16].

European Parliament and European Council's guidance 2008/50/WE published on 21st May 2008, referring to the quality and purity of air for Europe, points at the problem of air pollution (CAFE) [7]. This guidance forces the UE members to take corrective actions in places where exceeding acceptable pollution levels, particularly PM10 and PM2.5 and CO_2, have been noted.

A significant exceeding of suspended dust concentration standards seems to be a serious problem in Poland. According to EEA report from 2017, the amounts of premature death caused by exposition to MP2.5 dust equals 41 300 cases [8]. In big agglomerations and towns where detached

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** houses mostly occur, the process of burning low quality coal in household furnaces, fireplaces, local boiler houses are one of the most important sources of low emission dust and harmful gases. Biomass in form of granules (pellets) or burning wood are also a popular source of energy used in households. Physical, chemical and electrical qualities as well as grain composition of dust produced from burning biomass are extremely diversified depending on the kind of fuel and its humidity [19, 21].

Those fuels are often burnt in outdated boilers. It results from economic reasons. In recent years a system of bonuses has been introduced in Poland in order to encourage the users of outdated boilers and furnaces to replace them with new appliances. A big effort to enable as big as possible number of individual users the access to urban heating network has been done. However, all these activities tend to be long-lasting. Nowadays experiments on underground gasification are being carried out. Gas produced this method used as energy carrier will make possible to limit the emission of suspended dust formed during burning coal [14].

One of methods limiting air pollutants emission, particularly PM10 and PM2.5 fractions, is introducing an easy in usage ESPs which can be applied in households and local boiler houses equipped with a boiler of energy power up to 40 kW. Tests of this kind of devices, varying in construction solutions are being carried out by science centres [9, 18] as well as commercial products manufacturers [10] (OekoSolve – Switzerland, RWE Aktiengesellschaft – Germany, Ruff-Kat GmbH Holzkirchen – Germany, Zumikron Rüegg – Switzerland). In Department of Manufacturing Systems AGH University of Science and Technology such experiments have also been undertaken. They resulted in developing a construction of an ESP designed to be placed in a detached house's gas pass. The ESP limits dust pollution emission occurring during the process of burning solid fuels to the level below the one recommended in The European Council Guidance 2015/1189 [6] which estimates maximum solid particles emission in the in solid fuel automatically supplied boilers at 40 mg/m^3.

2. Examination method

2.1. Physicochemical properties of dusts

Physicochemical properties of dust from fuel combustion affect the choice of a constructional solution and the ESP electric parameters [12, 13]. Examination of a dedusting gas-dust aerosol process has been carried out for dust produced from burning coal and biomass. They are typical solid fuels used as heating energy carriers in households and local boiler houses.

While examining dust, particular physical and chemical qualities, essential in the process of electrostatic exhausted gases dedusting, have been defined:
- relative density (pycnometer method),
- humidity (gravimetric method),
- flammable parts content (gravimetric method),
- grain composition (Mastersizer 2000 Malvern Instruments Ltd. analyzer),
- dust layer resistivity (high voltage direct current method),
- dust layer breakdown voltage (high voltage direct current method).

2.2. ESP test stand

The examination of the dust grains separating process has been done in a laboratory ESP made of alloy steel H17N13M2. Technical parameters of the ESP:
- chamber diameter ø150 mm,
- active length 1000 mm,
- discharge corona electrode – exchangeable electrodes of varied contours and emissivity,
- variable-capacity dust feeder,
- air flow through the chamber generated by a centrifugal fan of changeable efficiency, providing the ability to change the flow velocity ranging from 1-10 m/s,
- supplying circuit: 1-phase 230 V AC, high voltage 10-70 kV DC, current I ≤ 2 mA,
- controlling-measuring circuit and purifying collecting electrode executive circuit.

During the experiment following measurements have been made: carrier (air) flow velocity through the ESP chamber, discharge electrode supply voltage, dust presence at the ESP outlet (using triboelectric dust meter) as well as its concentration measured by gravimetric method. A view of the laboratory ESP is shown in Figure 1.

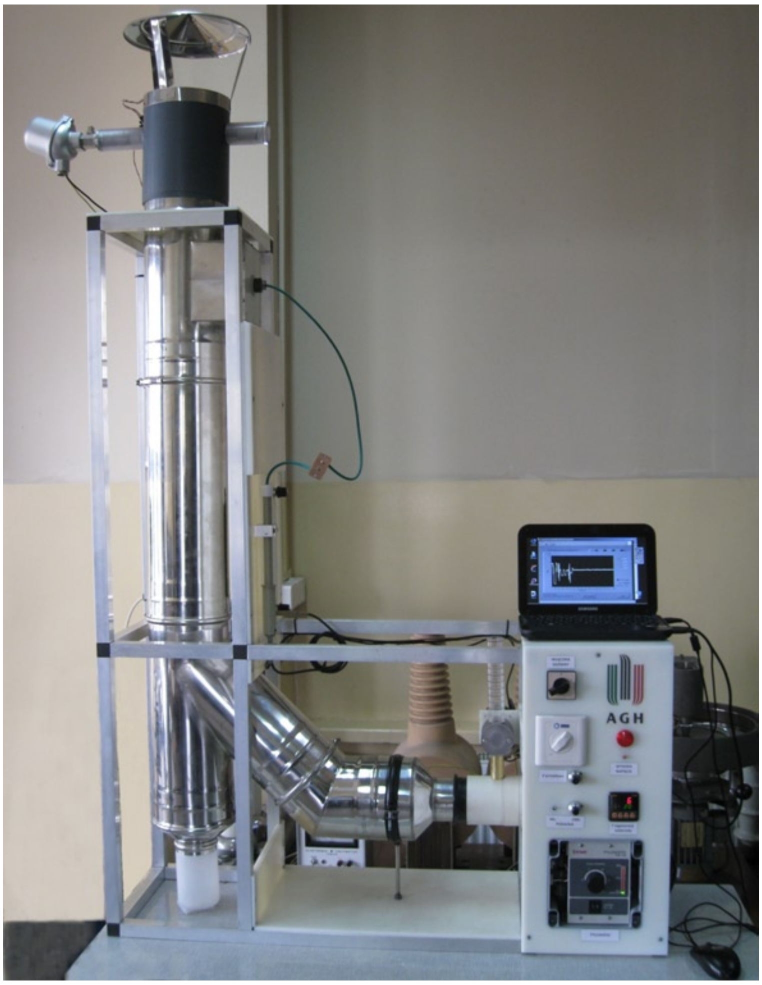

Fig. 1. The view of a laboratory ESP

The elements of the laboratory stand have been shown according to the tags in Figure 2. A centrifugal, mono-phase fan (1), supplied by the thyristor voltage regulation unit for inductive load of TPR-2N type provides the air flow through the ESP chamber. Using the regulation unit enables air flow velocity change ranging from 1-10 m/s.

In the inlet part (reducing pipe) of the ESP a variable-capacity dust feeder (2) has been placed. A stepping motor, its controller and a changeable frequency steering generator provide dust amount modified in a time unit. A nozzle (3) to additional compressed air loading from a compressor for low velocity of air flow in the ESP has been designed. This enables a better gas-dust aerosol producing process. The dust placed on the collecting electrode, after removing by rapping system is gathered in the container (4). In the upper (vertical) part of the ESP a junction box with an insulation board and a handle to replace discharge electrodes has been installed. There is a centrally placed discharge electrode inside the ESP

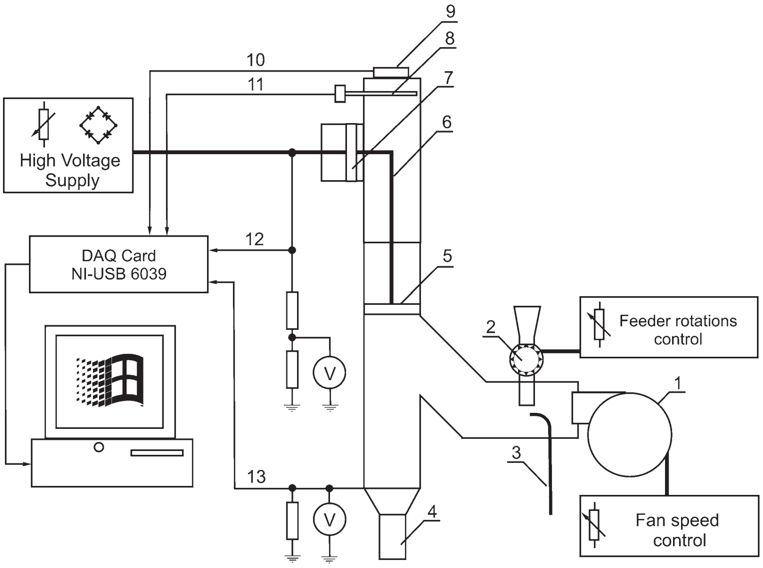

Fig. 2. Simplified diagram of the laboratory ESP 1 - fan, 2 - dust feeder, 3 - compressed air nozzle, 4 - separated dust container, 5 - lower discharge electrode holder, 6 - discharge electrode, 7 - upper discharge electrode holder, 8 - dust meter sensor, 9 - air flow velocity sensor, 10 - air flow measurement circuit, 11 - dust concentration measurement circuit, 12 - high voltage measurement, 13 - ESP current measurement.

chamber (5). A thick-walled pipe made of dielectric material, with a dust meter probe (6) and air flow velocity measurement unit (7) have been placed at the outlet of the ESP. Additionally, a system to purify the chamber from the dust deposited on its surface, enabling periodical removing it from the collecting electrode, has been designed.

Electric circuits of the stand consist of: discharge electrode high voltage supplier, high voltage measurement (11) and ESP current circuits (12). Air flow velocity through the ESP chamber is measured on-line with a measurement turbine (7) with a Hall effect sensor. Presence of the dust at the ESP outlet is recorded with the usage of a triboelectric dust meter. Voltage signals from the measurement circuits of the discharge electrode supplying voltage, current flowing between the collecting electrode and the circuit mass as well as the signal from the dust meter outlet were sent to data acquisition NI-USB6039 card. A measurement card working at sampling frequency of 1 kHz recorded averaged value of measured voltages. The data collecting program, working as a virtual XY recorder, enables recorded data visualization on-line. The data have been recorded in ASCII files in order to complete their further analysis.

2.3. The discharge of the electrode parameters selection

A tubular ESP designed for a household usage has only one discharge electrode, placed centrally in the chamber. The selection of its electric parameters has a crucial importance in a proper run of the exhausted gases dedusting process.

Basic criterion of the ESP discharge electrode parameter selection is providing such conditions that dust grains introduced into the ESP chamber could receive electric charge to make them migrate and deposit on the collecting electrode [2, 11]. Transmitting electric charge from gas ions to the dust grains plays the main role. Their source are phenomena occurring in the nearest surrounding the discharge electrode, more precisely, from the points on its surface where electron avalanche starts. The process of electric charge gathering by the dust grains in the area between electrodes can be described as their taking up electric charge. Electrically charged dust grains move mostly towards the collecting electrodes. The majority of dust grains are negatively charged and deposit on the grounded collecting electrodes of positive potential [15], when the resistivity of the dust layer placed on the collecting electrode significantly affects its characteristic [1].

The selection of the ESP discharge electrode type and its properties for household usage has been realized based on the basis of determined current-voltage characteristics of chosen discharge electrodes and discharge initial voltage.

Current-voltage characteristic *I-U* can be obtained by recording flowing current change in the area between electrodes as a function of discharge electrode supplying voltage. Measurements have been done changing discharge electrode supplying voltage in the range U=0-30 kV. The collecting electrode is connected to the positive end of the supplying system through a 0.05% tolerance decadal resistor. Recording the discharge electrode supplying voltage values and the current flowing in the inter-electrode space, proportionally to the voltage fall in the decadal resistor enables determining *I-U* characteristic. Voltage signals from discharge electrode supplying voltage measurement circuits as well as current flowing between the collecting electrode and the circuit mass are sent to the data acquisition card NI-USB 6039, connected to a computer equipped with data recording software. For each measuring point, at ΔU=500V step, an averaged value of measured voltage has been recorded. The recorded data have been filed in order to be analyzed further.

The initial voltage of the discharge electrode has been determined as a linear function $U/I=f(U)$ (reduced characteristic). The current-voltage characteristic of the discharge electrode and the initial corona voltage are the proof of the electrode emissivity, consequently, the ability to generate electrostatic field, where the dust grains can receive electric charge.

3. Examination results

Selected physical and chemical properties influencing significantly the electrostatic process of separating dust from the coal and biomass combustion have been shown in Table 1.

Table 1. Physicochemical properties of fly ashes from coal and biomass combustion

Physicochemical properties		Unit	Fly ash from combustion	
			Coal	Biomass
Relative density		kg/m^3	1902.0	2400.0
Moisture content		%	0.42	1.15
Flammable parts content		%	5.933	3.31
Dust layer resistivity	30°C	Ω/cm	$1.4\cdot10^{8}$	$1.1\cdot10^{10}$
	150°C	Ω/cm	$1.1\cdot10^{11}$	$1.3\cdot10^{11}$
Dust layer breakdown voltage		kV/mm	0.995	0.976

The compilation of the grain composition analysis results made with Mastersizer 2000 has been shown in Figure 3. The results indicate that the content of PM2.5 and PM10 grain fraction in dust do not exceed 20 vol%.

The selection of the ESP discharge electrode has been done by analyzing current-voltage characteristic and the discharge electrode initial corona voltage. It was established that the tabular ESP discharge electrode designed for a household usage should be characterized by high emissivity, possibly low initial corona voltage and high mechanic durability. Due to that reason, the usage of wire electrode in the ESP has been given up (so far popular in many solutions) [17]. During the process of selecting discharge electrode, it has been as-

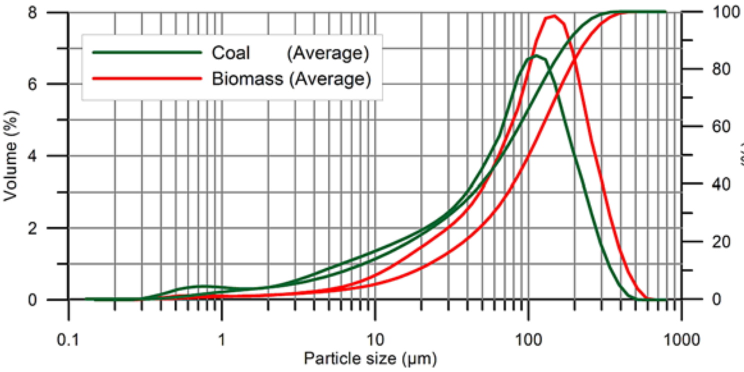

Fig. 3. The granulometric distribution of fly ashes from coal and biomass combustion

sumed that mast electrodes will be a much better construction. Owing to their rigidity, they can be successfully placed in ESP chamber by means of mono-point fixing from the top, which simplifies the ESP construction and eliminates the probability of short-circuit on conducting bridges of dust, which could deposit on the lower fitting element of the discharge electrode.

The emissivity measurement results for selected electrodes have been shown in Figure 4.

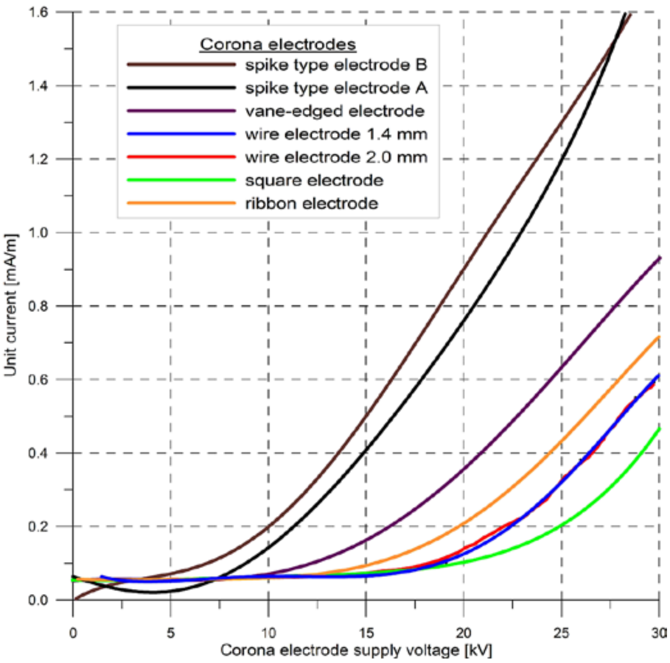

Fig. 4. Current-voltage characteristic of discharge electrodes

The analysis of the results proved that the construction of a mast spike type electrode supposed to be modified to receive better electric parameters. The measurements confirmed the correctness of such a solution. A mast electrode "A" typed is characterized by very high emissivity and low initial corona voltage U_0=5,7 kV.

Some initial assumptions have been done concerning the process of dedusting exhaust gases produced from solid fuels (coal and biomass) burning in fireplaces and heating boilers. Those assumptions referred to power of the applied boiler, sorts and properties of solid fuels, efficiency of dust separation by the ESP, simplicity of the constructional solution, minimizing its building and operating costs. Estimating the ESP efficiency of the dust separating, it has been defined that the dust concentration at the ESP outlet should not exceed 40 mg/m^3, was indicated in UE guideline 2015/1189 [6].

Taking under consideration the diversity of energy boilers operating in households, their technical state as well as parameters of fuels burnt in them, there is no possibility to define unmistakably the quality (physical and chemical dust properties) and the quantity (flow velocity, dust concentration at the boiler outlet) parameters of purified exhaust gases. In such case the most disadvantageous dedusting parameters should be accepted. Consequently, to reach the amount of dust aerosol which is necessary to obtain carrier flow velocity 1.0 m/s and 1.5 m/s assumed a concentration at the ESP inlet:

– 2000 mg/m^3 of air,
– 4000 mg/m^3 of air.

Dust separating efficiency by the ESP dust concentration was 7 to 12 times higher comparing to the calculated dust concentration for given boiler heating power and calorific value of fuels. Also the assumed carrier flow velocity through the ESP chamber was about twice higher than the one defined in calculations. A series of measurements changing the air flow velocity in the ESP chamber, dust concentration and discharge electrode supply voltage was carried out.

During the examination of the dedusting process the ESP operating current change has been defined as a function of the supply voltage for chosen dust concentration values at given velocity of the gas-dust aerosol flow through the chamber. The relationship between the value of the ESP inter-electrode current and the discharge electrode supply voltage has been shown in Figure 5.

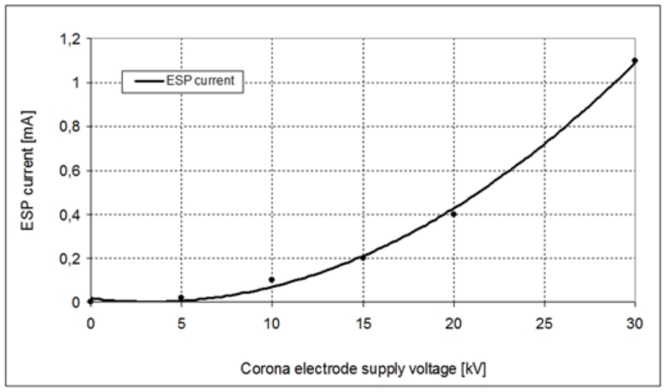

Fig. 5. The relationship between ESP current and the discharge electrode supply voltage

The ESP current measurements results proved a slight effect of dust concentration and the carrier flow velocity onto the current values. The current changes in the whole range of dust concentration changes and the carrier velocity have not exceeded 10%. It means that the ESP current depends mainly on its contours, the discharge electrode supply voltage and the current efficiency of the high voltage supplier.

On the basis of carried out measurements, the change of dust concentration at the ESP outlet has been defined as a function of the discharge electrode supply voltage. The results received for dust produced from coal and biomass combustion have been shown in Figure 6 and Figure 7.

The most important operating parameter for the ESP is a dedusting efficiency. Gaining high efficiency by the ESP confirms a proper selection of its geometrical features adjusted during the designing process. A correct selection of features has an influence on the discharge electrode parameters, as also the effectiveness. A selection of a high voltage supplier, its output voltage and current efficiency are also important. The results of coal and biomass fly ashes dedusting

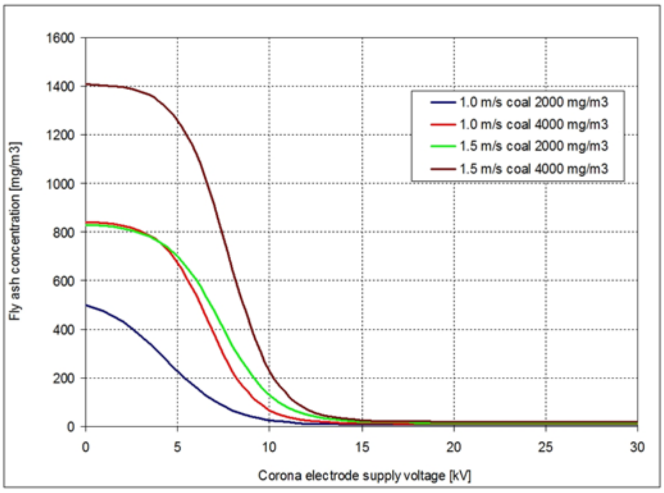

Fig. 6. The relationship between coal fly ash concentration at the ESP outlet and the discharge electrode supply voltage

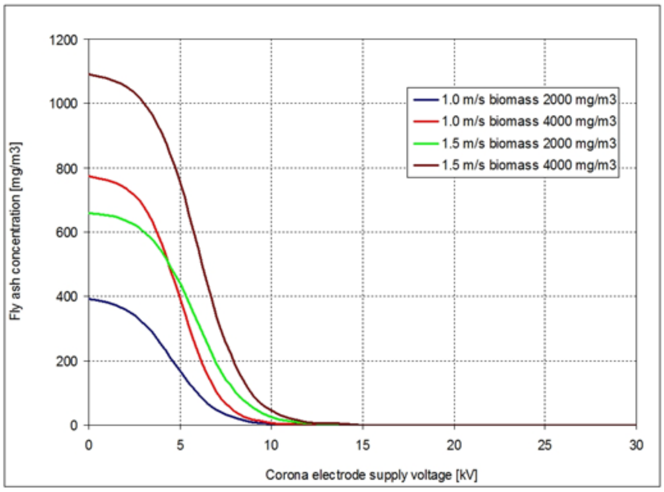

Fig. 7. The relationship between biomass fly ash concentration at the ESP outlet and the discharge electrode supply voltage

Table 2. ESP efficiency for coal fly ash for chosen values of discharge electrode voltage supply

Coal fly ash				
ESP Operating voltage [kV]	**Carrier flow velocity 1 m/s**			
	Dust concentration at the ESP inlet **2000** [mg/m^3] / Dust concentration at the ESP **outlet** [mg/m^3]	**ESP efficiency** [%]	Dust concentration at the ESP inlet **4000** [mg/m^3] / Dust concentration at the ESP **outlet** [mg/m^3]	**ESP efficiency** [%]
0	500.0	0.0	840.0	0
5	226.7	54.7	673.3	19.8
10	26.7	94.7	66.7	92.1
15	6.7	98.7	20.0	97.6
30	6.7	98.7	6.7	99.2
ESP Operating voltage [kV]	**Carrier flow velocity 1.5 m/s**			
	Dust concentration at the ESP inlet **2000** [mg/m^3] / Dust concentration at the ESP **outlet** [mg/m^3]	**ESP efficiency** [%]	Dust concentration at the ESP inlet **4000** [mg/m^3] / Dust concentration at the ESP **outlet** [mg/m^3]	**ESP efficiency** [%]
0	830.0	0.0	1413.3	0.0
5	700,0	15,7	1260.0	10.8
10	126.7	84.7	226.7	84.0
15	40.0	95.2	120.0	91.5
20	6.7	99.0	33.3	97.6
30	6.7	99.2	20.0	98.6

Table 3. ESP efficiency for biomass fly ash for chosen values of discharge electrode voltage supply

Biomass fly ash				
ESP operating voltage [kV]	Carrier flow velocity 1 m/s			
	Dust concentration at the ESP inlet **2000** [mg/m^3] / Dust concentration at the ESP **outlet** [mg/m^3]	**ESP efficiency** [%]	Dust concentration at the ESP inlet **4000** [mg/m^3] / Dust concentration at the ESP **outlet** [mg/m^3]	**ESP efficiency** [%]
0	393,3	0,0	773,3	0,0
5	166,7	57,6	393,5	49,1
10	6,7	98,3	6,7	99,1
15	6,7	98,3	6,7	99,1
30	3,3	99,2	6,7	99,1
ESP operating voltage [kV]	Carrier flow velocity 1.5 m/s			
	Dust concentration at the ESP inlet **2000** [mg/m^3] / Dust concentration at the ESP **outlet** [mg/m^3]	**ESP efficiency** [%]	Dust concentration at the ESP inlet **4000** [mg/m^3] / Dust concentration at the ESP **outlet** [mg/m^3]	**ESP efficiency** [%]
0	666.7	0	1100.0	0.0
5	440.0	34	753.3	31.5
10	26.7	96	46.7	95.8
15	3.3	99.5	6.7	99.4
30	3.3	99.5	3.3	99.7

efficiency for chosen values of the ESP discharge electrode supply voltage at the carrier flow velocity v=1.0 m/s and v=1.5 m/s have been compared in Table 2.

The analysis of the results presented in Table 2 indicates high ESP efficiency. Accepting the most unfavorable ESP operating conditions e.g. high velocity of flowing exhaust gases and high dust concentration at the boiler outlet, the discharge electrode voltage (for a ø150 mm diameter chamber) should equal about 20 kV. For such voltage, ESP operating current I will not exceed 0.5 mA.

The results of analogical ESP efficiency measurement for biomass fly ash are depicted in Table 3.

The analysis of the results indicates that in case of biomass fly ash at the discharge electrode supply voltage $U \geq 15$ kV, the suspended dust concentration at the ESP outlet is lower than the concentration level recommended by The European Council Guidance (40 mg/m^3). The measurements results shows above proved effectiveness of separation, both coal and biomass fly ashes, although these dusts have different physicochemical and electrical properties.

4. Conclusion

The experiment and the analysis of the measurements results were aiming at developing an idea of a construction of the ESP and a selection of its geometrical, electrical and processing parameters. This target has been reached, which can be confirmed by the received ESP efficiency. It has been defined the ESP operating parameters providing a proper run of the process of separating solid fuels fly ashes used in households.

The results of verifying examination carried out on a laboratory stand with the usage of coal and biomass fly ashes proved that the ESP separates dust according to the accepted assumptions. It has been confirmed by carrying out a dedusting test in which gas-dust aerosol concentration 12-times exceeded the concentration values resulting from the exploitation of an energy boiler in household conditions. In those tests dust was loaded to the ESP in such quantity to reach 4000 mg/m^3 of its concentration at the outlet. At supply voltage U=20 kV ESP efficiency was equal or greater than 97.6%. It means that selected operating conditions (with the parameters similar to model dust produced from coal and biomass combustion) caused a decrease in dusting from 300 mg/m^3 to values lower than 10 mg/m^3. Thus, the received results indicate for the correctness of the idea of an ESP construction.

The validation of the ESP constructional solution for households needs required examining the ESP device in real conditions. Due to that fact, the ESP of ø180 mm diameter chamber prototype has been made for household needs. It has been installed in a gas pass in a building heated with an energy boiler DEFRO Optima Comfort 15STD of 15 kW feeds with coal or wood pellets. That ESP has been equipped with a collecting electrode dust deposits dislodged system. It enables a proper run of the dedusting exhaust gases process. The ESP is supplied from one-phase 230V electric network. The supply circuits consist of: a high voltage supplier 30 kV DC, a microprocessor controller supervising ESP operation e.g. conjunction temperature exceeding the dew-point in the ESP chamber, the time interval of purifying the electrode from dust deposit, the appliance operating state etc. The estimated power consumption at nominal load does not exceed 30W.

The idea of the constructional solution shown above, after further exploitation experiments, will enable production of ESP suitable for individual needs.

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Bolesław KARWAT
Ryszard MACHNIK
Jerzy NIEDŹWIEDZKI
Magdalena NOGAJ
AGH University of Science and Technology
al. Mickiewicza 30, 30-059 Kraków, Poland
Faculty of Mechanical Engineering and Robotics

E-mails: karwat@agh.edu.pl, machnik@agh.edu.pl, jniedz@agh.edu.pl, nogaj@agh.edu.pl