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Development and research of charger operation modes type “needle-plate” for nanoparticle charging

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Abstract. A simple needle-plate charger with a gap of 16 mm for unipolar charging of silver nanoparticles in an air stream has been developed and manufactured. The charging efficiency and particle electrostatic losses of the designed charger were evaluated at various applied voltages and aerosol flow rates. With an increase in the applied voltage (corona discharge current) and the aerosol flow rate at a constant applied voltage, a decrease in the charging efficiency and an increase in the total losses of aerosol particles are observed. A charging efficiency of 43% with 38% electrostatic loss was achieved at a voltage of 8.1 kV (5.5 μA) and a flow of 10 L/min.

Keywords: charging efficiency, aerosol nanoparticle, unipolar charging, corona charger

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Разработка и исследование режимов работы зарядного устройства типа «игла-пластина» для зарядки наночастиц

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Аннотация. Разработано и изготовлено простое зарядное устройство типа “игла-пластина” с зазором 16 мм для униполярной зарядки наночастиц серебра в воздушном потоке. Эффективность зарядки и электростатические потери частиц разработанного зарядного устройства оценивались при различных приложенных напряжениях коронного разряда и расходах аэрозоля. В результате одновременного уменьшения расхода воздуха и снижения тока коронного разряда устройство показывает лучший результат выходной эффективности зарядки, чем при высоких значениях этих параметров. Эффективность зарядки 43% с электростатическими потерями 38% была достигнута при напряжении 8,1 кВ (5,5 мкА) и потоке 10 л/мин.

Ключевые слова: эффективность зарядки, аэрозольные наночастицы, униполярная зарядка, коронный заряд

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Introduction

The process of charging nanoparticles is of great importance in the fields of science and technology related to aerosols. The need to charge nanoparticles is seen, for example, in differential mobility analysis of submicron aerosol particles to measure distribution [1, 2]; deposition of nanoparticles at selected locations to form nanostructures [3]; reduction of coagulation to obtain higher concentrations of nanoparticles [4]. In this work, diffusion charging of nanoparticles by a unipolar ion cloud of a DC corona discharge using a "needle-plate" device is studied as the only suitable charging mechanism, as a result of which ions diffuse to the particle surface and charge transfer. Studies of such a device have already been performed for a monodisperse aerosol [5], while the external charging efficiency reached 45–50% for particles of 10 nm, which is a decent result for such a particle size. In our work, the device has a simpler design, sufficiently high efficiency 43% even for a polydisperse aerosol as a whole, and is also more resistant to contamination and has greater performance due to its larger size.

Materials and Methods

Using a multi-spark discharge generator (m-SDG), silver nanoparticles with a size distribution in the range from 16 to 500 nm were synthesized and transported in an air stream to a needle-plate charger (NPC), in which the distance between the electrodes was 16 mm. The charger itself is a PVC pipe with an internal diameter of 28 mm. In the side wall of the pipe, perpendicular to its main axis, a stainless steel needle with a tip curvature radius of 42 μm is inserted. A square stainless steel plate with a side of 18 mm is attached to the opposite part inside the pipe. When a voltage of 8.1–16.0 kV is applied to the needle and the plate is grounded, a corona discharge occurs between them, which serves as a source of ions. The charged aerosol was passed through an electrostatic precipitator (ESP), at the outlet of which the concentration of particles was measured using aerosol NP analyzer SMPS 3936. To determine the internal η_{intr} and external η_{extr} particle charging efficiencies, electrostatic losses L_E and the proportion of uncharged particles h, particle concentrations were measured when the NPC and ESP were turned on and off [5] after which the data were substituted into equations (1–4). A schematic representation of the experimental setup is shown in Figure 1.

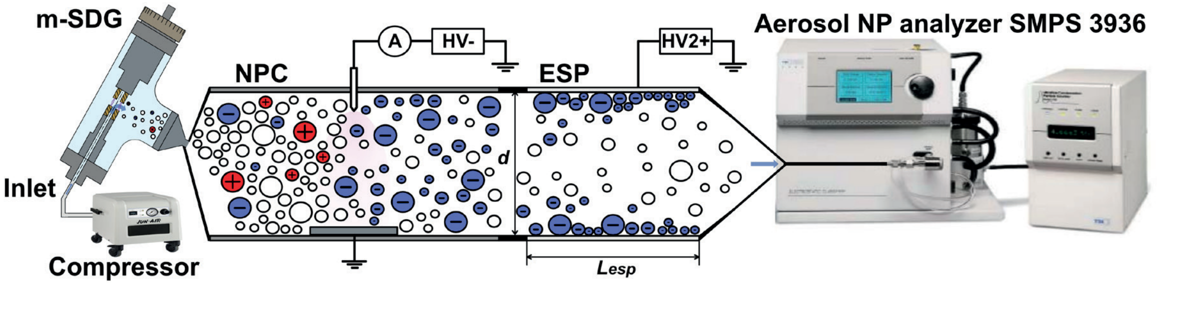

Fig. 1. The scheme of the experiment, which includes a multi-spark discharge generator (m-SDG), charger (NPC), an electrostatic precipitator (ESP) and an aerosol analyzer NP SMPS 3936

$$\eta_{extr} = \frac{n_2 - n_3}{n_1} \quad (1)$$

$$\eta_{intr} = \frac{n_1 - n_3}{n_1} \quad (2)$$

$$L_E = \frac{n_1 - n_2}{n_1} \quad (3)$$

$$h = \frac{n_3}{n_2} \quad (4)$$

where n_1 is concentration of particles at the outlet of the charger when the charger and electrostatic precipitator are OFF; n_2 is concentration of particles at the outlet of the charger when the charger is ON and the electrostatic precipitator is OFF; n_3 is concentration of particles at the outlet of the charger when the charger and electrostatic precipitator are ON.

Thus, η_{intr} shows the ratio of charged particles in the charger (including those electrostatically deposited in it) to the number of particles in the switched off charger. Further, η_{extr} shows the ratio of charged particles at the output of the charger to the number of particles in the switched off charger. Electrostatic losses L_E characterize the proportion of charged particles electrostatically deposited in the charger. Ultimately, it is necessary to achieve the highest value of η_{extr}, and for this it is necessary that the difference between η_{intr} and L_E be the largest. However, as the charging efficiency increases, the losses also increase, so it is necessary to find the optimal parameters of the charger.

Increasing the voltage U from 1.6 kV to 2.1 kV on a high-voltage power supply leads to an increase in the corona discharge current I from 10 μA to 225 μA, as well as to an increase in the ion concentration in the charging region (5), which positively affects the internal efficiency particle charging. On the other hand, this also brings an undesirable increase in the electrostatic losses of charged particles, since they are in a stronger electric field, move towards the plate with greater acceleration and settle on it.

$$N_i = \frac{I}{Z_i \cdot E \cdot A \cdot e} \quad (5)$$

where N_i is the concentration of ions in the region of the corona discharge; Z_i is electrical mobility of ions; E is electric field strength; A is effective anode surface area; e is elementary electric charge.

Results and Discussion

The study showed the dependence of fractions of uncharged and charged aerosol particles and losses of particles of the initial concentration at different air flow Q_{air} (Fig. 2, *b*). It has been found that increasing the air flow Q_{air} from 1 lpm to 20 lpm leads to a decrease in electrostatic losses L_E, but also increases the proportion of uncharged particles h. In the measured range, it can be noted that air flow Q_{air} = 1 lpm provides the minimum ratio of uncharged particles to charged particles at the output of the device, while Q_{air} = 20 lpm allows achieving the highest charging output efficiency η_{extr}. An increase in the voltage U in the NPC from 8.1 kV to 16 kV leads to an increase in the corona discharge current I from 5.5 μA to 59 μA and the concentration of N_i ions in the charging area, which reduces the external efficiency of η_{extr} charging particles from 43 to 6% due to an increase in the electrostatic losses of charged particles in the increasing electric field on the NPC plate. Chart of the fractions of uncharged and charged particles at the exit from the ESP and the losses of particles at different corona discharge currents in the NPC are shown in Fig. 2, *c*, *d*. At air flow Q_{air} = 10 lpm and a corona discharge current I = 5.5 μA, the output charging efficiency η_{extr} = 43%, and the fraction of uncharged particles h = 19%, while at Q_{air} = 20 lpm and I = 5.5 μA we obtain η_{extr} = 37% and h = 24%. As a result of analyzing the data from Fig. 2, *c* and Fig. 2, *d*, reducing the airflow while reducing the corona current shows a better result than with high values of these parameters.

Table 1

Influence of gas flow on values η_{int}, L_E and η_{extr}

U, kV	*I*, mkA	Q_{air}, lpm	η_{int}	L_E	η_{extr}	*h*
9.3	10	1	99.97%	92%	8%	0.03%
		5	99.7%	78%	22%	0.3%
		10	97.0 %	66%	31%	3%
		20	75.7%	39%	37%	24%

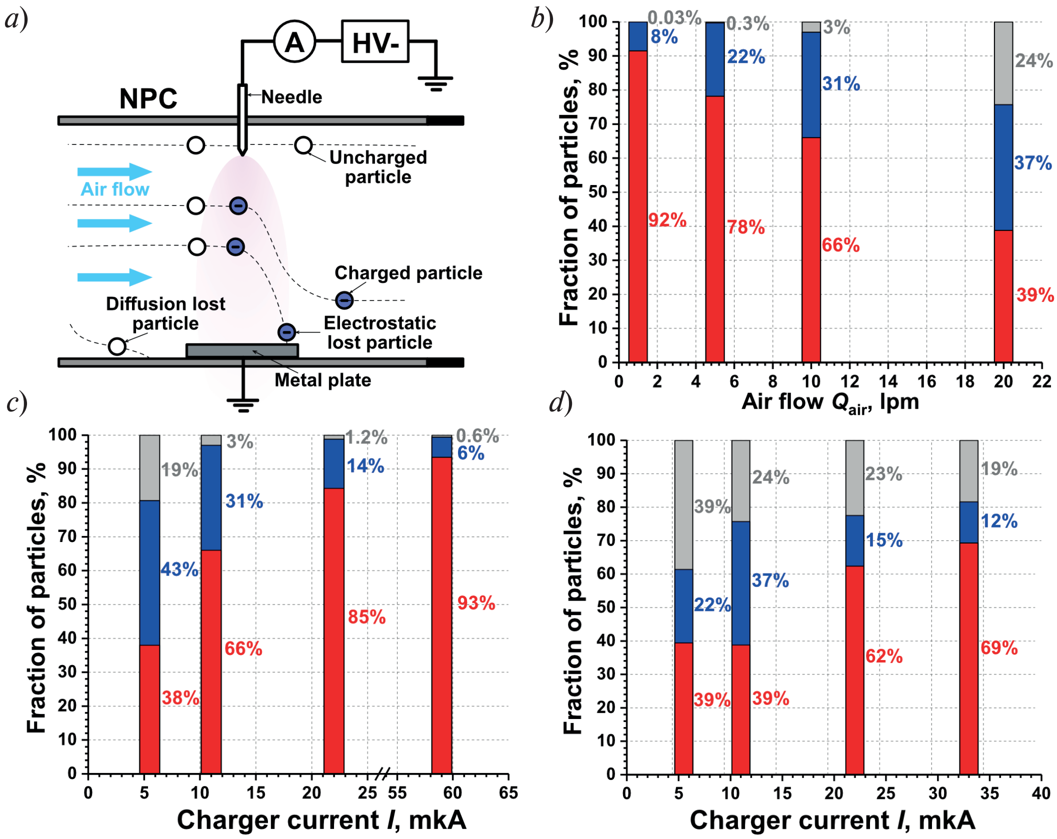

Fig. 2. Illustration of the particle charging and deposition processes occurring within the aerosol charger (*a*). Chart of the fractions of uncharged (gray) and charged (blue) aerosol particles and losses (red) of particles of the initial concentration at different air flow Q_{air} (*b*) and corona discharge current *I* with Q_{air} = 10 lpm (*c*) and Q_{air} = 20 lpm (*d*)

Table 2

Effect of corona discharge voltage on values η_{int}, L_E and η_{extr}

U, kV	*I*, mkA	Q_{air}, lpm	η_{int}	L_E	η_{extr}	*h*
16	59	10	99.4%	93%	6%	0.6%
12	22		98.8%	85%	14%	1.2%
9.3	11		97.0 %	66%	31%	3%
8.1	5.5		80.7%	38%	43%	19%
13.7	33	20	81.6%	69%	12%	19%
12	22		77.5%	62%	15%	23%
9.3	11		75.7%	39%	37%	24%
8.1	5.5		61.4%	39%	22%	39%

Conclusion

Using the example of a developed and manufactured needle-plate charger, the high efficiency of charging particles with sizes ranging from 16 to 500 nm with a small fraction of uncharged particles at the output is demonstrated. It was found that an increase in air flow increases the proportion of uncharged particles, but at the same time reduces losses. Increasing the corona discharge current has the opposite effect. By simultaneously reducing the airflow and reducing the corona discharge current, the device shows a better result of the charging output efficiency than with high values of these parameters. Parameters have been obtained that provide the highest output charging efficiency η_{extr} = 43%

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