

Wet electrostatic scrubbing for submicronic aerosols capture – potentialities and preliminary design criteria

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A theoretical model for the analysis of a wet electrostatic scrubber, WES, is reported. The model indicates that the WES systems allow a significant increase of the collection efficiency for submicronic particles respect to classical water scrubbers. The effect of the main process and design parameters on the collection efficiency is described in order to define preliminary criteria for the design and the operation of WES.

1. Introduction

The capture of submicronic aerosols from flue gases is a critical issue of environmental engineering. The actual collection efficiencies of the existing technologies are the minimum for particle diameters lying between 10 nm and 100 nm, in the so-called Greenfield gap. In this range both the mass and the diffusivity of the particles are too low to achieve efficient separations from the flowing gas (Seinfeld and Pandis, 1998). In the last ten year, a novel concept for particle capture by electrostatic forces has been introduced starting from two simple observations: 1. the aerosols present a superficial electric charge distribution due to triboelectric effects and the overall concentration of negative and positive charges are the same so that the average aerosol charge is usually zero; 2. water droplets can be easily charged (both positively and negatively) and dispersed in a flow of gas in order to attract the naturally charged particles.

The deriving technology, known as wet electrostatic scrubber, WES, usually consists in two subsequent water scrubber chambers with a modified atomization system that allows the electrical charging of the water droplets. The first chamber produce positively (negatively) charged droplets to remove negatively (positively) charged aerosols, the second one generate droplets of the opposite sign. Although there are some industrial applications of WES and some international patents, general design and scale-up criteria for wet electrostatic scrubbers are not available at the moment.

Henceforth, this paper reports a preliminary study aimed to the analysis of the potentiality of WES technology and to the assessment of design criteria for this kind of reactor. It is based on the use of theoretical models for the estimation of the particle

removal efficiencies in traditional water scrubbers coupled with model evaluations of particle-droplet electrostatic interactions. For the sake of simplicity this paper refers to an ideal case that considers a simplified description of the spray fluid dynamic and neglects the droplet electrostatic charging process. The goal of the model is to allow the assessment of preliminary design criteria for WES systems tracing the path for future investigations.

2. Theoretical framework

Detailed experimental analysis on wet scrubbers and wet electrostatic scrubbers are reported in the works of Tomb et al. (1972) and Cross et al. (2003) respectively. The last show a significant increase of collection efficiency for micronic particles by using a WES. Anyway, the theory of the particles capture by droplet scavenging is mainly derived from studies on atmospheric aerosol scavenging during rainfalls (Seinfeld and Pandis, 1998).

According to this studies, the instantaneous scavenging rate for particles of diameter d_p , $\hat{n}(d_p)$, by a water spray of droplets with size distribution $N(D_g)$, numerical concentration C_g and relative drop-gas velocity U_g is given by:

$$\hat{n}(d_p) = n(d_p, t) \cdot \int_0^\infty \frac{\pi}{4} (D_g + d_p)^2 \cdot U_g \cdot E \cdot C_g \cdot N(D_g) \cdot dD_g = n(d_p, t) \cdot \Lambda(d_p) \quad (1)$$

where $n(d_p, t)$ is the numerical particle concentration at the time t . The integral, named scavenging coefficient, $\Lambda(d_p)$, is defined over the entire range of droplet sizes and represents the inverse of the characteristic time for particle scavenging.

It is worth noting that the overall scavenging rate is the linear superposition of the contributes pertaining to each single scavenging drop. This is verified if the volumetric drop concentration is sufficiently low ($\varepsilon < 10\%$) to neglect droplet-droplet interactions, a well posed assumption for industrial wet scrubbers.

The collision efficiency, E , resumes all the features of the droplet-particle interactions accounting for capture mechanisms related to inertial effects, E_m (Slinn, 1983; Licht, 1988; Kim et al., 2001), hydrodynamic interaction, E_{HI} (Slinn, 1983; Jung and Lee, 1998), Brownian diffusion, E_D (Slinn, 1983; Jung and Lee, 1998), thermophoretic, E_{TP} , and diffusiophoretic, E_{DP} , phenomena (Seinfeld and Pandis, 1998) and electrostatic interactions, E_{Es} (Davenport and Peters, 1978). The numerical value of the overall collision efficiency E is the sum of each collision efficiency contribution.

A detailed description of the collision efficiencies is beyond the scope of this paper and can be found elsewhere (e.g. Seinfeld and Pandis, 1998). Anyway, it is worth noting the expression of the E_{Es} given by Davenport and Peters (1978) model is:

$$E_{Es} = \frac{16K_c C_g q_g q_p}{3\pi\mu_{gas} U_g D_g^2 d_p} \quad (2)$$

In Eq. (2) K_c , C_c and μ_{gas} are, respectively, the dielectric constant, and the particle Cunningham slip correction factor and the gas viscosity while q_p and q_g are the particle and the droplet charges. The capture of particles by electrostatic forces is higher for smaller particles and droplets moving at lower relative velocity.

The droplet charge depends on the electrical charging system and it can be considered as a fraction of the so called Rayleigh limit charge $q_p = k q_R$, that is the highest electrical charge that can be present on a droplet of a given diameter, D_g , without making it unstable and eventually tearing it apart. The value of q_R is given by:

$$q_R = e \cdot \sqrt{\frac{2\pi\sigma_w D_g^3}{K_c e^2}} \quad (3)$$

where e is the electron charge and σ_w is the droplet surface tension.

The charge on a particle mainly depends on its physical properties and its diameter as well as on its peculiar triboelectric charging. Detailed studies on different aerosol types have been reported by Johnston (1987) and Marra and Coury (1999), which, by numerical fit of experiments, expressed q_p as a function of d_p and aerosol properties as:

$$|q_p| = A d_p^B \cdot e \quad (4)$$

Recently also the charge distribution on motor vehicle exhaust particles have been studies by Matti-Maricq (2006).

Figure 1 reports the values of the collision efficiencies in function of the particle diameter. It is evident that electrostatic interaction is the most relevant collision mechanism for particle diameter below $1 \mu\text{m}$ overwhelming all the other collisional contributions. Only for particle diameter higher then $1 \mu\text{m}$ the inertial impacts prevails.

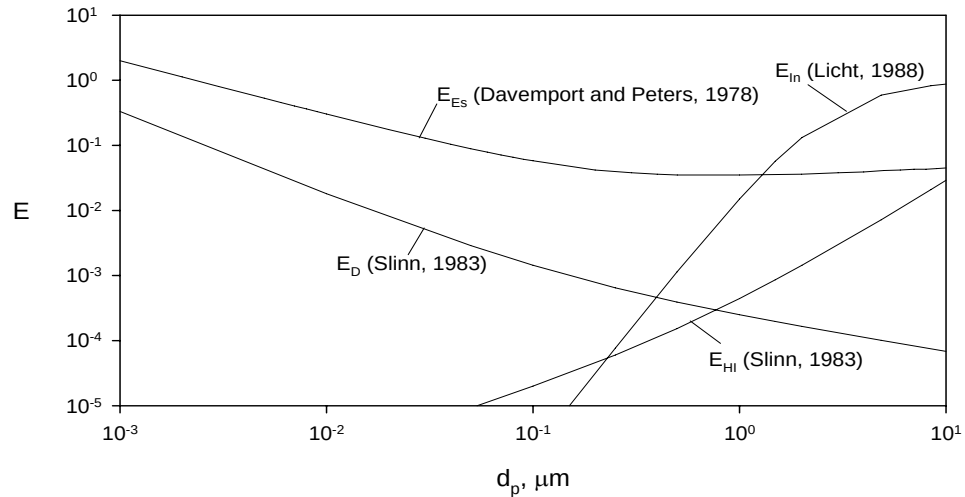


Figure 1 – Collision efficiencies for coal dust in contact with a single water drop ($D_g = 400 \mu\text{m}$, $U_g = 6 \text{ m/s}$, $k=0.1$) in function of particle diameters

3. Model application

The main goal of a WES is to achieve high collection efficiencies with low costs for equipments and process operations. The former is mainly proportional to the WES volume, i.e. to the required contact time and to the spray nozzles costs. The construction materials must be chosen to reduce electric dispersion with the ground and to assure safety operations. The operational costs are mainly proportional to the water consumption, that influences both the WES pressure drops and the cost for droplet charging.

In this study, the main process parameters for WES are considered to be the residence time and the water consumption, represented by a volumetric water fraction, ε .

In particular, this paper considers the ideal case of a gas flow ($P=100$ kPa, $T=25^\circ\text{C}$) containing a given concentration of coal dust modelled as spheres of the same size and uniformly distributed, which contacts an uniform water spray of identical monodisperse spherical droplets moving with the same relative velocity respect to the gas flow.

The particle population balance for a given d_p is described by the equation:

$$\frac{d}{dt} n(d_p, t) = \hat{n}(d_p) = -n(d_p, t) \cdot \Lambda(d_p) \quad (5)$$

whose solution, for a given initial concentration $n(d_p, 0)$ is:

$$n(d_p, t) = n(d_p, 0) \cdot \exp[-\Lambda(d_p)t] \quad (6)$$

Finally, the collection efficiency is:

$$\eta(d_p) = \frac{n(d_p, 0) - n(d_p, t)}{n(d_p, 0)} = 1 - \exp[-\Lambda(d_p)t] \quad (7)$$

In the following, Licht's (1988) model is used to calculate E_{in} , Slinn's (1983) equations are used for E_D and E_{HI} while Eq. (2) is used for E_{Es} and phoretic effects are neglected. The model is applied to reference conditions (Table 1) typical of industrial wet scrubbers. Coal dust particles, largely diffused in industrial facilities, are considered. In this case the parameters of eq.(4) are $A = 36.8$ and $B = 1.17$ (Johnston, 1987).

Table 1 – Reference conditions

Parameters	Reference values	Investigated range of variation
Particle diameter, d_p	$10^{-4} - 10 \mu\text{m}$	-
Dimensionless droplet charge, q_g/q_R	0 - 0.3	-
Droplet diameter, D_g	400 μm	50 - 600 μm
Droplet numerical concentration, C_g	$0.5 \cdot 10^7 \text{ m}^{-3}$	$1.5 \cdot 10^5 - 1.5 \cdot 10^7 \text{ m}^{-3}$
Contact time, t	3 s	-
Dimensionless drop-gas relative velocity, U_g/U_t	1	0 - 2
Volumetric volume fraction, ε	$2 \cdot 10^{-4}$	$10^{-7} - 6 \cdot 10^{-4}$

First of all, Figure 2 shows that the charging of scrubbing particles increases the collection efficiency for particles ranging between 0.1 nm to 10 μm . The effect is more valuable in proximity of the Greenfield gap (0.1-1 μm), confirming the potentiality of wet electrostatic scrubbing respect to traditional equipments for dust depuration.

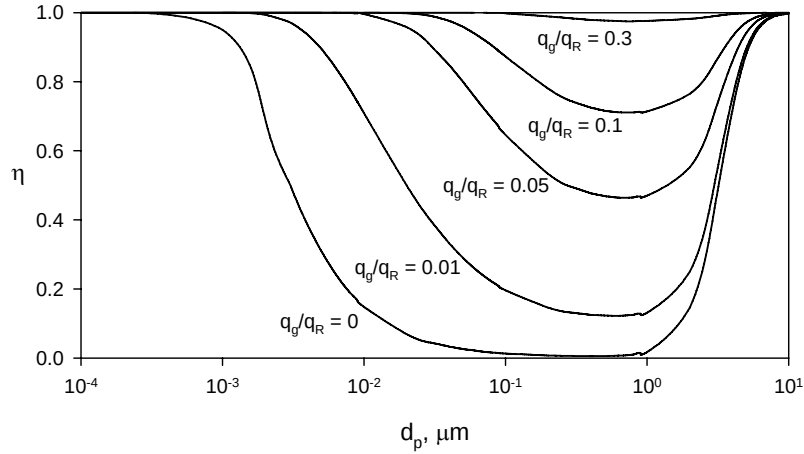


Figure 2 – Effect of droplet charge on the collection efficiency for different particle diameters

As evident from Eq.(4) the collection efficiency exponentially increases with the contact time. This result is shown in Figure 3 that reports the time required to reach 95% collection efficiency, $t_{95\%}$, for different particle sizes, showing that electrostatic interactions strongly reduce the required contact time. The efficiency improvement of a WES system is higher for finer particles due to the higher effects of electrostatic collection mechanisms (Figure 2). In this case, the contact time is reduced of several orders of magnitude by increasing the droplet charge. This means a significant reduction of reactor volume, with a major advancement respect to traditional water scrubbers.

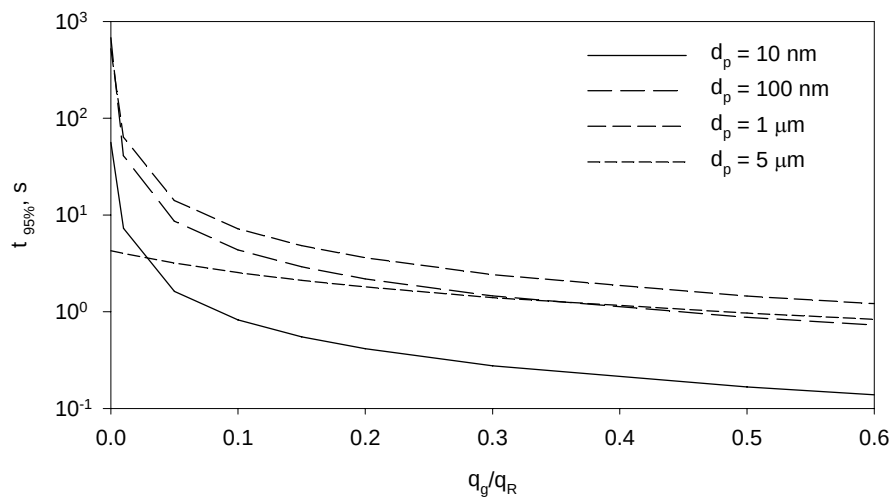


Figure 3 – Contact time for 95% collection efficiency function of dimensionless charge

Starting from this reference case, the effect of the dimensionless relative velocity (given by the ratio of U_g with the drop terminal velocity U_t), drops concentration and diameter are described in Figure 3 for two particle diameters representing the borders of Greenfield gap: 100 nm on the left; 1 μm on the right.

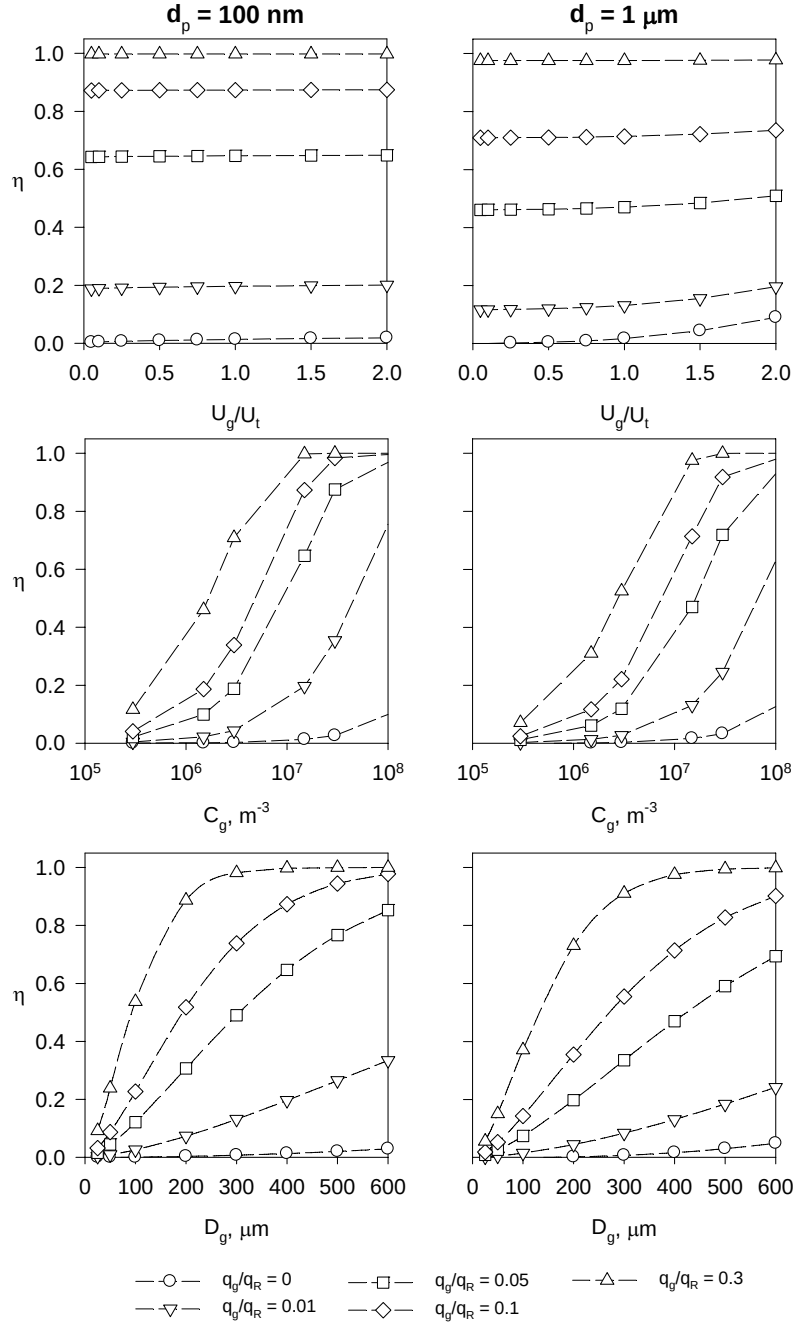


Figure 4 - Collection efficiency in function of process parameters

The model shows a negligible effect of relative velocity while the increasing of droplet concentration and droplet size increases the collection efficiency.

Indeed, the relative velocity determines both the value of E (it is worth of note that all the contribution decrease with U_g apart from the inertial impacts, which is only relevant for particles coarser than $1\text{ }\mu\text{m}$ *circa*) and of $\Lambda(d_p)$. The two effects are almost counterbalanced so that there is a limited dependence on U_g of η that becomes negligible for higher electrostatic contributions. Furthermore, it is worth remembering that after a short time, the sprayed drops approach their steady state terminal velocity and are rapidly dragged by the gas flow independently from their initial jet velocity.

These results allow considering cocurrent-countercurrent flows or crossflow as virtually equivalent. Anyway, cocurrent flow can be preferred to avoid the gas by-pass near the nozzles typical of crossflows and to assure a better dispersion of the droplets in the gas flow and higher contact times.

Furthermore, the collisional efficiency is proportional to the droplet-particle impact section (Eq.1) and, at constant C_g , this lead to the observed increase of η with D_g .

Finally, η increases with C_g due to its direct effect on the scavenging coefficient $\Lambda(d_p)$. Indeed, all these parameters change the specific water flow consumption of the WES, showing that the water consumption to achieve a given collection efficiency can be progressively reduced by increasing droplet charging.

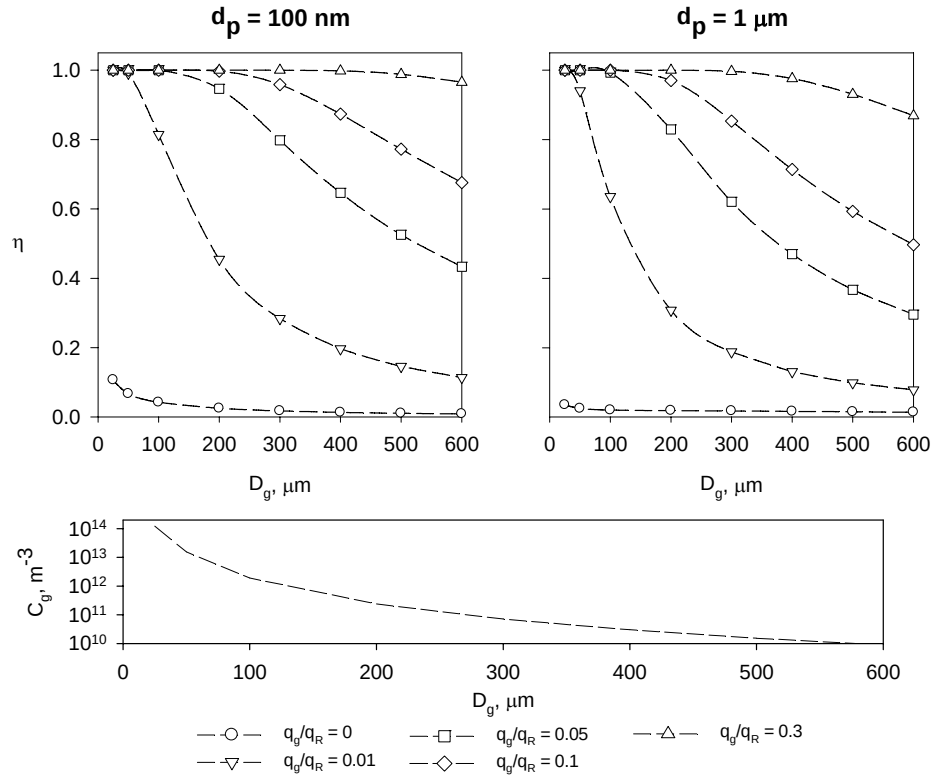


Figure 5 – Effect of droplet diameter on collection efficiency for $\varepsilon = 5 \cdot 10^{-4}$

The specific water consumption per unit flue gas volume can be represented as a water volume fraction in the scrubber, ε . For a given value of ε the size distribution and the concentration of the droplets are correlated variables dependent on spraying nozzle characteristics. Figure 5 shows the collection efficiency for $\varepsilon = 5 \cdot 10^{-4}$ by varying D_g together with the corresponding value of C_g . The model shows that to obtain higher efficiencies, it is more convenient to use higher numbers of finer droplets. This result is in perfect agreement with former experimental evidences (Tomb et al., 1972; Cross et al., 2003).

Conclusions

Wet electrostatic scrubbing represents a noteworthy process to improve the collection efficiency of submicronic particles from flue gases. This is confirmed by several experimental evidences and theoretical insights but, even if there are some industrial applications and some international patents based on such process, proper design and scale-up criteria for WES are not still available.

This paper is a first attempt to describe the functional dependencies of the collection efficiency on the main WES process parameters by using a simplified model for particle capture based on theoretical analyses of droplet-particle interactions.

Preliminary analyses of Tomb et al. (1972) and Cross et al. (2003) experiments with a simplified spray fluid dynamic model confirm that the model allows a good fit of experimental data, but, for the sake of brevity they are not reported here.

The model shows that the theoretical efficiencies become closer to unit over a wide range of particle diameters and that both reactor volume and specific water consumption can be minimized by increasing the electric charge on the scrubbing droplets. Furthermore, it suggests the use of water sprays of finer droplets and shows that cocurrent flows can be preferred to crossflows.

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