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MATHEMATICAL MODELLING OF OIL MIST ELECTROSTATIC SEPARATION

Mathematical modelling of oil mist separation in a small-size two-stage electrostatic precipitator has been presented. Basing on theoretical studies, a model describing the process of electrostatic separation has been proposed. The results of the simulation are in good agreement with those of the experiment.

NOMENCLATURE

b – distance between electrodes in collecting stage,
c_g – limiting concentration,
c_0 – inlet oil mist concentration,
Cu – Cunningham correction,
d_p – particle diameter,
E_p – electric field strength in collecting stage,
L – length of collecting stage,
Q, Q_t – total charge of oil mist droplet,
Q_d – diffusion part of droplet charge,
Q_f – field part of droplet charge,
U – value of interelectrode voltage,
U^* – level of interelectrode voltage,
U_m – mass fraction,
V – electric field potential,
V_g – volumetric aerosol flow,
V_0 – potential of positive electrode in charging stage,
V_p – potential of positive electrode in collecting stage,
v – velocity of gas flow in collecting stage,
w – settling velocity,

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ε – gas permittivity,
η – total efficiency,
η_f – fractional efficiency,
μ – gas viscosity,
ρ – mean density of positive ions within ionization zone.

1. INTRODUCTION

In recent years, many new air cleaning and conditioning devices have come onto the Polish market. Among them small-size electrostatic precipitators are of special significance. They are applied to separation of oil mist and welding smoke in different industrial branches.

The harmful effect of oil mist on human health has been recently reported on the basis of medical examination of workers [1].

The presence of oil mist in ambient air is connected with industrial processes where oil or water–oil emulsions are used as the means of cooling. Droplets of the mist can be formed as the result of mechanical breaking of the liquid coolant flux. These droplets have the size of about 10 μm. Another way of oil mist formation is the condensation of oil vapour. The droplets of diameters ranging from 0.1 to 2.0 μm are characteristic of this kind of mist [2]. Since the droplets of the condensation oil mist are very small, it is rather difficult to remove them from air. The separation within electrostatic field seems to be the best way of condensation oil mist removal.

Although small-size electrostatic precipitators are commonly used for various aerosol particle removal, our knowledge about the process of electrostatic separation is not sufficiently advanced. Particularly, there are very few descriptions of the dependence between operating parameters and efficiency. The simulating model would be usable in designing new precipitators. It would also allow us to find causes of incorrect operation of devices.

2. DESCRIPTION OF THE ELECTROSTATIC SEPARATION PROCESS

Small-size electrostatic precipitators, which are applied to air conditioning and industrial ventillation, differ from large precipitators used for flue gas dedusting. Ionization zone is separated from collecting zone, and the positive corona is applied instead of the negative one. The operation principle of a small-size two-stage precipitator is presented in figure 1.

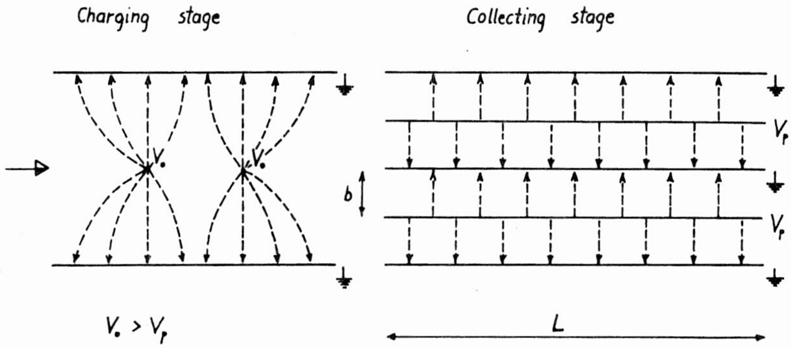

Fig. 1. Operation principle of small-size two-stage precipitator

2.1. POSITIVE CORONA

Within the ionization zone, in the vicinity of positive electrode, free electrons are accelerated by the electric field force. These electrons undergo collisions with aerosol molecules and as a result new electrons are knocked out. In such a way a cumulative ionization associated with the avalanche process proceeds. Positive ions produced are present in interelectrode space. The positive ions colliding with the aerosol particles (e.g. oil droplets), which are in the ionization zone, cause their charging. Simultaneously the distribution of electric potential is established. It can be described by the Poisson equation

$$\nabla^2 V = \frac{\rho}{\varepsilon}. \tag{1}$$

2.2. CHARGING AND COLLECTING OF PARTICLES

There are two main kinds of charging in electrostatic precipitator. The first one can be described as bombardment of the particles by positive ions moving under the influence of electric field. The second way of charging is connected with thermal movements of ions and it concerns submicroscopic particles [4].

Within the zone of capture, the charged particles are attracted to grounded electrodes and settled there. The electric field intensity within this zone can be considered as constant, according to the construction of electrodes.

3. TEST STAND

The investigation of oil mist separation was carried out using PEFO-1000 precipitator. Its commercial version was adjusted to meet the needs of the experiment. The test stand is presented in figure 2.

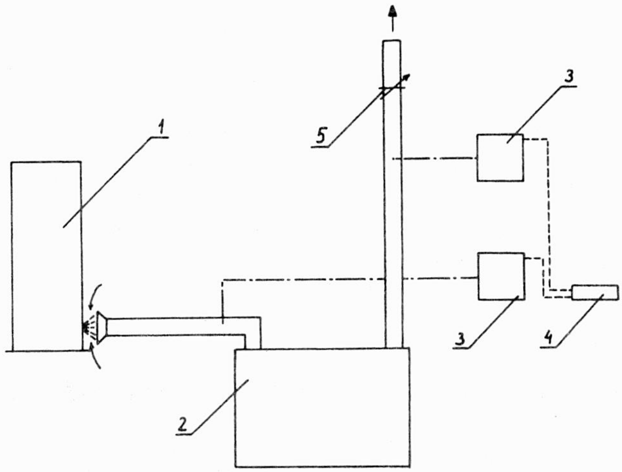

Fig. 2. Test stand
1 – oil mist generator, *2* – electrostatic precipitator, *3* – nephelometer, *4* – integrator, *5* – orifice

The condensation oil mist was produced in a special generator. The idea of its construction is presented in figure 3. Paraffin oil was being supplied to the generator using a peristaltic pump. Then the oil, flowing down gravitationally, was evaporating in the non-combustible atmosphere of nitrogen. The temperature in the generator was about 570 K. Oil vapours, getting out from the generator, were condensing and creating the mist [2].

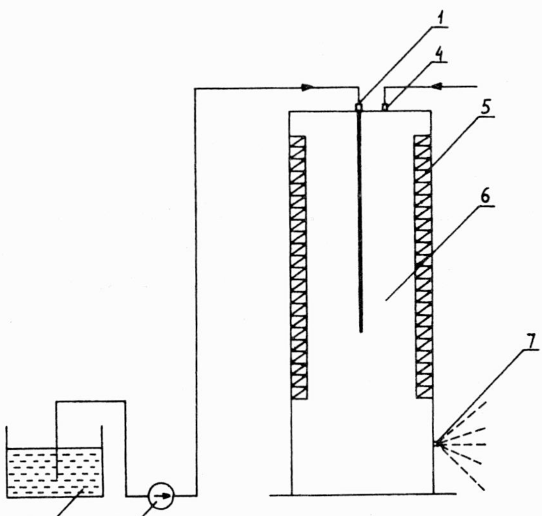

Fig. 3. Construction of the oil mist generator
1 – paraffin oil inlet, *2* – peristaltic pump, *3* – paraffin oil tank, *4* – nitrogen inlet, *5* – heating coil, *6* – space of evaporation, *7* – condensation oil mist outlet

The concentration of oil mist was being measured nephelometrically. The volumetric flow of aerosol was being measured at the purified air side. The ranges of electrode potential changes were as follows:

- in the charging zone: 4.5–12.4 kV,
- in the collection zone: 2.5–6.3 kV.

4. RESULTS OF EXPERIMENT

The aim of the experiment was to investigate the dependence between oil mist removal efficiency and two operating parameters: oil mist inlet concentration and volumetric flow of aerosol in the precipitator. The inlet concentration of the mist was being changed within the range 0–200 mg/m^3 and the volumetric flow of aerosol within the range 0.07–0.18 m^3/s. The results of the investigations are shown in figures 4 and 5.

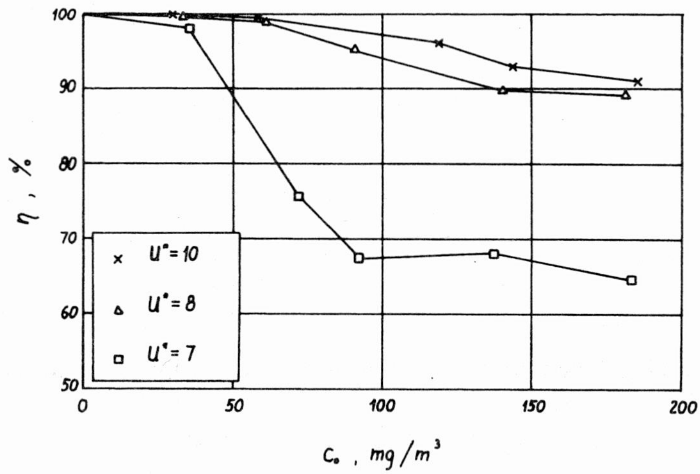

Fig. 4. Inlet oil mist concentration versus separation efficiency at various levels of interelectrode voltage. Volumetric aerosol flow: V_g = 0.18 m^3/s

Various levels of interelectrode voltage were used during the experiment. The respective values of positive electrode potentials are presented in the table.

For low concentration of oil mist in inlet air, high efficiency near 100% was observed. However, for higher concentration, a significant drop of efficiency occurred. Because of this fact a new term of 'limiting concentration' (c_g) was proposed.

For concentration higher than c_g the efficiency is lower than 99%. The value of limiting concentration depends on the potential of the positive electrode in the

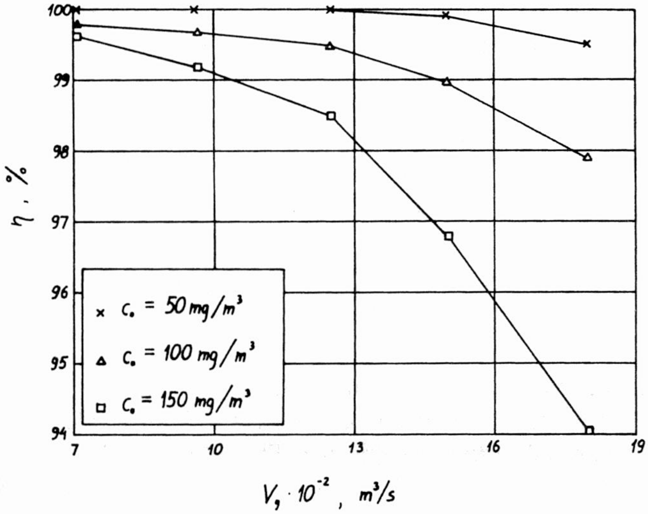

Fig. 5. Volumetric aerosol flow versus separation efficiency at various oil mist concentrations. Level of interelectrode voltage: $U^* = 8$

Table

Voltages used in the experiment

U^* –	U (kV)	V_0 (kV)	V_p (kV)
10	6.1	12.4	6.3
8	6.0	11.9	5.9
7	5.6	11.3	5.7

ionization zone (V_0). The empirical function $c_g = c_g(V_0)$ was found using parabolic regression

$$c_g = 2.19 V_0^2 - 21.8 V_0 + 3.2 \tag{2}$$

where c_g was expressed in mg/m^3, and V_0 in kV.

5. SIMULATION OF THE PROCESS

5.1. DISTRIBUTION OF ELECTRIC POTENTIAL WITHIN THE IONIZATION ZONE

Electric potential distribution was computed as a result of solving equation (1). For this purpose the finite difference method was applied. An example of the solution is presented in figure 6 in the form of equipotential lines. Basing on the potential distribution the mean value of electric field strength can be found. For the example presented, this mean value is equal to $1.35 \cdot 10^5$ V/m.

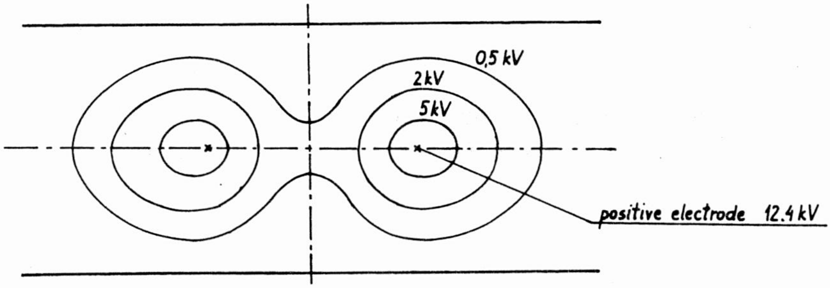

Fig. 6. Distribution of electric potential within the ionization zone at positive electrode potential $V_0 = 12.4$ kV

5.2. CHARGING OF OIL MIST DROPLETS

Total charge collected on a droplet in the ionization zone consists of the part connected with the field charging and the part connected with the diffusion charging. Simulation of both partial processes allowed comparison of their effects. The comparison was made for droplets of diameters within the range 0.1–2.0 μm (figure 7).

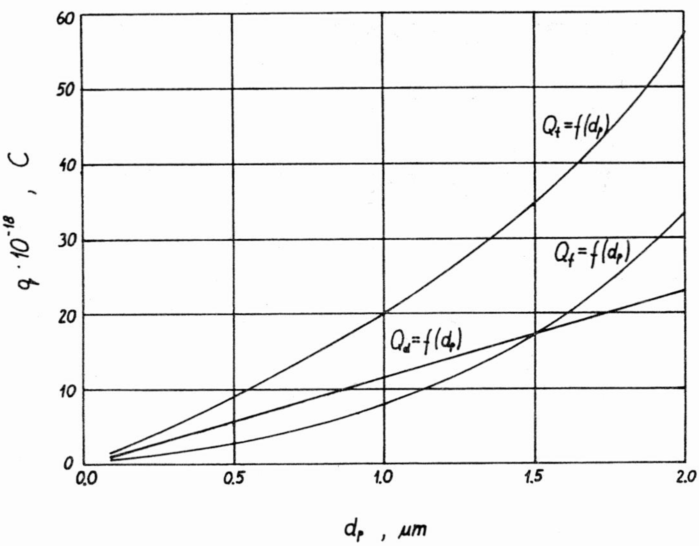

Fig. 7. Oil mist droplets charging simulation

Q_d – diffusion charge, Q_f – field charge, Q_t – total charge. Operating parameters: $U^* = 10$, $V_g = 0.18$ m^3/s

For oil mist droplets smaller than 0.5 μm, the diffusion mechanism of charging prevails. Within the range 0.5–2.0 μm both diffusion and field charging are of similar importance.

5.3. FRACTIONAL EFFICIENCY

Knowing the electric charge of the oil mist droplet and the field strength in the collecting zone of precipitator, settling velocity of the droplet can be evaluated in the following form

$$w = \frac{E_p Q}{3\pi \mu d_p} Cu. \tag{3}$$

Then fractional efficiency of separation can be evaluated from the expression

$$\eta_p = 1 - \exp\left(-\frac{wL}{bv}\right). \tag{4}$$

For the droplet charge Q, two possibilities exist. When the inlet concentration is higher than limiting concentration, the model needs correction because of the non-total droplet charging. Then

$$Q = \frac{c_g}{c_0} Q_t \tag{5}$$

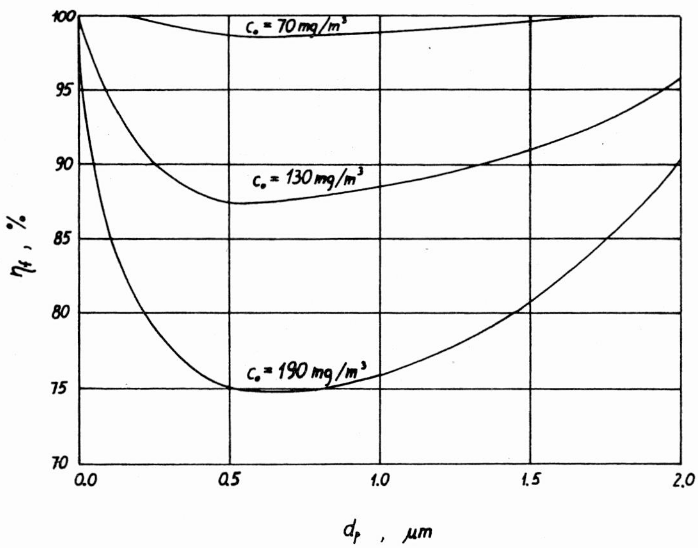

Fig. 8. Fractional efficiency for various inlet oil mist concentrations at operating parameters: $U^* = 8$, $V_g = 0.18$ m^3/s

where Q_t is the value obtained during the simulation (figure 7). When the inlet concentration is low, the value of Q is equal to that of Q_c.

The examples of fractional efficiency simulation are presented in figure 8. For the droplets of diameter about 0.5 μm, minimum of efficiency can be observed.

5.4. TOTAL EFFICIENCY

Standard fractional composition of condensation oil mist was assumed to find total efficiency of oil mist separation (figure 9). The results of simulation for different conditions are presented in figures 10 and 11.

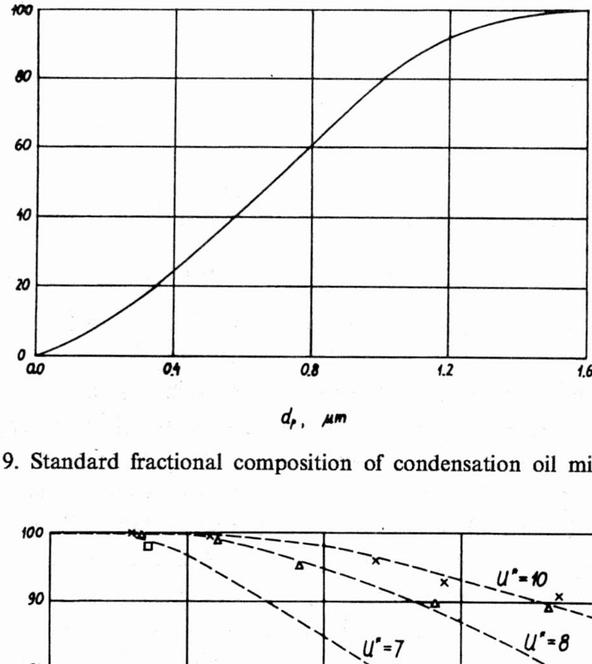

Fig. 9. Standard fractional composition of condensation oil mist [5]

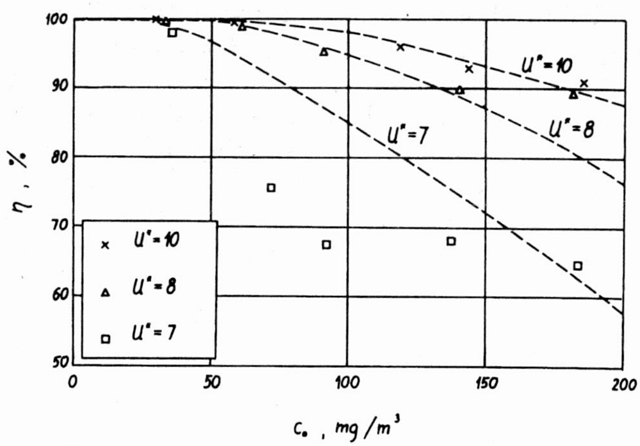

Fig. 10. Results of simulation. Inlet oil mist concentration versus total efficiency. Volumetric aerosol flux: V_g = 0.18 m³/s. Experimental results are put for comparison

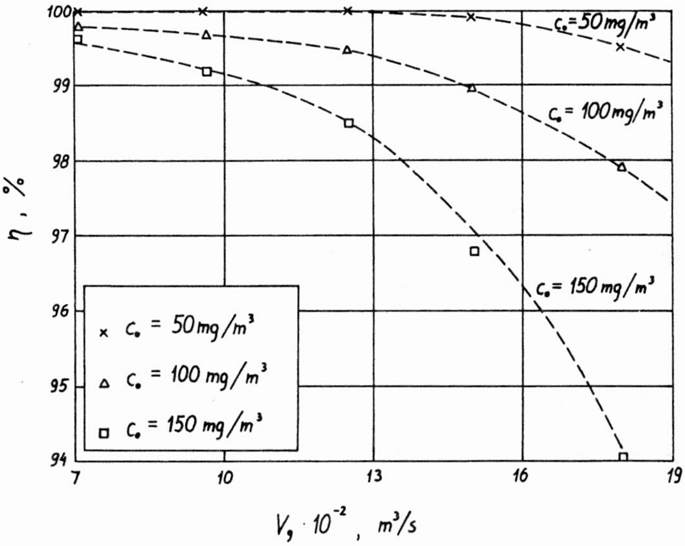

Fig. 11. Results of simulation. Volumetric aerosol flux versus total efficiency. Level of interelectrode voltage: $U^* = 8$. Experimental results are put for comparison

2. CONCLUSIONS

The results of the experiment and simulation allow us to formulate the following conclusions:

1. Increase of inlet oil mist concentration above the boundary value causes significant drop of separation efficiency. The amount of gas ions which charge the droplets is limited, and at high concentration only partial charging occurs.

2. The charging proceeds according to two major mechanisms. Diffusion charging occurs if the ion–droplet collisions are connected with thermal ion movements. In the case of field charging, the collisions are caused by accelerating of ions in the electric field. Diffusion mechanism is prevailing for droplets smaller than 0.5 μm. Within the range 0.5–2.0 μm both diffusion and field charging are of similar importance.

3. Fractional efficiency varies with droplet size. The lowest efficiency is characteristic of the droplets of diameter about 0.5 μm. For these droplets the settling velocity in the collecting zone has the lowest value. For smaller droplets the aerodynamic resistance strength is smaller. Droplets of diameters greater than 0.5 μm have greater electric charge.

4. Increase in the volume of aerosol flux (for oil mist concentration being constant) causes a drop of efficiency. The higher the inlet concentration, the less effective the oil mist separation.

МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ ПРОЦЕССА ЭЛЕКТРОАКУСТИЧЕСКОЙ СЕПАРАЦИИ МАСЛЯНОГО ТУМАНА

Представлены результаты исследований сепарации конденсационного масляного тумана в малогабаритном электрофильтре с разделенными зонами ионизации и захвата капель. На основе теоретических рассуждений предложена описывающая модель. Результаты моделирования сравнены с результатами физического эксперимента, устанавливая их хорошую взаимосогласованность.

5. The model proposed is in good agreement with the process run. The model can be applied for design purposes. It can also be used for maintenance of small-size two-stage electrostatic precipitators.

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MATEMATYCZNE MODELOWANIE PROCESU ELEKTROSTATYCZNEJ SEPARACJI MGŁY OLEJOWEJ

Przedstawiono wyniki badań separacji kondensacyjnej mgły olejowej w małogabarytowym elektrofiltrze z rozdzielonymi strefami jonizacji i wychwytu kropel. Na podstawie rozważań teoretycznych zaproponowano model opisujący proces. Wyniki symulacji porównano z wynikami eksperymentu fizycznego, stwierdzając ich dobrą wzajemną zgodność.

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