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Collection of fine particles in electrostatic precipitators : influence of EHD induced agitation and of particles disintegration

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Abstract: The paper focuses on two particular phenomena which contribute to the poor collection efficiency of fine particles (from $\sim 0.1 \mu\text{m}$ to $\sim 2 \mu\text{m}$) by electrostatic precipitators (ESPs). After considerations on the influence of turbulence which tends to decrease the collection rate, a conjecture is recalled on the action of the charged fine particles which is expected to give the main contribution in the generation of small eddies in ESPs. Results are presented of an experimental study of the collection efficiency η of cigarette smoke. The efficiency is found to decrease as the dust concentration is increased and the efficiency decrease is attributed to the increase in eddy diffusivity. The second phenomenon observed in the study is the disintegration of agglomerates in the ESP. A marked agglomeration process occurs because the smoke is kept in a big balloon during a few minutes; this agglomeration is more and more marked as the smoke concentration is raised. When charged in the ESP, some of the agglomerates disintegrate under the Coulomb repulsion, which increases the apparent collection efficiency η of the bigger particles ($> \sim 0.6 \mu\text{m}$) but clearly decreases η for the smaller ones ($< \sim 0.5 \mu\text{m}$).

Keywords: electrostatic precipitation, fine particles, electrohydrodynamics, EHD turbulence, electrical disintegration of aggregates.

1. Introduction

Industrial one-stage electrostatic precipitators (ESPs) typically consist in a series of grounded parallel plates through which the gaseous suspensions to be treated are flowing. Equally spaced ionising electrodes raised at high negative potential are located midway between the plates. The collection of particles involves the ionisation of the gas, the charging of particles, their migration towards the collecting electrodes and the removal of the dust layers from the collection surfaces. Most industrial ESPs treating very large fluxes of flue gases have collection efficiency in terms of mass higher than 99 or 99.9 % [1]. However the non-captured part consists mainly of fine particles as can be seen on Fig. 1 which shows the penetration, i.e. the proportion of particles issuing from the ESP. These fine particles are hazardous for health and more stringent regulations concerning air pollution control make it necessary to substantially increase their removal.

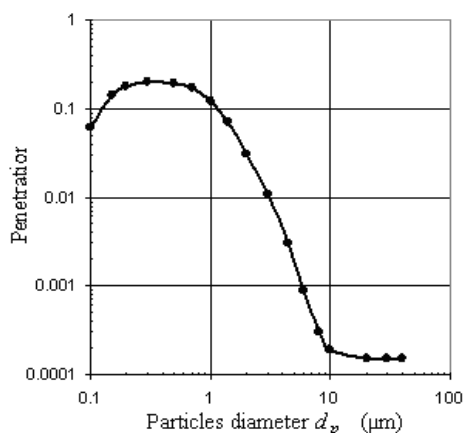


Figure 1 - Measurement on industrial sites of penetration versus the particle diameter. (From [2]).

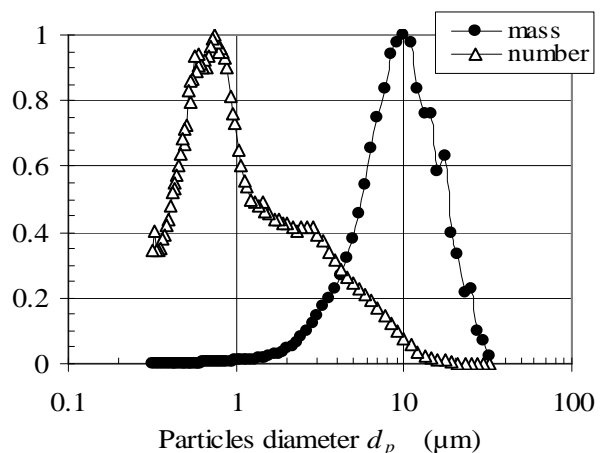


Figure 2 - Normalised size distributions in mass and in number of ashes collected in the last (4th) field of the ESP of a coal-fired power plant. (From [3]).

In order to improve the efficiency of ESPs, one has to first characterise the various phenomena which contribute to make the collection efficiency η_f so low and to estimate their relative influence. The first and well known reason for the low collection efficiency of fine particles is the small value of their drift velocity with respect to the gas. The second factor which influences η_f is the degree of turbulence of the gas flow; although the influence of this factor is recognised, the origin of the “turbulence” is not so clear and authors retaining the electrical forces usually generally consider the action of the field on the ionic space charge only. Here, we examine the effect of the space charge associated with fine particles. The third phenomenon which might play a non negligible role, at least in the case of flue gases issuing from coal-fired power plants, is the disintegration of agglomerates.

2. Particles charging and drift velocity

The particles in flue gases of coal-fired power plants have a size extending over four decades, from typically 20 nm to 200 μm , with the largest mass corresponding to particles of diameter d_p ranging from 10 to 100 μm [4]. The size distribution is characterised by several modes depending on the coal properties. Generally there is a mode of typical size on the order of tens or hundreds of micrometers [4]; these large particles originate from the ash mineral inclusions in the coal and are practically totally collected by the ESPs. Most often another mode has d_p values in the range of micrometers as can be seen on Fig. 2 relative to the ashes collected in the last field of the ESP of a coal-fired power plant in France (the peak observed in the number distribution curve of collected particles is at a d_p value $\approx 0.7 \mu\text{m}$ - different from the one characterising the fine ashes at the inlet of the ESP which collected the sample). The submicron particles in the flue gas have a size distribution centred at about 0.1 μm and they are dendritic clusters consisting of partly sintered primary ultra-fine particles of diameter $\sim 20\text{-}30 \text{ nm}$ [5]; the generation of ultra-fine primary particles is attributed to complex chemical processes giving volatilised suboxides or metals vapours which then reoxidise and lead to particles through homogeneous nucleation [5].

The low efficiency of ESPs for fine particles (with d_p ranging from 0.1 to 2 μm) is mainly due to the rather low drift velocity w_E of these particles with respect to the suspending gas. Two mechanisms are usually distinguished for particle charging. The first one is the field charging where the unipolar gaseous ions are assumed to follow the field lines and impact the particle. The saturation charge $q_{p,sat}$ acquired by the particle is proportional to the field and to the square of the particle diameter d_p [6]. This picture is valid when the mean free path of ions is fully negligible compared with the sphere radius. For small enough particle size, the charging mechanism by diffusion of ions is dominant. The simple theoretical approach of White [7] leads to a charge value q_p proportional to d_p and having a

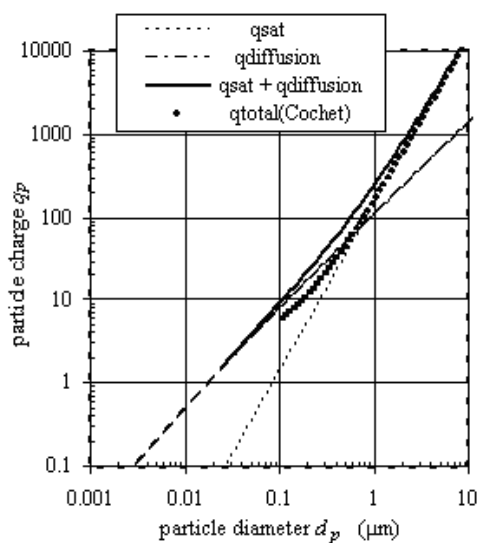


Figure 3 - Charge of spherical particles (in elementary charges e) as a function of their diameter ($\epsilon_r = 4$, $T = 403 \text{ K}$ ($130 \text{ }^\circ\text{C}$), $E = 4 \text{ kV/cm}$, $t_{charging} = 1 \text{ s}$).

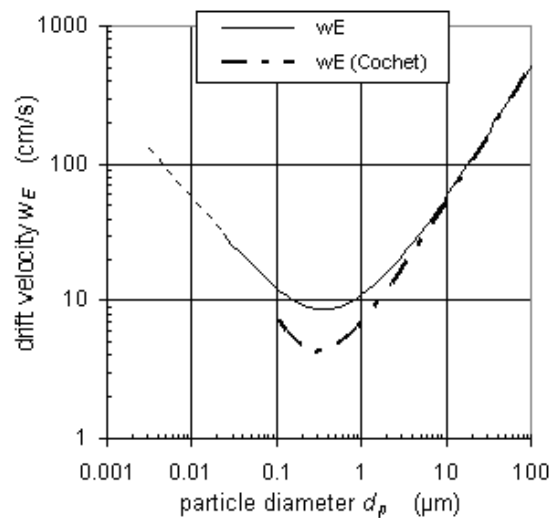


Figure 4 - Drift velocity of spherical particles as a function of their diameter ($\epsilon_r = 4$, $T = 403 \text{ K}$ ($130 \text{ }^\circ\text{C}$), $E = 4 \text{ kV/cm}$, $t_{charging} = 1 \text{ s}$).

logarithmic dependence on the time. In the diameter range 0.1 to 2 μm , the two mechanisms interplay and the sum of both contributions gives an upper bound for the particle charge (Fig. 3). In practice, in this size range, as a first approximation many authors retain the empirical formula of Cochet [8] :

Under a field E the particles with charge q_p experience the force $F_e = q_p E$ which tends to move them toward the collecting electrodes. Neglecting the inertial effects (typical time $\sim \mu\text{s}$), the drift velocity with respect to the gas is determined by the viscous force F_v compensating for F_e ; as the molecular mean free path λ_g is not much smaller than the particles radius, the friction force is smaller than in a continuum and the Stokes expression has to be divided by the Cunningham factor Cu [7]. The particle drift velocity w_E then is proportional to the field E and has a non trivial dependence on the diameter d_p as can be seen on Fig. 4. In typical conditions for ESPs, w_E for fine particles (d_p from 0.1 to 2 μm) ranges between 4 and about 10 cm/s. These values are much lower than the axial mean velocity of the gas flow and this is the main reason why it is difficult to collect the fine particles (there is a clear correlation between Figs. 1 and 4).

3. Influence of gas turbulence

The flow of the flue gas in the ducts is always turbulent because the Reynolds number $Re \sim 10^4$ is higher than the critical value $Re_{crit} \equiv 2000$. But the turbulent rate measured in ESPs is clearly higher than for the pure flow itself [9]. This is not surprising : there are electrical forces acting on the space charge and we will see in §4 how these forces can generate a strong agitation of the gas.

The fine particles convected by the mean flow are very sensitive to the velocity fluctuations of the gas. Indeed, for particles with $w_E < 10$ cm/s, the fluctuations of the gas velocity which are high enough can entrain them in the direction opposite to the electric force at some places. We are facing an intricate problem which can be simplified by using the concept of eddy diffusion of the particles [10] characterised by the coefficient D_t . The “mixing” property of turbulence results in a tendency to make the distribution of particles concentration more uniform, in particular in the z direction normal to the collecting plates. The Deutsch model considering a uniform distribution c in the z direction is equivalent to an infinite value of the z -component of turbulent diffusivity (Fig. 5). The model developed by Leonard et al. [10] is based on finite and uniform value of the eddy diffusivity further assumed to be isotropic. In this case, the z distribution of particles concentration c becomes more and more uniform as D_t is increased (see the qualitative illustration of Fig. 5).

In the turbulent models of particles collection, a boundary layer is considered where the diffusivity of particles steeply decreases down to zero (gas velocity = 0 on the plates). Assuming that each particle reaching the plate is captured, the flux of collected particles is proportional to the product $c(x, z=d) E(x, z=d)$ where $c(x, z=d)$ is the particles concentration on the plate. From Fig. 5 it is clear that higher turbulence intensity will result in lower collection efficiency. In practice, the collection efficiency also depends on the magnitude of the electric field. The pertinent parameter controlling the particles collection rate is the electric Peclet number Pe defined by [10] :

$$Pe(d_p) = \frac{w_E(d_p) d}{D_t} \quad (1)$$

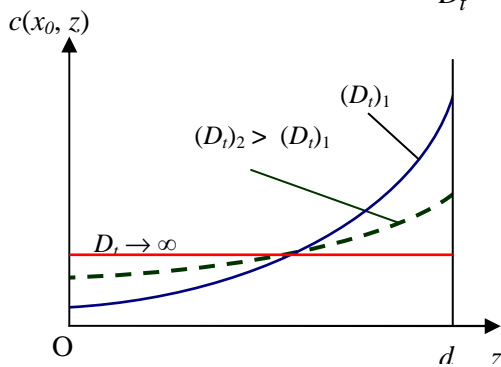


Figure 5 – Concentration of charged particles between the symmetry plane and the collecting plate (at distance x_0 from the inlet) for different D_t values.

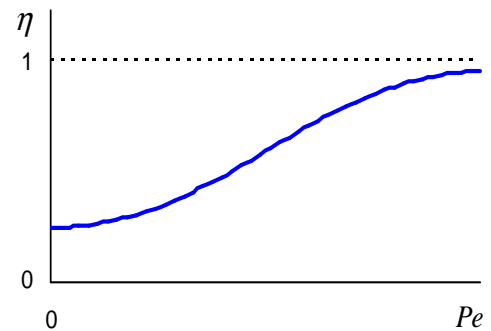


Figure 6 – Variations of the fractional collection efficiency as a function of the electrical Peclet number.

Pe reflects the effect of eddy diffusivity which tends to counteract the action of the field inducing the drift velocity w_E (and driving the particles towards the collecting plates). Increasing the field E and, therefore, the drift velocity of particles, is equivalent to decreasing the eddy diffusivity D_t . The influence of Pe is qualitatively illustrated by Fig. 6.

4. Turbulence generation by fine particles

The secondary flow induced by the electric force density distribution associated with the ionic space charge density (in the absence of charged particles) is noticeable and clearly contributes to the turbulence generation by producing eddies of typical size $\sim d$ (d : half width of the ducts), except in the case of negative wires due to the tuft corona inducing smaller size eddies. However this fact is not taken into account in most numerical simulations of ESPs which retain only the $k-\varepsilon$ scheme for turbulence distribution and evolution. Now, the charge density of particles very likely plays the primary role in ESPs by generating eddies of small size.

Generally an intense movement of the fluid is induced by the action of the field E on the space charge of density ρ resulting from corona effect in gases and from ions injection by one of the electrodes in liquids [11]. The primary electrohydrodynamic (EHD) phenomenon in this case of injected space charge is the strong positive coupling between fluctuations u' of the fluid velocity field u and perturbations of the space charge density ρ [12]. This coupling leads to a potentially unstable situation for a planar fluid layer with uniform unipolar injection. The motion sets in when the action of the electric force of density ρE overcomes the viscous damping, which leads to the following relation for the first fundamental non dimensional EHD parameter T [12] :

$$T = \frac{\varepsilon V_{appl}}{K \mu} > T_c \quad (2)$$

here ε denotes the fluid permittivity, V_{appl} the applied voltage, K the mobility of charge carriers, μ the dynamic viscosity and T_c is a critical value. For ions in air at ambient temperature, typically $(V_{appl})_c \cong 40$ kV but for charged fine particles, we would have $(V_{appl})_c \sim$ a few hundreds of volts [12,13]. It is therefore clear that the presence of charged fine particles can easily induce instabilities and, in practice, can create eddies of rather small size.

The fluid agitation contributes to the transport of the charge carriers; its effect is important when the typical fluctuations of fluid velocity u' are high enough compared with the drift velocity of charge carriers $w_E = KE$. The second basic non dimensional EHD number M defined by :

$$M = \frac{\sqrt{\varepsilon / \rho_f}}{K} \quad (3)$$

(here ρ_f stands for the fluid density) is the pertinent parameter to compare the velocities u' and KE [11,12]. For $M < \sim 1$ ($u' \ll KE$), the trajectories of the charge carriers are only very slightly perturbed by the fluid motion which has no significant influence on the distribution of ρ and on the passage of electric current (case of ions in air : $w_E \sim 100$ m/s \gg electric wind ~ 1 m/s). If, conversely, $M > \sim 3$ ($KE < u'$), the charge carriers are entrained by the fluid flow that they contribute to create and there is a significant increase of mean current density. Injected ions in dielectric liquids give the typical example of this situation [11,12]. The transition between the two regimes occurs for $M = 3$ [17]. The two parameters T and M are also pertinent for more complex EHD flows as obtained in asymmetric electrode configurations [13].

In the typical conditions of ESPs, the estimate of the charge acquired by the particles and of their mobility leads to estimates of the mobility parameter M , relative to the particles, which of course depend on the particles size [13]. For fine particles charged under a typical mean field $E \sim 5$ kV/cm, $M > 3$ [13]; therefore charged fine particles in gas have a behaviour analogous to that of ions in insulating liquids and a turbulent mixing which partly redistributes the particles charge density can be expected. The intensity of the generated turbulence will also depend on the concentration of charge carriers and this gives a way to test the pertinence of the proposed picture of the turbulence being mainly generated by the charged fine particles.

The above considerations are very general and concern problems with only one type of charge

carriers. In ESPs there are two types of charge carriers : ions and charged dust particles which both contribute to the space charge and therefore have distributions which are inter-related. For sustained corona discharges in gases, from Kaptzov hypothesis, the field E_{wire} on the ionising wire(s) is equal to the value it takes at the inception voltage V_{th} of corona discharge. For a clean gas (no dust), the global charge density $\tilde{\rho}_{total}$ affecting the field distribution is due to ions only and we have :

$$(\tilde{\rho}_{total})_{clean} = \tilde{\rho}_{ions} = (\tilde{\rho}_{ions})_0 \propto (V_{appl} - V_{th}) \quad (4)$$

where $\tilde{\rho}_{ions}$ is the global charge density associated with the ions. For a dusty gas, the field E_{wire} on the wire remains the same and is not affected by the dust concentration c_0 at the ESP inlet; we thus obtain:

$$(\tilde{\rho}_{total})_{dusty} = \tilde{\rho}_{ions} + \tilde{\rho}_p = cst = (\tilde{\rho}_{ions})_0 \quad (5)$$

$\tilde{\rho}_p$ being the global space charge density of particles. The total current I also has two components, I_{ion} and I_p ($I = I_{ion} + I_p$); the current densities write :

$$\mathbf{j}_{ions} = K_{ions} \rho_{ions} \mathbf{E}, \quad \mathbf{j}_p = K_p \rho_p \mathbf{E} \quad (6)$$

where K_{ions} , ρ_{ion} and K_p , ρ_p are the ions and particles mobilities and charge densities respectively. As the ratio $K_p/K_{ion} \sim 10^{-3}$, for a dusty gas we have :

$$I \approx I_{ions} \propto \tilde{\rho}_{ions} \equiv (\tilde{\rho}_{ions})_0 - \tilde{\rho}_p \quad (7)$$

and the current should decrease with the dust concentration c_0 . In practice the relative current decrease should give an estimate of the mean space charge associated with the charged particles :

$$\frac{\tilde{\rho}_p}{\tilde{\rho}_{ions}} \cong \frac{I_0 - I}{I} \quad (8)$$

For fine particles, except just around the wires, the particles drift velocity is lower than the gas velocity so that the distribution of ρ_p is controlled mainly by the flow which, itself, is determined by the total space charge distribution $\rho_{ion} + \rho_p$. When ρ_p becomes comparable to ρ_{ion} a marked change in the mean gas flow pattern is expected along with a significant rate of turbulence induced by ρ_p .

5. Influence of particles concentration on collection efficiency

5.1. Experimental set-up

The study of fine particles collection was carried out using a laboratory ESP characterised by a duct of width $2d = 9$ cm and height $h = 29$ cm. The test cell of total length $L = 100$ cm is divided in two sections of 50 cm in length. Initially a set of 9 equidistant ionising wire electrodes was used to create the space charge in the first section. In the second field, a plate can be introduced and polarized to create a uniform field of collection E_c in the two half-ducts. The efficiency of particles collection is

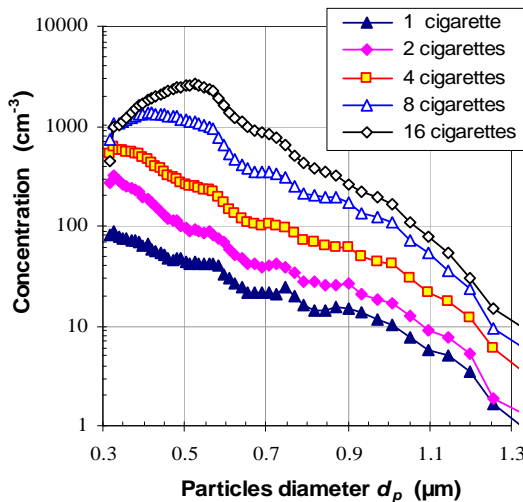


Figure 7 - Size distributions (in number) of particles of "Gauloises" cigarettes smoke for different numbers of burnt cigarettes.

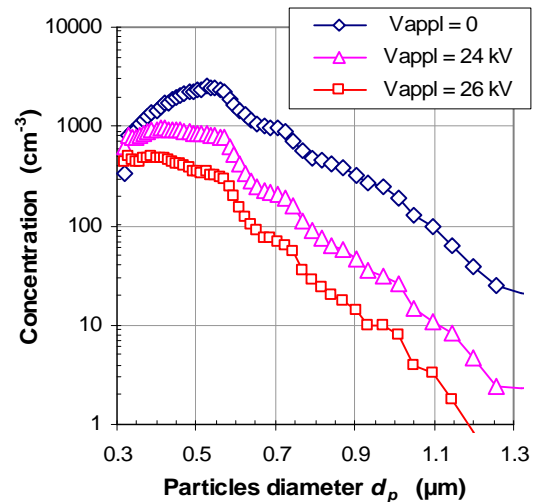


Figure 8 - Size distributions of smoke particles (16 burnt cigarettes) for two applied voltages (9 ionising wires in the first section).

determined from concentrations measurements with and without applied field, using an optical counter (TOPAS LAP320) on scales ranging from 0.3 μm to 20 μm .

The study has been performed with cigarette smoke filling a balloon of about 2.5 m in diameter ($\sim 8 \text{ m}^3$). Starting with the empty balloon, the air pushed by a fan flows through a paper filter, then through a box where some cigarettes are burning and progressively fills the balloon. Once the balloon is full, the accumulated smoke is directed to the test cell. As the optical counter has a lower bound for the measured diameter of 0.31 μm , French cigarettes (trademark : Gauloises) were used which generate particles of not too small size (99% of particles with $d_p <$ about 1.05 μm). Fig. 7 shows the size distributions for different numbers of burnt cigarettes. For 8 and 16 burnt cigarettes, the curves exhibit a maximum for $d_p \cong 0.4 \mu\text{m}$ and $0.55 \mu\text{m}$ respectively. The increase of mean size of particles results from an agglomeration of smaller particles.

5.2. Results

With the set of 9 vertical equidistant ionising wires ($\phi = 1 \text{ mm}$) perpendicular to the horizontal air flow of mean velocity $U_0 = 0.4 \text{ m/s}$ ($E_2 = 0$ in the second section), the measurements were performed by filling the balloon and counting the particles for successive sequences with and without the voltage applied on the wires (typical results are shown in Fig. 8). The fractional efficiency of collection of particles η_f as a function of their size d_p has been determined from the distributions as shown in Fig. 8 for five smoke concentrations. The major interesting fact indicated by Fig. 9 is the clear tendency of η_f to decrease as c_0 is increased. Note that the concentration influence is most marked in the range 0.3 to 0.5 μm and that the low η_f values obtained for the smoke generated by burning 16 cigarettes partly arise from the disintegration of charged agglomerates under the influence of Coulomb repulsion.

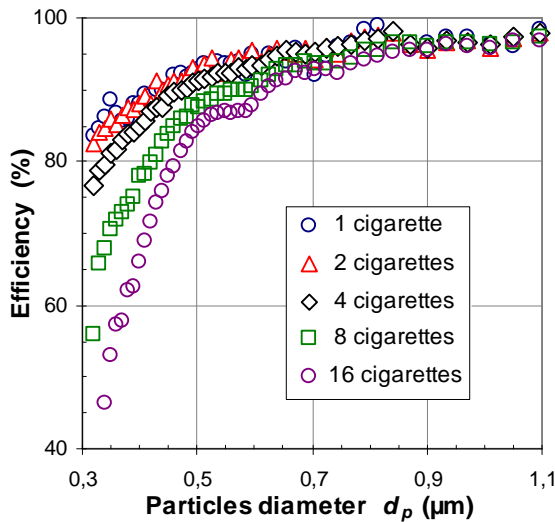


Figure 9 - Fractional efficiency of collection η_f versus particles diameter for various smoke concentrations c_0 (9 ionising wires, $V_{appl} = 26 \text{ kV}$).

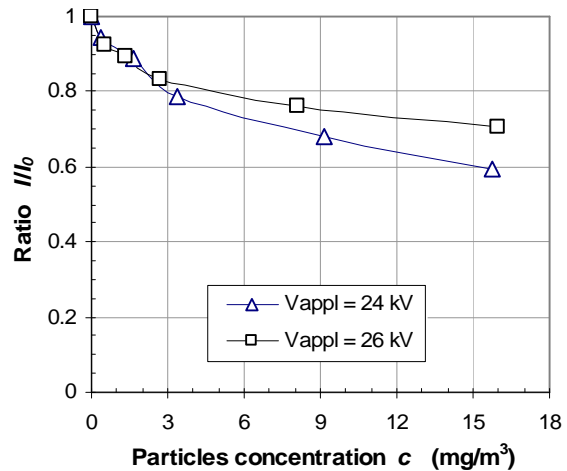


Figure 10 - Ratio of the currents I for a flow of smoke and I_0 for filtered air ($U_0 = 0.4 \text{ m/s}$) as a function of c_0 (9 ionising wires)..

The efficiency decrease with the particles concentration is presumably due to the increase in secondary flow and turbulence intensities. The results appear to be consistent with those obtained by Podlinski et al. [18]. In particular a marked decrease in discharge current was obtained as shown in Fig. 10. This indicates that for the highest smoke concentrations, the space charge associated with the charged particles represents 30 to 40% of the total space charge.

6. Particles disintegration

In order to have η_f measurements in conditions comparable to those of ref. [18], the set of 9 wires was replaced by a unique ionising wire ($\phi = 0.5 \text{ mm}$) located at $x_0 = 21 \text{ cm}$ from the inlet. The measurements of size distributions without and with applied voltage were performed for a mean

velocity of the gas flow $U_0 = 0.4$ m/s, $V_{appl} = 23.5$ kV and various smoke concentrations. The curves of fractional collection efficiency η_f (Fig. 11) clearly show that, in the range 0.3 to 0.5 μm , η_f tends to decrease when the particles concentration c_0 is increased; conversely it tends to increase for $d_p > \sim 0.6$ μm . An interesting observation is that for high concentrations (8 and 16 burnt cigarettes), negative values of η_f are obtained, which means that, at the outlet, there are more - very fine - particles than at the inlet of the test cell : as can be seen on Fig; 9, for 16 burnt cigarettes the concentrations of particles of diameter ranging from 0.3 μm to about 0.4 μm are higher after the action of the corona discharge ($V_{appl} = 23.5$ kV) than at the ESP inlet.

Fig. 7 clearly indicates that the mean size of the particles increases as the concentration of the smoke is increased. This implies a noticeable agglomeration of the fine particles in suspension. Now, when an aggregate captures electric charges (here positive ions), these charges distribute over the different elements constituting the aggregate which then experiences a Coulomb repulsion so that it can disintegrate. This process of disintegration of aggregates explains why there are so many small particles issuing from the ESP and also why the relative number of the biggest particles at the outlet decreases when the smoke concentration is increased (this corresponds to an increase in effective fractional collection efficiency η_f). The process of dispersion of aggregates was also present in the first series of experiments with the set of 9 wires (§5.2). But the addition of the influences of the successive wires partly damped the effect clearly exhibited by the unique wire experiment. Nevertheless, there remains a noticeable effect of the dispersion of aggregates in the range $d_p = 0.3$ to 0.4 μm as can be seen on Fig. 9.

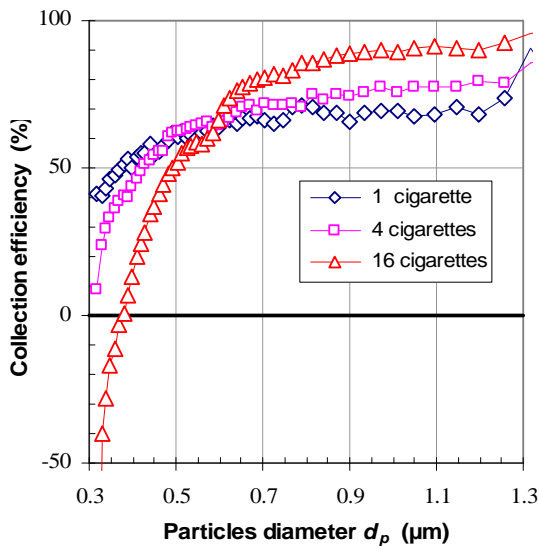


Figure 11 - Fractional efficiency of collection $\eta_f(d_p)$ in the first section with a unique ionising wire for 3 different smoke concentrations ($V_{appl} = 23.5$ kV).

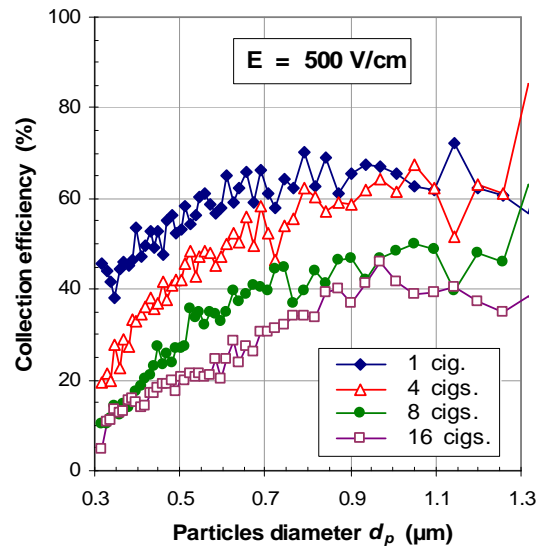


Figure 12 - Fractional efficiency of collection in the second section of the test cell for different c_0 values (applied uniform field $E_2 = 0.5$ kV/cm).

In order to eliminate the influence of disintegration of aggregates when determining the fractional collection efficiency, we performed measurements in the second section of the test cell where the field is uniform, where there is no particle charging (no ionic space charge) so that, presumably, no disintegration of aggregates occurs. A voltage $V_{appl} = 20$ kV was applied on the wire in the first section of the ESP and the mean air velocity was again $U_0 = 0.4$ m/s. In the second section of the ESP a field E_2 was applied and the efficiency was determined from the size distributions without and with field E_2 . The results shown on Fig. 12 for $E_2 = 0.5$ kV/cm confirm that the efficiency decreases with the smoke concentration for the whole diameter range in which the measurements are significant. The difference of these results with those relative to the first section of the test cell (§5.2) is clear and can be ascribed to the absence of disintegration of aggregates in the second section. For all diameter values $d_p < \sim 1$ μm , the efficiency η_f decreases as the particles concentration is increased. This is consistent

with the picture of the turbulence intensity increasing with the mean charge density associated to the charged fine particles.

7. Conclusions

This study performed on cigarette smoke shows that there is an important effect of agglomeration of fine particles when the smoke concentration is high enough. The mean size of aggregates increases with c_0 , which supports the picture of agglomeration of slightly sticky particles through collisions due to their Brownian motion. The rather unexpected phenomenon we observed is the disintegration accompanying the charging of the aggregates by the ions created by corona discharges. Such a disintegration process implies rather limited adhesion forces between the particles constituting the aggregates. Extrapolation of the existence of such a disintegration process in industrial ESPs is not possible because of the very large variety of the particles collected in these ESPs. We can just suggest that this process might play a role in electrostatic precipitation and might partly explain the difficulties in collecting the fine particles.

By taking into account the influence of disintegration of aggregates occurring in the first section of our ESP, the presented measurements show that the fractional collection efficiency η_f of the particles decreases as their concentration c_0 is increased. From the general considerations on the effect of turbulence on collection efficiency (§3) illustrated by Fig. 6, the decrease of η_f with c_0 implies that the corresponding electric Peclet number Pe also decreases. The results concerning the influence of dust concentration on collection efficiency appear fully consistent with the observations and measurements of gas flow which show a modification of the mean flow pattern and an increase in turbulence intensity []. In addition to their interest concerning the collection of fine particles in ESPs, the results on efficiency decreasing as the dust concentration is increased provide an indirect proof of the increase of the turbulence rate and give a support to the conjecture that an important source of turbulence in ESPs is "intrinsic", through the action of the space charge associated with the fine particles (characterised by a low mobility).

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