Nanoparticle and fine particle collection efficiency using an electrostatic precipitator: a description of the specific physical processes

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1. Introduction

Electrostatic precipitators are the most widely used method for collecting particles in a flue gas. The particle size is an important parameter in determining their collection [1]. Nanoparticle and fine particle are difficult to collect. Despite a plethora of analytical and numerical work on the electrostatic precipitation process in the literature, the behavior of these particles in an electrostatic precipitator has been rarely discussed [2].

Figure 1 shows a typical evolution of particle collection efficiency as function of particle size. Collection efficiency falls linearly in log term until about 2.5 micron. Then, in nanoparticle and fine particle zone, the slope of the curve changes, showing two flexes at approximately 0.5 µm and 30 nm [3].

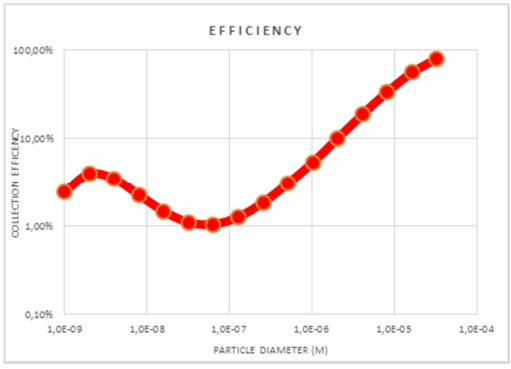

Figure 1. Variation in particle collection efficiency as a function of size

Why does the curve shape change? In literature, a physical comprehensive explanation is missing.
This article describes the change in physical settings and the different physical phenomena involved.

From a macro point of view, there are two modifications of physical settings.

The first one is that particles reach the same size as air molecules. This fact is also called transition from a continuum regime (ions are so small compared to a particle that the suspending ions act as a continuous fluid flowing around the particles) to a free molecular regime (particle and ions have a comparable size and behave according to perfect gas law).

The second change concerns charge discretization: the electric charge is lower the 10 units and the non linear effect of an integer number of charge has a strong impact on collection efficiency.

How this macro changes impact the particle collection efficiency? Three main physical processes are involved.

The first change concerns the charging mechanism. The charging by field mechanism, dominant for particle greater than 2.5 micron, become negligible for smaller particles while the charging by diffusion becomes the main charging phenomena.

The second change is the modification of drag forces. When the particle size is comparable or smaller than the average free path of a molecule, the particle collide less with molecules and slide between them. Therefore, for particles smaller than 0.5 µm, their velocity toward the collecting electrodes increases and consequently the collection efficiency increases too.

The third phenomena is partial charging, as it is called in literature. For particle less than 50 nanometer, average charging can become less then the charge of one electron. As particles carry an integer number of electric charges, there is a fraction of particle distribution with zero charge, decreasing significantly the collection efficiency.

The paper describes and quantifies these three physical phenomena through simplified modeling.

The concentration of dust particles in the airborne is an important parameter in public health. Current and future international agreements will impose increasingly strict limits on the emission of these particles, this is especially true of fine and nanoparticles (< 2.5 micron).

The effect of a particle on the human organism depends on its size. So-called nano and fine particles are able to reach the walls of the alveoli in the lungs and produce an inflammatory reaction [4, 5]. The scale of this reaction greatly increases for particles < 0.1 micron (In Fig. 2 the particle size is compared to the size of the cells from the bronchial epithelium.) The presence of the particles gives rise to oxidative stress and an inflammatory reaction. [6].

Electrostatic precipitators are the most widely used method for collecting particles from flue gases. The particle size is an important factor in determining the collection efficiency of electrostatic precipitators and similar particulate dust collectors such as baghouses.

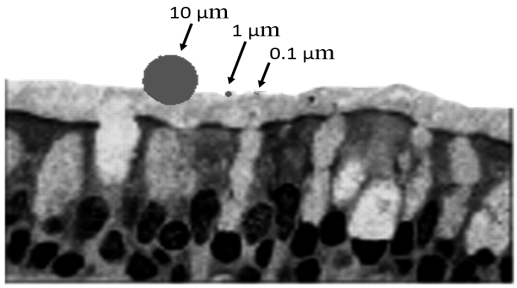

Figure 2. Illustration of the size of fine particles relative to the dimensions of bronchial epithelial cells [4]

Figure 3 shows the variation in particulate collection efficiency as a function of the size of the particles (that are typically encountered in an electrostatic precipitator). The fall in efficiency between 100 and 1000 nanometers which is observable in both laboratory and industrial situations, has already been documented in the literature. However, the region of the graph below 100 nanometers has not been the object of great attention in the literature. It is characterized by a reduction in collection efficiency as the particle size falls below 30 nanometers. Only data originating from laboratory experimentation is available for such small particles [7, 8].

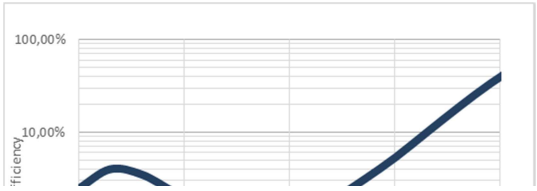

Figure 3. Efficiency of particle collection in an electrostatic precipitator as a function of particle size [7]

What physical phenomena considered in relation to particle size, give rise to a curve of this shape? For particle size greater than 2.5 micron, these phenomena are relatively well known. The particles are captured by charging and attracting them to a collecting surface in an electric field.

The physical phenomena are the following:

- Flue gases flow through the electrostatic precipitator
- An electric field is created applying an electric potential
- Ions are produced near the wires by an electric discharge
- Ions migrate
- Particles are charged electrically and migrate
- Collection of particles on the plates and their removal by rapping.

The collection efficiency is linear in a log scale (see Figure 3) for particles of a diameter greater than 2.5 µm. However, when looking at fine and nanoparticles there are two inflections. In the literature, a comprehensive explanation of the mechanisms involved is lacking. The objective of this paper is to present an explanation of these mechanisms.

2. Why the collection efficiency trend changes for fine and nano particles?

To answer the question "Why the collection efficiency trend changes?", firstly, it is necessary to consider two physical environment modifications. Secondly, three main physical processes changes that have an impact on collection efficiency will be identified.

The first physical environment change is about space. As particle diameter is decreasing, their size reach the molecule size. So the flow regime changes. Large-sized particles may be considered to be in a continuum regime; the surrounding air molecules are very small and the ions are, in relative terms, extremely small. As the particle size falls, their size becomes comparable to that of air molecules. This is considered as a molecular regime where the particles and the molecules behave according to the perfect gas law. Between these two regimes is a transitional regime (see Fig. 4).

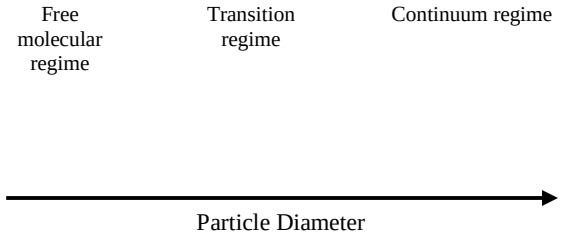

Figure 4. Change of regime as particle diameter decrease (from right to left): continuum regime (molecules are smaller than particles), transition regime (molecules and particles become of comparable size), free molecular regime (particle and molecule are of comparable size and behave according to perfect gas law)

The second physical environmental change concerns charge behavior. As the average charge falls below one electron per particle, a discretization effect starts to operate which greatly affects collection efficiency.

In order to understand how this physical environmental change impacts the dust particles, we identified three main physical processes.

The first process is a change in particle charging mechanism. The predominance of particle charging by the electric field decreases in relation to that by diffusion as the particle size falls.

The second process is drag forces modification. As

the particle size reaches a value that is comparable to the mean free path of gas molecules in the fluid (typically 0,1 µm) the hypothesis of fluid continuity no longer holds.

The third is the fact that a nanoparticle carry either a 0 or 1 electron charge. Whereas, the average charge carried by a particle is less than 1.

These three physical process and impact will be described by basic modeling; a modeling complex enough to be representative of the reality, yet simple enough to be presented by equations for clarity.

3. Particle charging as a function of size

For large particle, over 2.5 µm, the trend of the collection efficiency is linear in log scale. For smaller particle this curve presents two inflections. How does the particle charging contribute to these two observations?

After describing the two mechanisms for particle charging by electric field and by diffusion, the contribution from each mechanism will be quantified by a simplified modelisation. Finally, the impact of the charge on the collection efficiency will be considered.

3.1. The two charging mechanisms

The charging of the particles is one of the key mechanisms in the collection of dust particles by an electrostatic filter. The force exerted on the particle by the electric field depends on the charge that it carries.

A particle is charged by two mechanisms, these are usually called charging by electric field and charging by diffusion.

In **electric field charging**, the ions are carried to the particles by electric convection due to an electric field *E*.

The ions migrate along the lines of the electric field to reach the surface of the particles. Field charging takes into account the local field distortion which appears near the surface of the particle. Consequently, the charge occurs only in the zone of the field lines *S* – entering the particle:

$$\frac{\mathrm{d}q}{\mathrm{d}t} = \int_{S^-} \rho_i \mu_- E \, \mathrm{d}s \,, \tag{1}$$

where:

S – presents the surface of the field lines entering the particle,

E – is the electric field,

ρ_1 – is the ion concentration taken to be constant in the neighbourhood of the particle,

μ_- – is the mobility of these ions.

The charging process continues until the field lines entering the particle disappear, this occurs when the limit charge is reached.

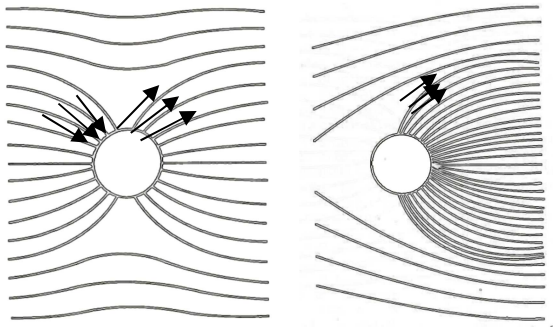

Figure 5**.** The field lines enter and leave an uncharged particle (left). At charge saturation no field lines enter the particle (right)

In **charging by diffusion**, the charges are attached due to thermal agitation. Charging by diffusion takes into account the probability of the impact of ions on the particle's surface due to thermal stochastic speed and the concentration of ions surrounding the particle.

If it is assumed that the ions charge the particle by natural agitation (the diffusion mechanism) it is possible to write:

$$\frac{\mathrm{d}q}{\mathrm{d}t} = \int_S \tilde{\rho}_i Pr \, \mathrm{d}s \,, \tag{2}$$

where:

S – represents the surface charged by diffusion,

– is the ion concentration in the neighbourhood of the particle,

Pr – is the probability that an ion will attach itself to the surface.

The speed of charging and the charge carried by the particle is a function of the size of the particle. The smaller the particle, the smaller the surface area available to receive impacts and to carry charge.

3.2. Quantifying field and diffusion charging

The charging of particles in an electrostatic precipitator field may be described by making certain assumptions and employing models. Using a simplified but representative model and taking into consideration the concept of limit charge (or saturation charge), the relative contribution of the two charging mechanisms may be quantified.

The following assumptions are made: the particles are considered as spheres, the field of a given particle does not affect the field of a neighboring particle and the electric field is uniform. The **charging by electric field** may then be expressed by the simplified model of Pauthenier [9]. This model quantifies the limit according to the equation:

$$q_{sc} = 12\pi\varepsilon_0 \frac{\varepsilon_r}{\varepsilon_r + 2} E \, r^2 \,, \tag{3}$$

where:

ε_0 – is the vacuum permittivity,

ε_r – is the relative permittivity,
r – is the particle radius,
E – is the electric field.

If it is assumed that there is no interference from the electric field and the kinetic theory of perfect gases (White's simplifying assumptions) applies, the rate of charging by diffusion can be given by the following equation:

$$\frac{dq_{sd}}{dt} = r^2 e \rho_i \sqrt{\frac{8k_b T\pi}{m_i}} \exp\left\{-\frac{e\, q_{sd}}{4\pi\varepsilon_0 R k_b T}\right\}\left(1-\frac{q}{q_{sd}}\right), \quad (4)$$

where:
q is the charge of the particles,
E is the charge of an electron,
k_b is Boltzmann's constant,
T is the temperature of the ions,
m_i is the average mass of an ion,
q_{sd} is the saturation charge,
ρ_i is the ion density,
e is the elementary charge,
R is the universal gas constant.

The equation shows that there is also a "limit charge" for charging by diffusion:

$$q_{sd} = 4\pi\varepsilon_0 \frac{k_b T}{e} r\,, \quad (5)$$

ε_0 is the vacuum permittivity,
T is the temperature,
r is the particle radius,
e is the elementary charge,
k_b is Boltzmann's constant.

Working with these assumptions together with the concept of limit charge, the charging contribution as a function of the particle's size of the two mechanisms can be described and understood. The total limit charge, overall and by charging mechanism, carried by a particle, as a function of its diameter is given in Figure 6.

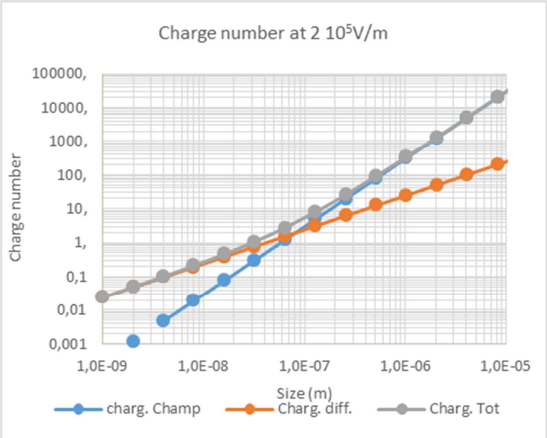

Figure 6. A simplified comparison of particle charging by field and by diffusion as a function of particle size

The two mechanisms of particle charging, by electric field and by diffusion, differ as function of particle size. Electric field is the principal charging mechanism for particles larger than 1 micron. For particles smaller than 0.01 micron, the situation is reversed and charging by diffusion prevails. In the intermediate zone between 0.01 and 1 µm, the contribution to charging by the two mechanisms is Deutsch's of the same order of magnitude.

3.3. Impact on collection efficiency

The efficiency of particle collection changes as a function of the charge they carry. Furthermore, this charge, originating by electric field charging and by diffusion, is related to the particle size.

In order to distinguish between the effects of the charging and drag force phenomena on the collection efficiency, the figure below only takes into consideration the two charging mechanisms and ignores any modifications of drag forces.

The charge q carried by the particles at infinite time corresponds to the charge by electric field q_{sf} (equation (3)) and by diffusion q_{sd} (equation (5)).

The collection efficiency according to simplification is given by:

$$w_1 = \frac{\left(q_{sf} + q_{sd}\right)E}{6\pi r\mu}\,, \quad (6)$$

$$\eta = 1 - \left[e^{-\frac{Aw_1}{Q}}\right], \quad (7)$$

where:
w_1 is the migration velocity,
μ is the gas viscosity,
E is the electric field,
r is the particle radius,
A is the collection area,
Q is the flue gas flow rate,
η is the collection efficiency.

Figure 7 shows the variation in the collection efficiency for an electrostatic precipitator field where firstly, only electric field charging is considered (dotted line), and secondly, where charging by electric field and diffusion are considered together (continuous line). The area of the collecting surface is 20 m^2, the electric field is 20 kV/m, $\varepsilon_r = 5$, the temperature is 130°C and $\mu = 1.02 \cdot 10^{-4}$.

The collection efficiency falls due to a modification in the particle charge. For particles > 2.5 µm electric field charging predominates. As the charge carried by the particles lessens, the collection efficiency falls which explains the downward slope of the line in Fig. 7. For particles < 2.5 µm charging by diffusion plays an increasing role and reduces the loss in collection efficiency.

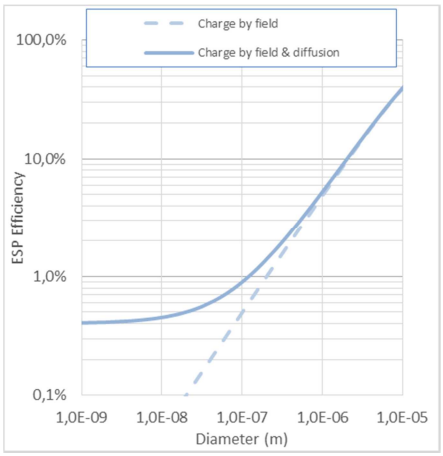

Figure 7. The effect on collection efficiency of taking into account particle charging by diffusion

However, the change in the principal charging mechanism as the particle size falls does not account for the change in the slope at about 0.5 µm. Another phenomenon, a change in drag forces is operating.

4. The impact of drag forces on the collection of submicron particles.

For particles of a diameter smaller than 0.5 µm, the fall in collection efficiency stops and an increase is observed. The latter cannot be attributed to the particle charge. Could this variation in collection efficiency be accounted for by a change drag forces?

4.1. Modification in the drag forces

As the size of the particles fall and these particles approach the region where the fluid no longer possesses the properties of fluid continuity, the maximum air speed of the particle increases. The particle's speed is limited by a drag force (resulting from the impact of air molecules on the particle). However, if the particle's size is of the same order of magnitude as the air molecules, the drag forces fall. This is the case for particles smaller than 0.5 µm. The increase in particle speed leads to an increase in collection efficiency.

To take into account this effect in calculating the maximum speed of the particles, a correction factor known as the Cunningham slip correction factor is used. This correction factor is function of the rate of the mean free path of the molecules λ and the size of the particle, (in this case the radius r) which gives the Knudsen's number (λ/r).

The value of Cunningham's coefficient can be given in different forms, for example by the following formula:

$$C = 1 + 1.246\,\lambda/r + 0.42\,\lambda/r \exp\left(-0.87\,r/\lambda\right), \quad (8)$$

where:

$$\lambda = \frac{k_b T}{\sqrt{2}\pi\sigma^2 p} \text{ (used in previous paragraph),}$$

k_b – the Boltzmann constant,
T – temperature,
p – pressure,
σ – air molecule diameter,
r – particle radius.

The variation in the value of Cunningham's coefficient as a function of particle diameter and temperature is given in Fig. 8.

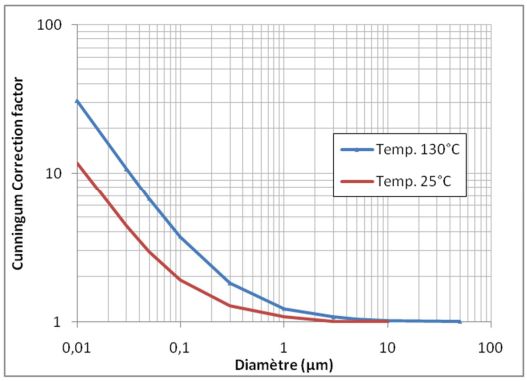

Figure 8. Variation in the Cunningham slip correction factor as a function of particle diameter and temperature

Cunningham's factor is 1 for particles with a diameter greater than 10 µm. Its value increases significantly for particles with a diameter of less than 1 µm.

4.2. Impact of drag modification on collection efficiency

Changes in the drag forces, as taken into account by the Cunningham factor, modify the curve of the collection efficiency of submicron particles. This factor is introduced into the collection efficiency expression (equation (7)) according to the equation:

$$w_1 = \frac{qEC}{6\pi r\mu}, \quad (9)$$

w_1 is the migration velocity, μ the gas viscosity; r the particle radius, E the electric field, C the Cunningham factor.

Figure 9 shows the variation in particle collection for an electrostatic field with and without the Cunningham factor. The area of the collecting surface is 20 m^2, the electric field E is 20 kV/m, the relative permittivity $\varepsilon_r = 5$, the temperature is 130°C and μ = 1.0 10^{-4}.

Where only charging by electric field and by diffusion are considered, the collection efficiency continued to fall as the particle diameter became smaller. Modification in the drag forces affecting submicron particles explains the change in the slope of the collection efficiency graph at about 0.5 µm. This

inflection is related to an increase in the particle limit speed as the drag forces fall.

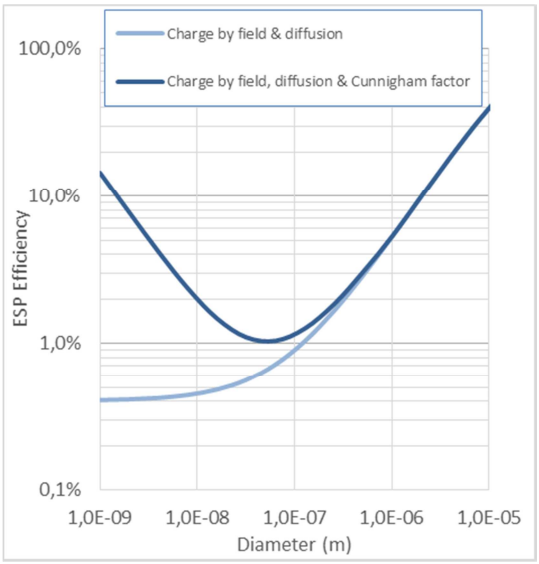

Figure 9. Effect of the introduction of the Cunningham factor on collection efficiency

5. Changes in the collection efficiency slope and the effect of discrete particle charging (partial charging)

The collection efficiency increases for particles with diameters between 0.1 and 0.05 µm and then falls again for particles smaller than 0.05 µm. The literature confirms this observation both in laboratory experimentation and simulated results. So a local maximum in collection efficiency is discernable for nanoparticles [10].

This modification in the slope of the collection efficiency may be explained by the partial charging of particles smaller than 0.1 µm.

5.1. What is partial charging?

Particle charging occurs through electric field and diffusion mechanism as described before.

Particles that are smaller than a micrometer are principally charged by diffusion. But what charge do they carry?

The size and number of ultrafine particles are such that the average charge carried by these particles becomes comparable or less than the unit charge of an electron. (see Fig. 10).

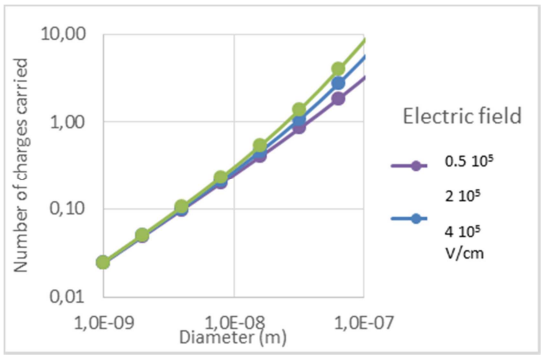

Figure 10. Average charge of particles normalized to an elementary charge as a function of particle size (calculated with simplifying assumptions) [11]

In this particular case, the particle motion calculation cannot be done with the average charge. For a given diameter, some of the particles will have a unit charge while others will carry no charge. As the particle speed is related to the charge it carries, the particles charged with a unit charge will have a speed that is proportional to the electric field, (they are subject to a force: qE). The uncharged particles are not subject to the force of the electric field. This difference has a great impact on the collection of ultrafine particles. Accordingly, with nanoparticles, the charge distribution should be taken into account instead of the average charge level.

5.2. Impact of partial charging on collection efficiency

The partial charge of particles can be represented by different models. For this study a simplified model which allows the collection efficiency to be quantified was chosen [12], [13].

When the average charge $\bar{}$ is smaller than 1, it is possible to introduce a correction for the collection efficiency and to define a fraction $\bar{}$ of the particles which carry a unit charge and a fraction (1–α) which go through the electrostatic precipitator. The resulting collection efficiency, using Deutsch's formula, is given by the collection of a particle carrying a unit charge (this is equivalent to using the corresponding migration speed w_1) multiplied by the fraction of charged particles from which the fraction of uncharged particles has been deducted. The global collection efficiency is thus given by:

$$\eta = 1 - \alpha e^{-\frac{Aw_1}{Q}} - (1-\alpha), \qquad (10)$$

η – collection efficiency,
w_1 – the migration velocity,
A – the collection area,
Q – the flue gas flow rate,
α – the normalized mean charge.

To demonstrate the impact on the collection efficiency of the partial charge, Fig. 11 show a part of the collection efficiency calculated with an average

charge (line 3) for nanoparticles and for an actual charge carried by the particles (line 4).

A fall in collection efficiency is observed at about 20 nanometers.

At a particle size of less than 20 nanometers, the phenomenon of partial charging explains the fall in collection efficiency.

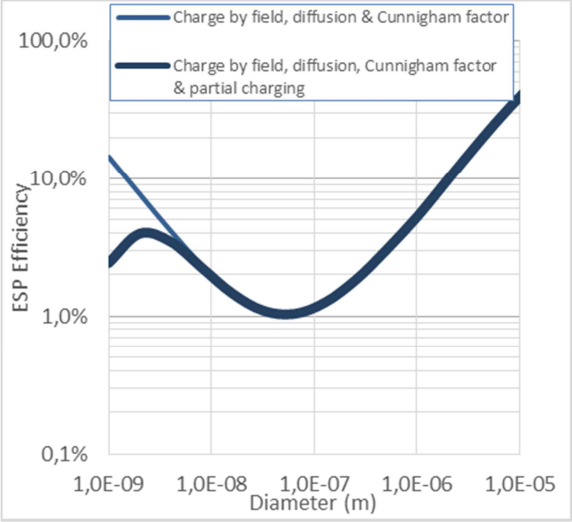

Figure 11. Variation in the collection efficiency of particles with and without taking into consideration partial charging

6. Conclusion

The effects of fine particles and nanoparticles on public health have led to current discussions for increasingly stringent regulations to restrict emissions. The size of the particles is a determining factor in the efficiency of collection of an electrostatic precipitator. The fall in collection efficiency is neither linear nor straight forward. Descriptions of the physical phenomena which explain the collection characteristics are to be found in the literature. However, a comprehensive and unifying explanation of these phenomena has been lacking.

The two principal changes linked to the size of the particles are: (i) the medium cannot be considered to be continuous, (ii) the charge on a particle is a discrete value.

These changes, when they are considered in conjunction with three physical phenomena; firstly, the significant contribution made by charging by diffusion compared to that by electric field charging, secondly, changes in the limit speed because of drag force changes, and finally, the partial charge of these particles, all have an impact on the collection efficiency curve (Fig. 12).

Models [14, 15, 16] for the collection of fine and nanoparticles must take into consideration all the phenomena described and quantified in this paper.

An understanding of the physical phenomena and the demonstration of the importance of particle size, indicates the value of pursuing the description of fine particles still further.

This is necessary, firstly, because the collection efficiency is not a linear function of the number of charges carried by a particle. The overall collection efficiency of monodisperse nanoparticles cannot be predicted without taking into account the charging distribution as opposed to using an average charging level.

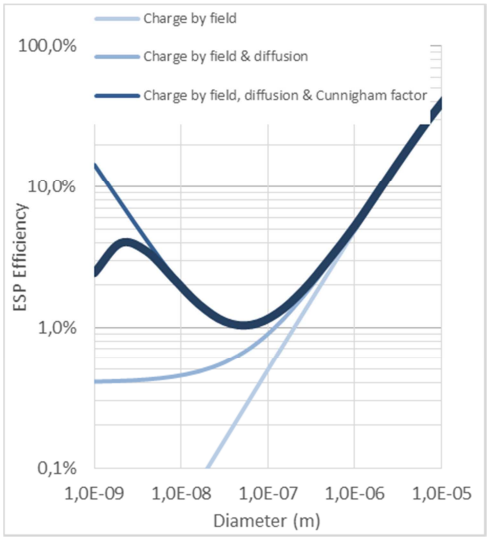

Figure 12. Effects of charging by the field (line 1), cumulated with charging by diffusion (line 2), cumulated with a modification of the fluid regime (line 3) and cumulated with the partial charge phenomena (line 4) on the collection efficiency of fine particles

Secondly, it is important to know the size distribution at the filter entrance if the global efficiency is to be ascertained. Usually for particles with a diameter greater than µm, the concentration and collection efficiency are expressed as a mass. However, for fine particles, they must be expressed as a number [8, 17, 18]. This presents the difficulty of passing from quantifying as a mass to that of a number. In size distribution by number there is no distinction between the particles. In size distribution where the collection efficiency can be measured in terms of surface area or volume, the particles have an influence which is proportional to this measure (mass, size, surface…). The difference can be considerable; the volume of a sphere with a radius of 10 µm is a 1000 times greater than a sphere with a radius of 1 µm. Given that ultrafine particles have a very low mass, the description of particles entering an electrostatic precipitator must be adapted so that the collection efficiency of ultrafine particles can be correctly evaluated.

How can new regulations take into account that the collection efficiency is not a linear function of the particle size?

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