CHARGING THROUGH ELECTRIC FIELD - THE LIMITING ELECTRIC CHARGE OF PARTICLES IN ELECTROSTATIC FILTERS

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Abstract: The technological process of electrostatic precipitators involves several interconnected physical mechanisms. In practice, one of the main challenges is the removal of the layer of collected particles from the collection surface, as cleaning methods can reintroduce particles into the gas flow, thereby reducing collection efficiency. Other factors affecting the performance of electrostatic precipitators include the uneven distribution of gas velocity, the bypassing of electrified regions by particle-laden gas flows, and the re-entrainment of particles during periods when the collected material is not being removed.

Key words: electrostatic filters, electric charge, Corona effect, particle separation.

1. INTRODUCTION

Charging particles with an electric charge is the fundamental step in the electrostatic filtration process. Due to the significance of Coulomb's force, it is desirable for particle charging to occur at a high potential. Although electric precipitation is possible under conditions of bipolar charging, unipolar charging is far more efficient and, therefore, more commonly used. Fundamentally, there is no difference between positive and negative charging; both are equally effective for the same applied potential.

In practice, however, the choice of polarity is determined by other factors. For industrial filtration, negative polarity is preferred due to its greater stability and higher voltage and current values. For air purification, positive polarity is favored because it generates a smaller amount of ozone. In both cases, the primary criterion is to achieve the highest possible number of charged particles.

In principle, particles in gases can become charged through various mechanisms. In fact, uncharged particles are extremely rare and are considered exceptions. For instance, natural fog carries a significant electric charge due to the effects of cosmic radiation.

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In many applications, the flue gas environment and the composition of fly ash are such that the layer of collected particles limits the maximum usable voltage and current.

Due to the inherent complexities of the electrostatic precipitator process and the difficulty in justifying limits in practical applications, developing a fundamental model that adequately describes the electrostatic deposition process remains a formidable challenge [2].

To separate particles from a biphasic medium using an electrostatic precipitator, the following operations are required:

- charging the particles in the biphasic medium with an electric charge;
- moving the dust particles toward the collection electrodes;
- depositing the particles onto the collection electrodes;
- removing the material from the collection electrodes for disposal outside the electrostatic precipitator.

Each electrostatic filter consists of two main parts: the collection chamber, through which the gas flow to be purified passes, and the electrical equipment that supplies the chamber with high-voltage direct current. Inside the chamber are the primary components of the system: the collection electrodes and the discharge electrodes (Corona).

2. CORONA DISCHARGE IN DIRECT CURRENT

Corona discharge is an autonomous and incomplete discharge that occurs at a certain potential difference applied to an electrode with a small curvature, forming a limited zone around it known as the corona discharge layer.

The optical characteristic of the corona discharge layer is a pale bluish luminescence, resulting from the recombination of ions accompanied by faint crackling sounds.

The phenomenology of unipolar corona discharge in direct current depends on the polarity of the applied voltage.

In the case of negative polarity, the corona discharge is characterized by the following stages:

- weak current generation: Ionization processes occur when the discharge is not autonomous, and no luminescent phenomena are observed;
- appearance of Trichel pulses: These are characteristic pulses that indicate the onset of a more defined discharge, with a higher rate of ionization;
- formation of a luminous corona around the emission electrode: A visible bluish glow appears around the discharge electrode, marking the active corona region;
- development of streamers: These are elongated, branching structures that form as a result of the corona discharge, which may eventually lead to a full breakdown if conditions allow [2], [3], [6].

In the initial stage, near the electrode with a small curvature radius, electrons appear either by detachment from a negative ion or through secondary emission.

As ionization processes intensify (see fig. 1), the electric field strengthens, and positive charge accumulations begin to form in the region.

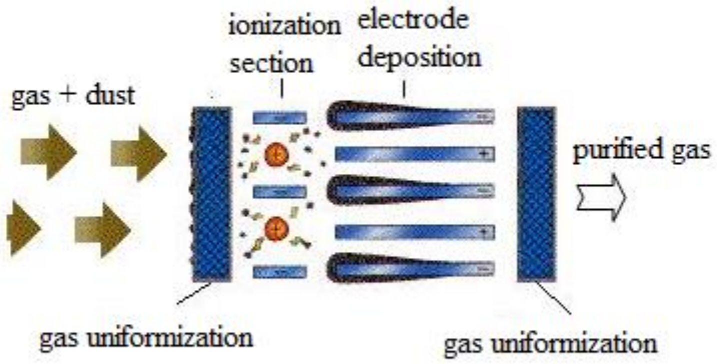

Fig.1. The ionization process

In the dark zone immediately adjacent to the emission electrode, the processes of ionization and excitation are slowed down.

As the electrons travel toward the anode, they lose some of their initial energy, and the intensity of the field gradually decreases. Electrons attach to molecules, leading to the formation of negative ions, characteristic of negative corona discharge.

After the dark zone, there follows a region of high concentration of positive ions, which leads to the uniformization of the field and thus a reduction in its intensity. The processes of ionization and excitation decrease to zero, and the Faraday dark zone appears [5].

The initial intensity of the discharge electric field is determined by the electrical conditions required for the onset of the corona discharge.

The threshold for the onset of corona discharge depends on several factors:

- the radius of the curvature of the electrode,
- the shape of the emission electrode,
- the shape of the collection electrode,
- the distance between the electrodes,
- the polarity of the emission electrode,
- the shape of the applied voltage wave on the emission electrode,
- the temperature of the medium,
- the pressure of the medium.

All of these factors cannot be captured by mathematical expressions to determine the exact threshold for the onset of corona discharge.

F.W. Peek, generalizing the results, provided a formula for the initial intensity required for the onset of corona discharge. The formula is typically expressed as:

$$Ei = A \cdot \delta \cdot \left(1 + \frac{B}{\sqrt{r}}\right) \text{ [kV/cm]} \quad (1)$$

For gases that have the same number of molecules per unit volume, the product of the coefficients A and B is a known quantity. For a curvature radius of the emission electrode ranging from 3,7 x 10^{-4} m to 11,6 x 10^{-4} m the coefficients have the following values: A = 31,02 and B = 0,308.

3. ELECTRIC CHARGING OF PARTICLES IN ELECTROSTATIC FILTERS

Numerous experimental investigations have concluded that most particles found in various natural suspensions or resulting from certain industrial processes carry electric charges, with uncharged particles being extremely rare. For example, measurements of the free electric charges on raindrops indicate that the average charge ranges from 10 to 100 elementary charges per drop, depending on altitude and storm intensity.

Laboratory studies have shown that in the case of fine particles in the air, nearly all particles are charged (equally positive and negative), and the average charge per particle increases with the particle's diameter. Similar investigations on other fine particles have revealed significant electric charges on aerosols. The natural electric charges occurring in industrial aerosols have also been extensively studied.

These measurements have shown that most industrial dispersions are charged, with the charge typically distributed equally between positive and negative, making the particle suspension electrically neutral as a whole. The average particle charge is small but not negligible [5].

Specific charges of particles generated from furniture grinding processes were found to be on the order of 10^4 elementary charges per gram, representing only 5%-10% of the charge obtained through the corona effect in precipitators.

Industrial steam generally exhibits an even lower charge, often zero or close to zero in most cases.

Despite the numerous possibilities for particle charging, only a few are effective in air purification. Most methods produce ambipolar charging with a low charge. As the number of charged particles increases, it becomes evident, for example, that doubling the charge doubles the separation force, thereby reducing the size of the precipitator required.

As a general principle, economic considerations dictate that particle charging should be as high as possible. Theories and extensive experience have concluded that high-potential unipolar corona discharge is by far the most effective method for producing highly charged particles for air purification purposes.

Consequently, researchers have focused their attention on charging methods that utilize the corona effect (or "cold plasma").

Particles present in a gas carry an electric charge accumulated due to frictional phenomena (triboelectrification), thermal effects, or natural terrestrial radiation. The magnitude of the electric charge accumulated by a particle depends on its intrinsic properties (such as electrical resistivity and permittivity), as well as the electric field existing in the given space.

However, these charges are typically too small for an externally applied electric field to significantly alter the trajectories of these particles. Effective action of an electric field requires the particles to carry as large an electric charge as possible.

As demonstrated in previous chapters, such an electric charge can only be accumulated when particles pass through a region with an electric field sufficiently intense to produce strong gas ionization.

To explain the process of charging particles with electric charge, the following considerations will focus exclusively on spherical particles [5].

An intense electric field causes all ions to move along the field lines, leading to collisions between the particles and the ions. These collisions ultimately result in the ionization of the particles: this is the mechanism of charging through an electric field. For particles with diameters larger than 1 μm, this charging mechanism is predominant.

In practice the field charging mechanism is predominant for particles with diameters greater than 0,5 μm. The diffusion charging mechanism predominates for particles with diameters smaller than 0,2 μm. For particles with diameters between 0,2 μm and 0,5 μm, both processes are significant.

4. ELECTRIC FIELD CHARGING - LOAD LIMIT CHARGE

The mechanism by which a particle can become electrically charged will be explained by illustrating how a certain number of ions accumulate on its surface, their motion being driven by the action of an electric field.

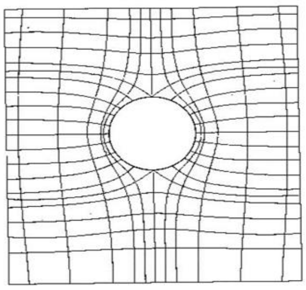

Fig.2. Electric field lines and equipotential lines for a conducting sphere in a uniform field

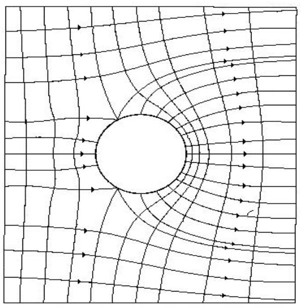

Fig.3. Electric field lines and equipotential lines for a partially charged conducting sphere in a uniform electric field

Let us first consider a conductive particle in the shape of a sphere with a radius a, carrying a negative electric charge of $-q$, and placed in an electric field (Fig. 4). The goal is to identify the forces acting on a negative ion with charge $-e$, located at a point A, such that $OA = a(1+v)$, where v is a multiplication coefficient. Only the radial component of each force will be considered, treating as positive those forces that tend to push the ion away from the particle.

The electric field E exerts a force F on the ion, given by the relation:

$$\vec{F}_1 = -e \cdot \vec{E} \quad [\text{mN}] \tag{2}$$

and its component according to the OA direction:

$$F_1 = -e \cdot E \cdot \cos\theta \quad [\text{mN}] \tag{3}$$

where θ is the angle between Ox and OA.

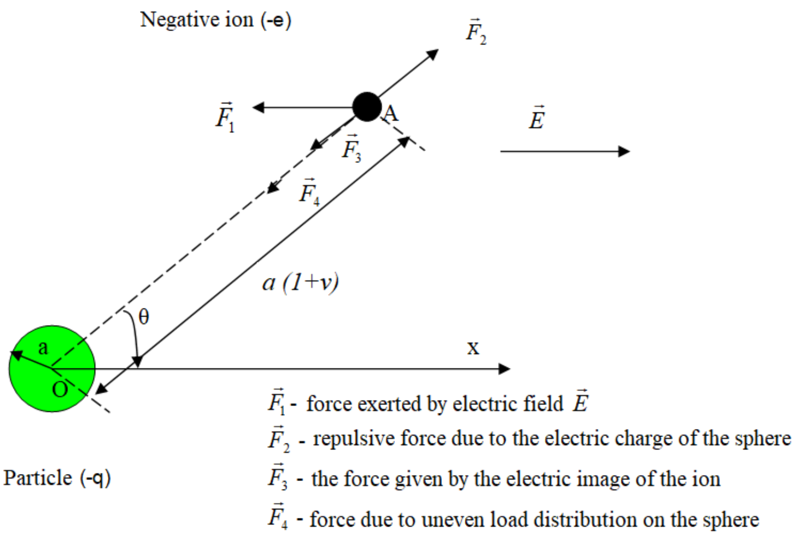

Fig.4. The forces exerted on a negative ion in the proximity of an electrically charged particle

The negative electric charge of the sphere repels the negative ion with a force given by Coulomb's law:

$$\vec{F}_2 = \frac{1}{4 \cdot \pi \cdot \varepsilon_0} \cdot \frac{(-e) \cdot (-q)}{[a \cdot (1+v)]^2} \cdot \vec{r} \quad [\text{mN}] \tag{4}$$

respectively:

$$F_2 = \frac{1}{4 \cdot \pi \cdot \varepsilon_0} \cdot \frac{e \cdot q}{[a \cdot (1+v)]^2} \quad [\text{mN}] \tag{5}$$

The electric image of the ion in relation to the sphere (particle) (Fig. 5) exerts an attractive force on it, given by the expression:

$$F_3 = \frac{1}{4 \cdot \pi \cdot \varepsilon_0} \cdot \left[\frac{R_v \cdot a}{\left(R_v^2 - a^2\right)^2} - \frac{a}{R_v^3} \right] \cdot e \cdot (-e) \quad [\text{mN}] \tag{6}$$

where R_v is given in (Fig. 5.).

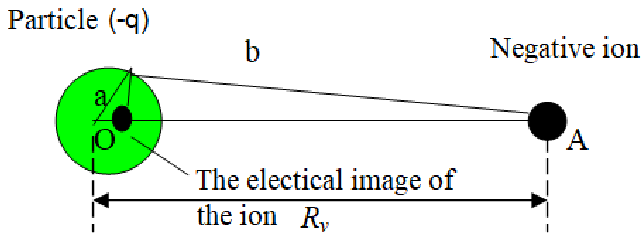

Fig.5. Define the geometric quantities needed to calculate the force created by the electric image of the ion

The non-uniformity of the electric charge distribution on the surface of the particle leads to the appearance of a force, whose radial component is given by the relation:

$$F_4 = -\frac{2 \cdot E \cdot e \cdot \cos\theta}{(1+v)^3} \quad [\text{mN}] \tag{7}$$

The radial component of the total force acting on the particle, charged with the electric charge obtained by the algebraic summation of the radial components of the forces $F_{1\text{-}4}$, is given by the relation:

$$F_T = -E \cdot e \cdot \cos\theta \cdot \left[1 + \frac{2}{(1+v)^3}\right] + \frac{e}{4 \cdot \pi \cdot \varepsilon_0 \cdot a^2} \left[\frac{q}{(1+v)^2} - \frac{e}{4 \cdot v^2} \cdot \frac{2 \cdot (1+v)^2 - 1}{(1+v)^3 \cdot \left(1 + \frac{v}{2}\right)^2}\right] \quad [\text{mN}] \tag{8}$$

If this component is negative, the ion moves closer to the considered spherical particle. However, the total force F_T determines the movement of the ion only when the distance between the ion and the particle is sufficiently small, thus only for low values of v, which leads to the expression:

$$F_T = -E \cdot e \cdot \cos\theta \cdot \left[1 + \frac{2}{(1+v)^3}\right] + \frac{e}{4 \cdot \pi \cdot \varepsilon_0 \cdot a^2} \cdot \left[\frac{q}{(1+v)^2} - \frac{e}{4 \cdot v^2}\right] \quad [\text{mN}] \tag{9}$$

As observed in the previous relation, the total force F_T depends on the angle θ between the direction of the electric field E and the direction of motion of the considered ion. Let the charge of the particle be q. Under these conditions, the force F_1 becomes zero when the angle θ has the value θ_0, given by the relation:

$$\cos\theta_0 = \frac{1}{4 \cdot \pi \cdot \varepsilon_0 \cdot E \cdot a^2} \cdot \left[\frac{(1+v)^3}{(1+v)^2 + 2}\right] \cdot \left[\frac{q}{(1+v)^2} - \frac{e}{4 \cdot v^2}\right] \tag{10}$$

For the intensity of the electric field E = 1800 V/m, the radius of the particle a = 10 µm, the elementary charge e = 1,6 x 10^{-19} C, and the particle's electric charge equal to 10.000, 30.000, and 38.000 elementary charges, Pauthenier and Moreau-Hanot plotted the points where the radial electric field cancels out and changes its sign (Fig. 6.).

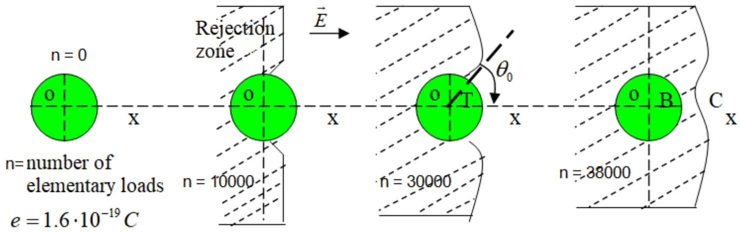

Fig.6. The evolution of the repulsion zone in the vicinity of the particle for various sizes of the electric charge load and E = 1800 V/m.

If the electric charge of the particle is small, the interaction force between the ion and the particle is negative (causing the ion to move closer to the considered particle) regardless of the distance OA (value of v), which leads to an increase in the charge accumulated on the surface of the sphere (particle). If the charge of the particle q increases, $cos\theta_0$ increases (i.e., θ_0 decreases), so the repulsion zone closes around the sphere (Fig. 6). Therefore, at a certain point, the particle will be completely surrounded by a repulsion zone that the ions can only overcome if thermal agitation gives them enough kinetic energy.

Thus, as long as the electric charge on the surface of a particle does not reach a limiting value, certain negative ions in the vicinity of the particle, accelerated by the electric field, can be attracted (accumulated) by it [1].

The equation F_T = 0 cannot be solved algebraically; however, in the region where v << 1 and $\frac{e^2}{a^2 \cdot v^2}$ are negligible, the expressions for the force F_T and $cos\theta_0$ can be written as:

$$F_T = -3 \cdot E \cdot e \cdot \cos\theta + \frac{e \cdot q}{4 \cdot \pi \cdot \varepsilon_0 \cdot a^2} \quad \text{[mN]} \tag{11}$$

$$\cos\theta_0 = \frac{q}{4 \cdot \pi \cdot \varepsilon_0 \cdot 3 \cdot E \cdot a^2} \tag{12}$$

The electric charge accumulated on the particle will reach a limiting value $q_p{}^s$ when θ_0 = 0, that is, when the ions can no longer reach the surface of the sphere. In this case, the expression for the limiting electric charge can be written as:

$$q_p{}^s = 4 \cdot \pi \cdot \varepsilon_0 \cdot \left(3 \cdot E \cdot a^2\right) \quad \text{[C]} \tag{13}$$

Defining the ratio:

$$\lambda = \frac{q'}{q_p{}^s} = \frac{q}{4 \cdot \pi \cdot \varepsilon_0 \cdot \left(3 \cdot E \cdot a^2\right)} \tag{14}$$

we obtain the following expression for F_T:

$$F_T = E \cdot \cos\theta \cdot \left[y_1 + (\lambda - 1) \cdot y_2\right] + \frac{y_3}{a^2} \quad \text{[mN]} \tag{15}$$

$$y_1 = e \cdot \frac{3 \cdot (1+v) + 2 \cdot \cos\theta}{\cos\theta \cdot (1+v)^3} \tag{16}$$

$$y_2 = \frac{3 \cdot e}{\cos\theta \cdot (1+v)^2} \tag{17}$$

$$y_3 = \frac{1}{4 \cdot \pi \cdot \varepsilon_0} \cdot \frac{-e}{4 \cdot v^2} \tag{18}$$

Pauthenier and Moreau-Hanot noted that the ion repulsion zone completely surrounds the sphere when the value of the ratio λ is 1.014, and it increases very rapidly if λ continues to grow. However, according to the definition, the ratio λ cannot exceed unity (the electric charge accumulated through this mechanism cannot exceed the limit charge $q_p{}^s$). The net value exceeding unity of the ratio λ can be explained by the fact that this particle charging mechanism neglects the phenomenon of charge by diffusion (the capture of ions that move due to the diffusion phenomenon).

Under these conditions, Pauthenier and Moreau-Hanot plotted the curve $F_T(v)$ for λ = 1,014. The negative ion under consideration is subjected to a repulsive force in a region with a width of 1 μm, which is equivalent to 12 times the average mean path of an ion in air. For this reason, the probability of an ion reaching the surface of the sphere due to thermal agitation is very low [3], [4]. This leads to the conclusion that the additional electric charge that can reach the particle's surface through this path is negligible compared to the amount of charge already accumulated. To generalize this result, Pauthenier and Moreau-Hanot calculated the values of the ratio λ, creating a repulsion zone of 1 μm for different particle sizes (see Table 1). In the table, it is observed that the ratio λ increases as the particle radius decreases. Pauthenier and Guillien compared the calculated limit value of the electric charge with the measured values, using large steel balls. The deviations between the experimental results and those calculated with the equations:

$$F_T = -3 \cdot E \cdot e \cdot \cos\theta + \frac{e \cdot q}{4 \cdot \pi \cdot \varepsilon_0 \cdot a^2} \quad \text{[mN]} \tag{19}$$

$$\cos\theta_0 = \frac{q}{4 \cdot \pi \cdot \varepsilon_0 \cdot 3 \cdot E \cdot a^2} \tag{20}$$

are 1-2%.

Table 1. ***The values of λ***

$a = 3 \times 10^{-4}$ mm	$\lambda = 1{,}1$
$a = 5 \times 10^{-4}$ mm	$\lambda = 1{,}04$
$a = 10^{-3}$ mm	$\lambda = 1{,}014$
$a = 2 \times 10^{-3}$ mm	$\lambda = 1{,}0028$

In the case where the particles have significant electrical resistivity (located in the range of insulating materials), the expression for the limit of the accumulated electric charge can no longer be calculated using relations 19 and 20 [3], [4].

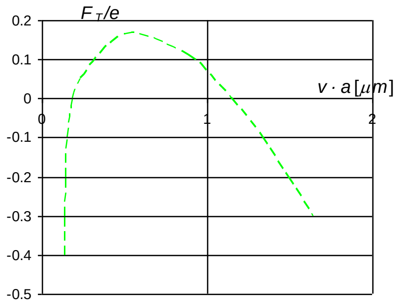

Fig.7. Curve of variation of the force F_e with v

Brigard finds the following calculation relation:

$$q_p{}^s \approx 4 \cdot \pi \cdot \varepsilon_0 \cdot \left(p \cdot E \cdot a^2\right) \quad [\text{C}] \tag{21}$$

where: $p = 1 + 2 \cdot \left(\frac{\varepsilon_r - 1}{\varepsilon_r + 2}\right) = \frac{3 \cdot \varepsilon_r}{\varepsilon_r + 2}$, with ε_r the particle's electrical permittivity.

In the case where the dimensions of the particles are comparable to the mean free path of ions in air λ_{air} = 0,065 μm, Cochet proposes a calculation expression for the limit of the electric charge, similar to the relation: $q_p{}^s \approx 4 \cdot \pi \cdot \varepsilon_0 \cdot \left(p \cdot E \cdot a^2\right)$ where only parameter p is changed:

$$q_p{}^s = \left\{\left(1 + \frac{\lambda_{aer}}{a}\right)^2 + \left(\frac{2}{1 + \frac{\lambda_{aer}}{a}}\right) \cdot \left(\frac{\varepsilon_r - 1}{\varepsilon_r + 2}\right)\right\} \cdot \pi \cdot \varepsilon_0 \cdot (2 \cdot a)^2 \cdot E \quad [\text{C}] \tag{22}$$

where: λ_{air} is the mean free path of ions in the air, ε_r is the relative permittivity of the particle, and E is the electric field intensity.

Using the above relation, curves were created showing the variation of the accumulated electric charge for different values of the electric field intensity, depending on the particle diameters, at a temperature of 150°C (Fig. 8) (the permittivity is conventionally considered: ε_r = 10) [3], [4].

According to (Fig. 8), for an electric field intensity of E = 3 x 10^5 V/m, a particle with a diameter of d_p = 0,1 μm will accumulate 5 elementary electric charges, while for d_p = 9 μm, the number of accumulated elementary charges will be 10,000.

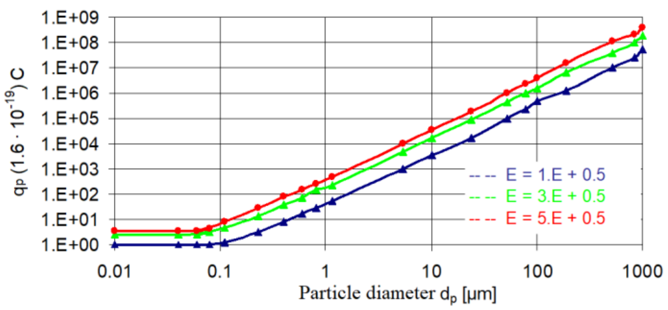

Fig.8. The charging of particles with electric charge as a function of their diameter for different values of electric field intensity.

From the previously presented information, it can be observed that thermal agitation can only have a negligible influence on the value of the limit electric charge accumulated by a particle with a radius around 1 μm, placed in an electric field.

The expression for the electric charge as a function of time is:

$$q = q_p{}^s \cdot \frac{t}{t + \tau_q} \quad [\text{C}] \tag{23}$$

where: τ_q is a time constant, called the characteristic charging time, which depends on the density of negative ions and their mobility: $\tau_q = \dfrac{4 \cdot \varepsilon_0}{\mu \cdot n_i \cdot e}$ where μ and n_i represents the density of negative ions.

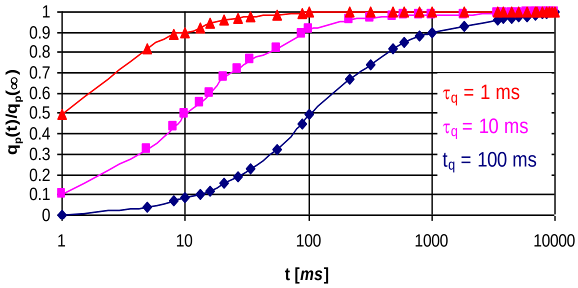

Fig.9. The evolution of the process of charging particles with electric charge over time for characteristic charging times of 1, 10, and 100 ms, using Cochet's relation

Using relation 22 for determining the limiting electric charge, in (Fig. 9) the charge of the particles is shown for different values of the charging time τ_q. It can be observed that for a particle characterized by a specific charging time of τ_q = 1 ms, the charge accumulated after a time interval of t = 10 ms is approximately 10% of the value q_p^s (the charge that would be accumulated over a very long time interval, identical to the limiting charge), while for a particle with τ_q = 100 ms, the accumulated charge will be 90% of the value q_p^s.

4. CONCLUSIONS

The charging of particles by an electric field is a crucial process in the operation of electrofilters, achieved by generating an intense electric field between electrodes. The ions generated by corona discharge move toward the particles, transferring their electric charge.

Particles have a limiting electric charge that can be reached during the charging process. This limit is determined by the balance between electrostatic forces, the dielectric resistance of the medium, and the electrostatic repulsion effects between the already deposited ions and those in motion.

To maximize the efficiency of electrofilters, it is essential to adjust the operating parameters to ensure that the particles reach the optimal electric charge without exceeding the charging limit. This involves precise control of the electric field and environmental conditions, as well as the proper selection of insulating materials.

In practice, achieving and maintaining the limiting electric charge may be affected by the accumulation of deposits or degradation of insulating materials. Ongoing research in the development of more durable materials and electric field control technologies can help overcome these limitations, enhancing the durability and efficiency of electrofilters.

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