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STUDY OF A NEWLY DEVELOPED LOW-POWER COLD PLASMA ELECTROSTATIC FILTER FOR PURIFICATION OF GAS FLOW FROM ULTRAFINE POLYDISPERSE PARTICULATE MATTER

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Abstract. *The extraction of particulate matter (PM) from gas streams is a major challenge in industrial and environmental settings, especially for ultrafine and polydisperse particles that conventional filters capture inefficiently. This study investigates a low-power cold plasma electrostatic filter designed to improve energy efficiency under these constraints. The device operates at electrode voltages up to 6 kV, unlike conventional electrostatic precipitators requiring high energy input, reducing operating costs. It uses cold plasma ionization to create an electric field that captures ultrafine particles (0.4–10 microns) with over 99% efficiency at gas flow rates of 1 m/s. Experiments show an average deposition efficiency of 88% for particles below 1 micrometer, even at concentrations of 35,000 particles per liter. These results demonstrate its suitability for industrial gas purification and emission control. The findings emphasize cold plasma advantages, lowering voltage requirements and enabling compact designs for stationary and mobile systems. Future research will examine current intensity and electrode design to further improve performance in applications with fluctuating pollution loads and flow conditions.*

Key words: *Electrostatic filter, Ultrafine particulate matter, Cold plasma, Low power*

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1. INTRODUCTION

The cleaning efficiency of the gas stream by conventional methods does not allow the required level of cleaning to be achieved. Increasingly, work has been proposed to capture particulate matter (PM). Most of the research is focused on cleaning up polluted gas emissions from energy production sources, both on the scale of individual plants and on the scale of an entire process line or industrial site. For example, emissions from different types of solid fuel combustion boilers are being investigated. Dilution technologies are being investigated to reduce PM concentrations [1]. There are scientific papers that describe the results of studies on gas stream cleaning using liquid fuels from renewable sources as well as experimental data obtained under natural conditions from the combustion of edible oil.

The technologies used for gas stream cleaning are based on the characteristics of the pollutants and the parameters of the plant process line. Conventional cyclone-type units are used in many configurations with efficiencies of up to 90% for PM below 5 μm [2,3]. The installation of an electrostatic apparatus is suitable exclusively for fine cleaning or recovery of the process fraction; however, it has many limitations as an independent unit and the operation of the electrical system requires special expertise [4-7].

The removal of PM is considerably simpler technologically and actually more efficient when the dust stream is as homogeneous as possible, with a uniformity of flow and a small range in concentration and size. The multi-channel cyclone has only relatively recently been used to clean the contaminated gas stream of high concentration and a relatively wide range of ultrafine PM (UFPM) and coarse PM. However, the centrifugal forces applied by the cyclone are insufficient to remove the finely dispersed PM that is moving through a turbulent air stream. Fine PM is removed using electrostatic precipitators [4-8]. However, these filters, which can operate in environments with high flow of PM gas, are bulky due to the nature of the technology, that is, the large distance between the charging and deposition electrodes and, therefore, are not suitable for low flow rates and mobile devices [9]. There are studies on the application of conventional treatment plants under specific environmental conditions and agglomeration of PM, making maintenance of these technologies difficult [10-12].

An alternative approach is to apply additional treatment of the PM stream upstream of the treatment plant to agglomerate the PM. An approach is to apply cold plasma technology, which changes the state of the PM stream and also precipitates some of the PM using electrostatic force [13]. The generation of high-energy electrons, ions, reactive groups, excited-state molecules, and atoms in such a device allows additional collisions to trigger physical and chemical reactions. This technology is being investigated in industrial gas and engine exhaust cleaning systems, where the effect of ion wind occurs in the electric field interaction [14]. The electric field and, in particular, its different characteristics, have a significant impact on changing the flow state when aerodynamic processes are less intense, for example, at low flow velocities or in high-volume channels. The effect of electric flow allows for increased precipitation of PM, in particular by reducing the weight of UFPM among all fractions [14-16]. The behavior of the gas flow under the electric field is particularly dependent on the characteristics of the latter, and its proper control allows prioritizing the composition of the contaminated flow according to the demand, in this case, to achieve a higher cleaning efficiency.

Traditionally, electrostatic filters use a corona to transfer charge to particles in the electrostatic field zone. In the process, an electrical and thermal zone is created. In turn, the use of cold plasma is poorly understood, but it has its advantages. To create a strong

electrostatic field, a voltage of no more than 10 kV is used, and the current strength is much lower, no more than 500 mA, than conventional generators. However, the efficiency of using cold plasma to electrify particles is comparable to that of the conventional method, and at peak voltages it is even more effective. Special importance should be given to the control of the flow velocity in the cold plasma zone. Since a relatively low voltage is used, the volume of the impact area of the particles is therefore not that large.

Cold plasma generated in the LVCPEP system is a non-thermal plasma formed under a high electric field gradient at relatively low applied voltage (4–6 kV). In such a discharge, the electron temperature is significantly higher than the bulk gas temperature, enabling ionization without substantial gas heating. The ionization region produces free electrons, positive and negative ions, and excited species. These charged species interact with suspended particles through two dominant charging mechanisms:

(i) diffusion charging, which is dominant for ultrafine particles (<0.3 μm), and
(ii) field charging, which becomes dominant for particles >0.3–0.5 μm.

The acquired particle charge q increases the electrostatic force acting on the particle:

$$F_e = qE \tag{1}$$

here F_e is the electrostatic force, q is particle charge and E is the electric field strength.

The resulting particle migration velocity toward the collecting electrode is:

$$v = \frac{qE}{3\pi\mu d_p} \tag{2}$$

where μ is the gas dynamic viscosity and d_p is the particle diameter.

Additionally, ion motion generates electrohydrodynamic (EHD) ionic wind, which modifies local flow structures, reduces boundary layer thickness, and enhances particle transport toward the collecting surface.

The combination of enhanced particle charging and EHD-assisted transport explains the high fractional efficiency observed even at relatively low applied voltage.

Usually, the particle enters the zone of action of the electrostatic field with an initial velocity that depends on the gas-flow velocity. Consequently, when the particle crosses the zone and is perpendicular to the ionization electrode, its vertical motion y depends on the drift velocity v and has the form of a parabola:

$$y = \frac{1}{2}\left(\frac{\rho E}{m}\right)\cdot\left(\frac{x}{v}\right) \tag{3}$$

where m is the particle mass, and x is the distance travelled by the particle under the influence of the electric field [17].

The motion of particles in an electrostatic field is often cyclic. If the wave is single-phase sinusoidal, the particle velocity is equal to the wave velocity, but in asynchronous mode the particle velocity is much smaller, it occurs at peak frequency:

$$f = \frac{\sqrt{g \cdot k}}{\pi} \tag{4}$$

here g is a specific parameter of the electrostatic field, and $k = 2\pi/\lambda$ is the wave number, and λ is the wavelength [18].

The principle of charge transfer Δq to the particle from the ionizer wall can be represented using the condenser model [19]:

$$\Delta q = k \cdot C \cdot V \tag{5}$$

$$C = \frac{\varepsilon_0 \cdot S}{z_0} \tag{6}$$

with k denoting the charging efficiency, C is the capacitance, V the total potential difference, ε_0 is the absolute permittivity of the gas flow, S is the contact area, and z_0 is the peak distance between the electrode plane and the particle.

A particle content of the flow is not uniform in electrostatic precipitators, but collisions with the ionizer surface can be counted in thousands per second. In this way, the charge of particles generated by repeated collisions with the surface can be formulated. For this purpose, a transformed capacitor model is used. A continuous quantity dq/dn is used to obtain the charge q as a function of the number of particle-wall collisions n:

$$\frac{dq}{dn} = k \cdot C \cdot V \tag{7}$$

$$q_\infty = \frac{V}{k} + \frac{z_0}{k} E \tag{8}$$

here dq/dn is the incremental particle charge per collision.

The study of aerodynamic parameters is critical from a technological point of view. By examining changes in the gas flow in the characteristic sections of the cleaning system, the optimal efficiency of the cleaned air or the speed of the supplied stream is determined together with the observed load losses, and the characteristics of the electric field are selected according to the design of the device and the physical properties of the deposited PM and its constituent elements [20–22]. When individual devices are used, the theoretical design parameters are taken into account, in which the standard device achieves maximum efficiency. The speed of gas flow is about 0.5–2 m/s in a conventional electrostatic filter, and some industrial-scale ionizers are capable of operating at 0.5–5 m/s; however, in general the optimal flow is about 1 m/s [23, 24]. The theoretical parameters of improved or significantly changed cleaning technologies do not necessarily reach optimal indicators; therefore, they are determined by tests and applied only to the original device. The use of complex cleaning technology is even more demanding, since the parameters of successive, separately used devices must be coordinated, and their variability at these stages should not be critical for neighboring devices connected in the technological line.

In this work, using electrostatic PM deposition technology with the help of cold plasma, the task was to experimentally study the dependence of the capture efficiency of UFPM fractions at low voltages applied to the corona electrode. The idea behind developing a purification device based on the electrostatic principle is to achieve high efficiency in depositing particles of a wide range of sizes from a gas flow. The novelty of the design and parameters of this precipitator allows comparable characteristics to be achieved with low power required for the ionization process. In addition, the use of this type of small-sized technology is sufficient to handle the traditional volume flow rate of gas for the precipitation of high particle concentrations.

2. MATERIALS AND METHODS

A previous study of cyclones [23] was presented, including the design of the electrofilter based on the physical prototype of the newly developed centrifugal electrostatic precipitator. The primary version of the stand was made under laboratory conditions to study the aerodynamic parameters of the gas flow. The principal design of the apparatus is shown in Fig. 1.

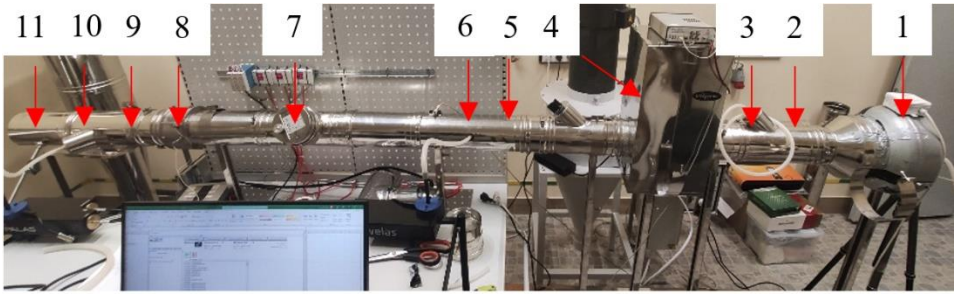


Fig. 1 An experimental electrostatic precipitator bench with (1) air flow fan, (2) air flow rate test point before an equalization section, (3) ultrafine particulate matter injection from the dosing system, (4) equalization section, (5) static air flow pressure before the apparatus, (6) particulate matter concentration test point before cleaning, (7) regulation valve, (8) electrostatic precipitator, (9) static air flow pressure toward the apparatus, (10) particulate matter concentration test point after cleaning, (11) air flow rate test point toward the apparatus.

A low-voltage cold plasma electrostatic precipitator (LVCPEP) stand consists of a fan of variable flow rate connected with the gas flow inlet duct. The gas flow passes through the duct system including equalizer to minimize flow turbulence, pressure-adjustable valve, and site for pressure, flow rate, and concentration tests. Only a brief text view of the technology is provided as a European patent application is being prepared for this apparatus, which will be submitted for consideration in the near future. The filter assembly consists of a capsule housing with insulating inserts, with a housing length of 300 mm and an outer diameter of 160 mm. The electrical circuit contains a transformer, a current equalizer, and a voltage regulator. The system allows a voltage of up to 6 kV to be achieved at a current of 290 mA, with the possibility of stepwise voltage reduction. The volumetric flow rate of gas supplied to the precipitator was studied in the range from 50 m^3/hour to 110 m^3/hour. To study the degree of precipitation in a wide range from 0.2 μm to 10 μm, quartz sand particles with a median size of 2.5 μm were used.

The LVCPEP design consists of a longitudinal spiral located along the entire cross section of the gas pipe. Isolator elements are located on the peripheral sections in each quarter, as well as in the internal channels, to fix a constant area of the peppered section along the entire length of the cold plasma ionization electrode. Voltage regulation is performed by means of a transformer, voltage and current supplied to the ionizer are measured.

A flow rate study was carried out using Testo 440 and Testo440dP, and the hot wire probe included a temperature and humidity sensor connected to the tube and controlled the flow parameters, volumetric flow, gas flow velocity, pressure loss and standard measurement

conditions, temperature, relative humidity and barometric pressure. Technical data of the multimeter: measuring range 0-50 m / s, -20 to +70 °C, 5–95%RH, 700–1100 hPa; accuracy ±(0.03 m/s + 4% of the measurement value (m.v.)) (0 to 20 m/s), ±0.5 °C (0 to +70 °C), ±3.0% of Relative Humidity (RH) (10 to 35% RH) and ±2.0% RH (35 to 65% RH), ±3 hPa; resolution 0.01 m/s, 0.1 °C, 0.1 % RH, 0.1 hPa.

All experiments were carried out using a Palas RGB 1000 fine particulate matter dispenser. Particle sampling locations before purification and after purification were performed using a Palas Welas Digital 3000 laser particle analyzer and detectors operating on the principle of optical light-scattering. Measurement range of 0.2 to 10 μm; up to 128 size channels per measuring range; concentration range of 1 particle/cm^3 or 1 thousand particles/liter up to 106 particles/cm^3 or 106 thousand particles/liter. By experimentally measuring the numerical concentration of PM before and after purification, the degree of purification of the technology was determined. When evaluating the mass concentration of PM, the minimum value recorded by the device is not less than 0.001, otherwise the result is 0.

The deposition efficiency of the purification apparatus was investigated in a few cases: without dosing; with dosing and at 4 kV voltage and current 30 mA; with dosing and at 4 kV voltage and current 40 mA; with dosing and at 5 kV voltage and current 40 mA; with dosing and at 5.5 kV voltage and peak current 124 mA; with dosing and at 6 kV voltage and peak current 287 mA. All cases were analyzed at 1 m/s gas flow, corresponding to a gas flow of approximately 75 m^3/hour.

Each test was repeated not less than five times for statistical analysis of uncertainty until a constant measurement value was obtained under the same meteorological conditions. Measurement equipment was connected at significant points.

3. RESULTS

To investigate the effectiveness of the cold plasma action on gas flow with UFPM in the gas pipe system, the gas flow was reshaped so that the LVCPEP action section had a gas flow velocity of 1 ± 0.05 m/s. In this way, the velocities at intermediate points and pressures presented in Table 1 were obtained throughout the experimental bench chain.

Table 1 Velocity and static pressure of gas flow in an experimental low-voltage cold plasma electrostatic filter model

Test point	1	2	4	5	6	7	8	9	11
Gas flow rate, m/s	1.75	1.40	0.60	1.20	1.04	1.03	1.02	0.99	0.83
Static pressure, Pa	45	42	15	28	25	23	21	18	11

The gas flow rate was chosen to be the same for all studies, that is, the input gas flow rate was equal to 1.75 m/s, which corresponds to 127 m^3/hour. The reduction in static pressure across the line is not significant and is mostly due to local pressure losses at the gas duct extensions and at the flow equalization section, and from site 5 to site 9 it was equal to 10 Pa. A total pressure value of 50 Pa or less does not require an energy-consuming air flow source, so operating costs are minimal.

Various investigations of numerical changes in PM concentration were carried out before and after the electrostatic cold plasma filter and the dependence on the UFPM

fraction was determined ranging from 0.1 μm to 10 μm was determined, the results of the average values are presented in Fig. 2.

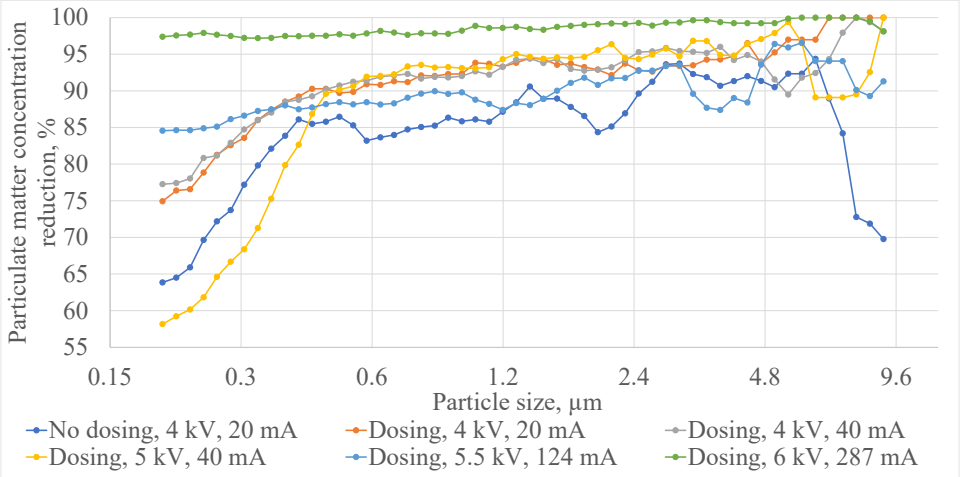
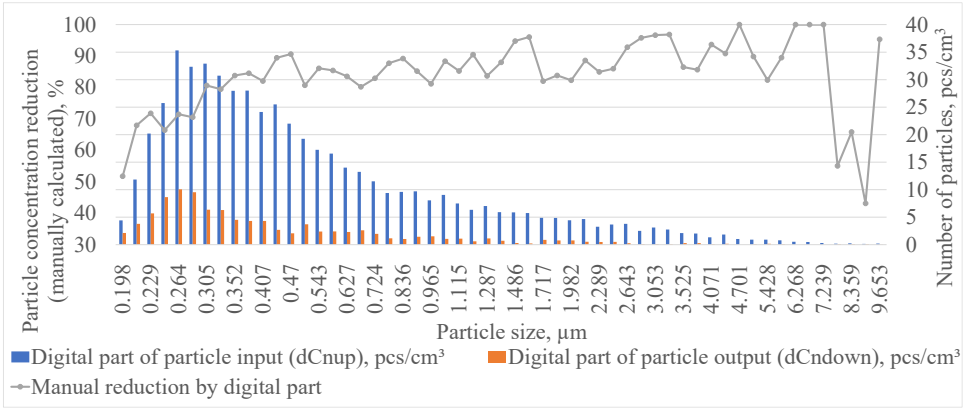


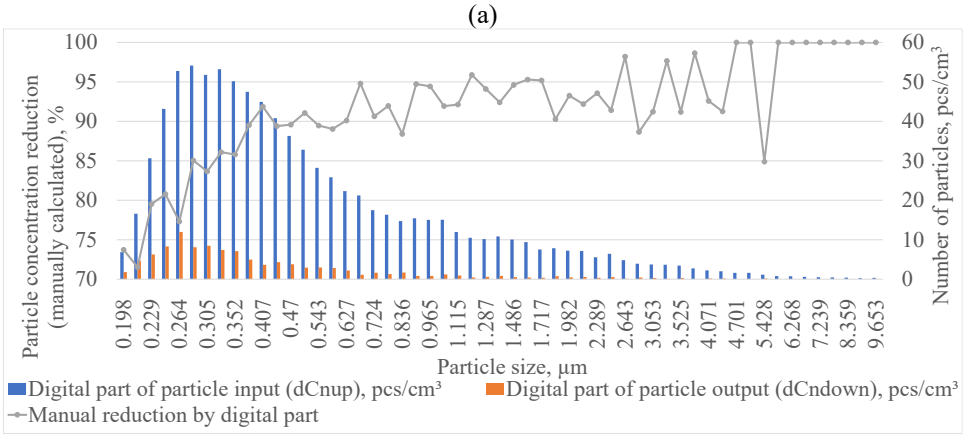
Fig. 2 The dependency of fractional efficiency expressed as the number of concentrations of particle matter reduction on the particle size for all cases of voltage and current cold plasma analysed

Of all the cases investigated, the case at a voltage of 5 kV and a current strength of 40 mA is the least effective. Under these conditions, the charge is not sufficiently transferred to the UFPM fractions of 0.2 to 0.41 μm, when the mean deposition value is 68%. However, PM greater than 0.4 μm is deposited with at least 85% under this electrostatic field, and PM of size 1.2–10 μm are removed from the flow with an average efficiency of 94.8%. LVCPEP at the expense of not so large voltage, the working phase reaches a numerical PM concentration of not less than 10 thousand PM/liter. This indicator is confirmed by the results obtained without PM dosing, when the PM fractions were equal to 0.2-0.4 and 7.2-10 μm, they were deposited with less than 80% efficiency, and it is also possible to notice non-uniformity in the entire range of PM fractions, when the values fluctuated between 85.1–93.4%. It is also determined that the most critical component of LVCPEP is the current strength, and a current greater than 40 mA produces the most effective field for PM electrification. When the voltage increases, especially above 4 kV, the deposition of UFPM of sizes between 0.2–0.5 μm increases significantly. For medium-sized PM, the trend is similar in all cases, but a voltage of 6 kV increases the deposition of larger PM by 3.3–5.8%.

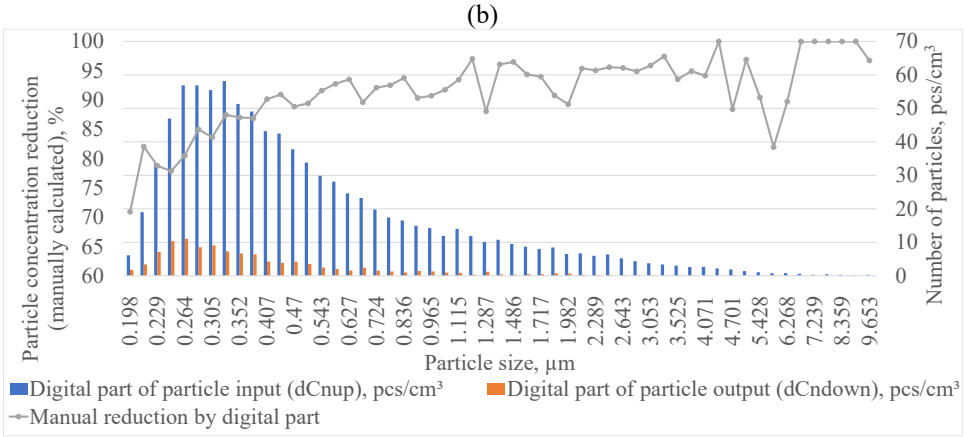
Purification efficiency studies were carried out with a flow without PM dosing, with numerical PM concentrations in the range of 10-35 thousand PM / liter. The applied voltage to the ionizing electrode was 4 kV and the current intensity was 20 mA. Detailed results are shown in Fig. 3a. The variation in fractional deposition without dosing (Fig. 3 (a)) in the gas stream shows that the efficiency reaches 75–85% at a relatively low numerical concentration of PM. The PM of size 0.229-0.543 size prevailed, and the UFPM amount reached up to 20-35 thousand PM / liter. The output concentration of UFPM with a size in the range of 0.229-0.305 μm was equal to up to 5 thousand PM / liter.



(a)



(b)



(c)

Fig. 3 Dependence of particle number concentration reduction in input and output on the particle size of cold plasma ionizer at 4 kV voltage and 20 mA current without dosing (a), 4 kV voltage and 20 mA current with dosing (b), 4 kV voltage and 40 mA current with dosing (c)

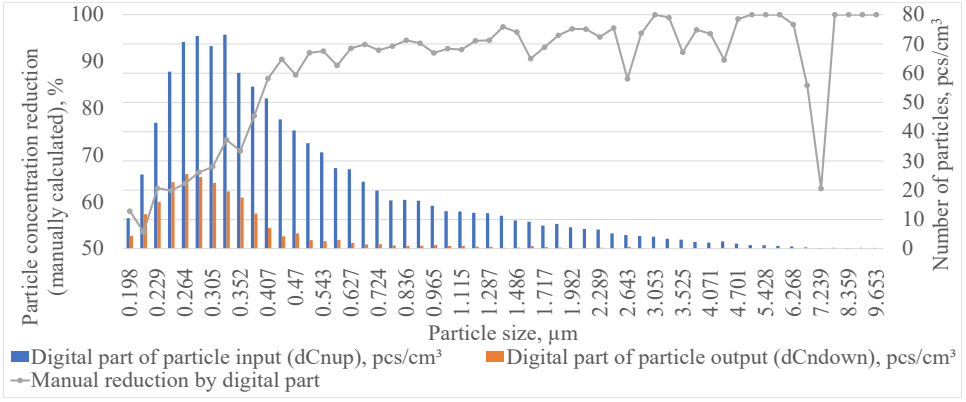
Studies were used to approximate the working conditions of the electrostatic precipitator close to those of the industrial ones. Dosing of solid particles with feed into the inlet gas pipe, with a dosing mechanism of up to 2 mm / hour, the numerical PM concentration reached 20-60 thousand PM / liter. The applied voltage to the ionizing electrode was 4 kV and the current intensity was 20 mA. Detailed results are presented in Fig. 3 (b). The PM dose increased the number of particles by more than a factor of 2, with an average efficiency of 91.7%. Ultra fine particles are deposited with at least 71.5%, and, for example, the peak value at 0.724 is 94.8%. Insignificant drops in efficiency are identified with particles larger than 3 μm, when the minimum efficiency is 84.9%. The particulate dose with a constant feed rate of up to 2 mm/hour, the numerical PM concentration remained between 20-70 thousand PM / liter. The applied voltage to the ionizing electrode was 4 kV and the current was increased to 40 mA. The detailed results are shown in Fig. 3 (c).

When the current strength is increased up to 40 mA, the deposition efficiency of UFPM reaches 90.9%, and in the full range of fractions, the value is even higher, 91.5%. The numerical concentration of PM with the exclusion of the 0.237 μm and 0.255 μm PM fractions was equal to no more than 10,000 particles / liter.

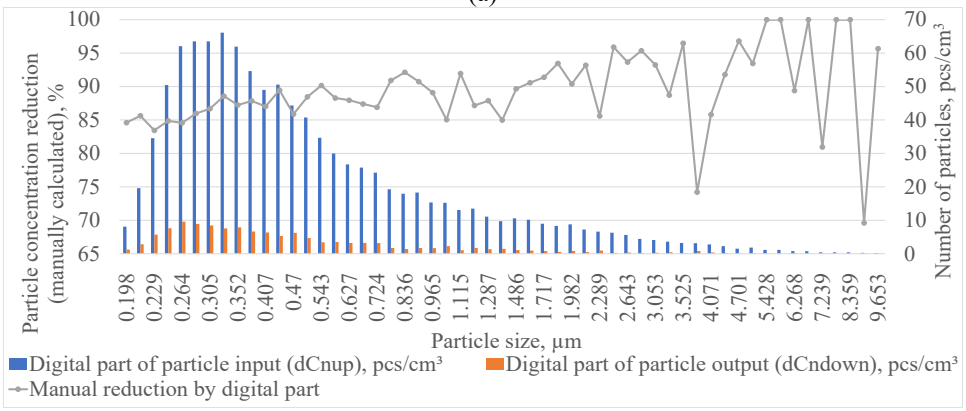
4. Discussion

With a long-term dose of particulate matter at a constant feed rate of up to 2 mm/hour, the numerical PM concentration increased and was in the range of 20 to 80 thousand PM / liter. The applied voltage to the ionizing electrode was increased to 5 kV, and the current was equal to 40 mA. Detailed results are presented in Fig. 4 (a). At higher voltages in the LVCPEP ionizer system, a much stronger field of charge transfer to the particles is created, which is reflected in the deposition efficiency of all particle fractions. However, a field of this magnitude actively charges PM larger than 0.4 μm, which can be seen in the 86.4% deposition rate. At the same time, UFPM is still deposited with 53.5-73.2% efficiency and output concentrations exceeding 20 thousand PM/liter. By establishing constant particle dosing, only the applied voltage to the ionizing electrode was increased to 5.5 kV and the current was set to 124 mA. The detailed results are shown in Fig. 4 (b). With a further increase in the values of the electrical characteristics of the filter system, there are more fluctuations because of the non-uniformity of the electrostatic field with minima and maxima, so fluctuations in the efficiency in the deposition values of adjacent PM fractions were observed. However, the average efficiency increased and is 86% for UMPM 0.2-0.4 μm, 88.9% for PM 0.4-1 μm and 91% for PM 1-10 μm. The maximum efficiency was achieved for the deposition of particles of 5.4-8.4 μm and was equal to up to 100%. All values of PM output concentration are less than 10,000 PM / liter, and the numerical concentration of particles above 0.75 μm is less than 24 thousand PM / liter.

The final study was conducted at the peak value for this cold plasma ionizer circuit when the applied voltage to the ionizing electrode was 6 kV and the current was 287 mA. The detailed results are presented in Fig. 4 (c). No changes in the numerical PM concentration values were observed. The highest deposition efficiency was obtained at the highest electrostatic field strength in the system, with a minimum efficiency value of 95.8%. Small variations in the efficiency values between adjacent fractions of PM were also obtained, with an average efficiency value of 98.6%, and PM greater than 2.7 μm with intermediate decreases was deposited with an efficiency of 100%. The highest output numerical concentration was 2.119 thousand PM / liter, but in 95% of the cases the concentration value was less than 1 thousand PM / liter.



(a)



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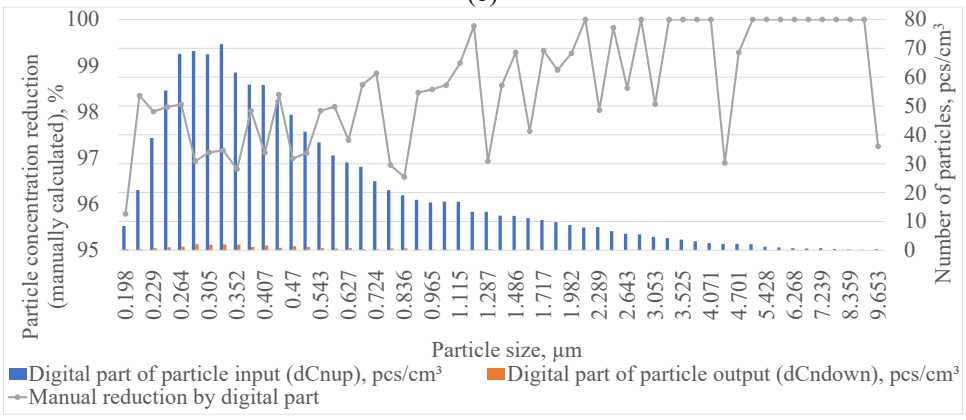

(c)

Fig. 4 Dependence of particle number concentration reduction in input and output on the particle size of cold plasma ionizer at 5 kV voltage and 40 mA current with dosing (a), 5.5 kV voltage and 124 mA current with dosing (b), 6 kV voltage and 287 mA current with dosing (c)

Not only the numerical reduction but also the mass reduction of UFPM is critical for additional purification analysis of UFPM. The low mass of small-diameter particles is not as critical as larger particles, e.g., more than 5 µm in size. The results of the reduction of the PM mass concentration averaged from the six studies according to their fractions in the range of 0.1-10 µm were obtained in Fig. 5. The results are reflected only for PM greater than 0.898 µm, since the mass concentration of PM analyzing all cases was recorded less than the minimum value recorded by the measurement instrument.

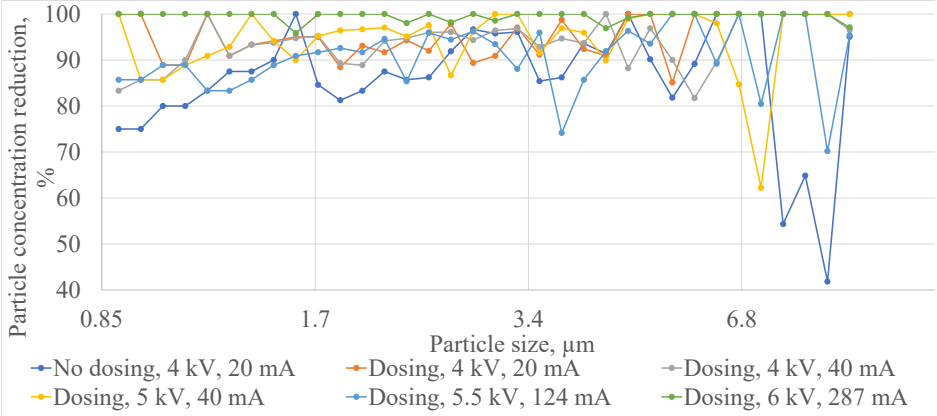

Fig. 5 The dependence of fractional efficiency expressed as the mass concentration of the particle reduction on the particle size for all the cases analysed

Taking into account the deposition efficiency with the distribution of the mass PM concentration, we can conclude that the situation has not changed significantly. In the case with a maximum electrostatic field voltage of 6 kV, only a few PM size positions do not reach the full purification of 100%, all values for a size greater than 1.597 µm. A trend was also observed that in all cases particles smaller than 0.836 µm were completely deposited. There could be another explanation for this; because the mass was too low after purification, the mass of the UFPM approached zero. Also, in such cases, because of the low concentration of the flue gas, the concentration before purification may be lower than the concentration after purification. The average mass PM concentration efficiency in all cases for PM of size 0.836-1.982 µm is 91.6% and the maximum 99.7%. PM greater than 1.982 µm was deposited with an average efficiency of more than 94%, with a maximum of 99.5% when the voltage was maximum. The results obtained from the study prove the effect of a low-power cold plasma electrostatic field, especially on small fractions of PM. The application of this newly invented technology is effective at medium and high concentrations of PM in the gas stream, not less than 30 thousand particles/liter.

The use of traditional electrostatic precipitators has proven itself in many areas of production for effective precipitation and separation of particles from gas flows. The technology studied in this work is characterized by low power consumption, which is a significant advantage, especially in areas with high-voltage power supply difficulties. Consequently, this technology can be integrated into systems with low energy consumption and long service life. The small size of the device also expands the possibilities for its use in a single housing near sources of pollution for the precipitation of particles at the earliest

possible stage. The cleaning device is made of materials resistant to temperatures up to 500 °C and is equipped with an ionization system that generates a low concentration of ozone due to its low power consumption. According to initial data, the ozone concentration inside the channel does not exceed 3 ppm. Thanks to the improved design with spiral elements, the contaminated gas flow is distributed evenly throughout the intermediate channel of the precipitator. At the same time, the layer of precipitated particles does not create a large load on the electrodes due to the expanded active surface, which has a beneficial effect on the effectiveness of cold plasma.

5. CONCLUSION

The improved technology in the newly developed electrostatic filter device according to the research performed proved its efficiency with the use of low voltage for the ionization of ultrafine particulate matter. Ultrafine particles of 0.5 μm or less with an average efficiency of 84.5% are deposited in the cold plasma field created at a voltage of 4 kV. When the field voltage is increased to 6 kV, the efficiency reaches 97.5% for particles smaller than 0.5 μm, with an overall efficiency of 98.5% for PM sizes between 0.2 and 10 μm. The results mentioned above are achieved with a gas flow of 1±0.05 m/s in the ionization zone and a total air flow rate equal to 127 m^3/hour at the inlet of the system. In further studies, it is planned to test the system at different variations of current strength and at constant voltage and determine the dependence, as well as change the design of the ionization element to increase the ionization field zone of cold plasma and charge transfer for the deposition of ultrafine particles.

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