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Wet electrostatic scrubbers for the abatement of submicronic particulate

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ABSTRACT

Water electrostatic scrubber (WES) represents an alternative technology for the abatement of that submicronic fraction of particulate – belonging to the so-called Greenfield gap – usually hardly captured with other cleaning techniques. The promising potentialities of WES are recognized by the scientific and industrial communities, but the design of this kind of reactor is far from being optimized.

This work reports a mathematical model to evaluate the particle removal efficiency in wet electrostatic scrubbers. The model is used to find out optimal working condition of WES units, through the maximization of the particle collection efficiency in function of different process parameters: contact time, specific water consumption, water/gas relative velocity, size and charge of sprayed droplets. The model has been validated by comparison with different experimental data available in literature, both for charged and uncharged scrubbers. Then it is applied to a reference case study to obtain generalizable results.

The model shows that the process optimization for micronic and submicronic size particles follows different criteria. For micronic particles, the collection efficiency increases for higher water/gas relative velocity, with a small effect of droplet diameter and a moderate increase with the droplet charge. On the contrary, in the Greenfield gap, the water/gas velocity plays a secondary role in the capture mechanisms, while a substantial increase of collection efficiency by improving the droplet charge level and reducing the droplet size has been observed.

With reference to the actual performances of water spraying and charging devices, the model predicts that a collection efficiency as high as 99.5% can be reliably obtained in few seconds with a water consumption of 100 ml/m^3 by adopting droplet diameters around 100 μm and charge to mass ratio from 1 to 3 mC/kg, corresponding to droplet charge equal to 10–30% of Rayleigh limit.

1. Introduction

The emission of particulate matter entrained in flue gases of industrial and vehicles exhausts is one of the major health and environmental concerns. Very fine inhalable particles can remain suspended in the atmosphere for a long time, travel long distances from the emitting sources and, once inhaled, they can reach the deepest regions of the lungs and even enter in the circulatory system. Therefore, the lower the particle size, the higher its toxicity. Due to their chemical and physical characteristics, fine particles can produce significant effects on human health [1–11]: they act both directly, by favoring the accumulation of substances in the respiratory tract, and indirectly, as a carrier of hazardous substances. Health hazards include heart diseases (strokes, high blood pressure, arteriosclerosis, heart attack) and altered lung functions (asthma, difficult or painful breathing, chronic bronchitis), especially in children and elder people. Fine particulate matter associated with diesel engine exhausts is also recognized as a carcinogenic substance and is listed as a mobile air toxic source.

Adverse consequences of particulate matter on the environment are related to reduction of visibility in cities and scenic areas, as well as to large scale effects on climate due to its influence on atmospheric radiative phenomena [12].

Even if larger fractions of the aerosols generated by anthropic activities derive from process industries and combustion units, major exposure risks for human beings are also related to those sources active in urban areas, such as domestic heating and diesel engines emissions. Primary urban sources of diesel exhausts are located in areas of intense vehicular traffic, near train or bus stations. A significant contribution in coastal cities derives from harbours areas due to the emissions of harbored or maneuvering vessels.

The new diagnostic methods for the analysis of particle size and concentration in gas streams have clearly pointed out that the particulate matter emitted by combustion sources is characterized by a particle size distribution ranging from few nanometers up to several microns, while the one produced by diesel engines is usually smaller than 0.5 μm [13–15]. As a direct consequence, environmen-

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Nomenclature

C_c	Cunningham correction factor
D	droplet diameter (m)
D_{BR}	particle Brownian diffusivity (m^2/s)
D_w	water diffusivity in the gas (m^2/s)
d_p	particle diameter (m)
E	total collision efficiency
e	elemental electric charge (C)
E_{BD}	collision efficiency due to Brownian diffusion
E_{DI}	collision efficiency due to directional interception
E_{Dph}	collision efficiency due to diffusiophoresis
E_{Es}	collision efficiency due to electrostatic attraction
E_{In}	collision efficiency due to inertial impaction
E_{Th}	collision efficiency due to thermophoresis
H	ratio between particle and droplet diameter
k_B	Boltzmann constant (J/K)
K_c	Coulomb constant (Nm^2/C)
k_g	gas thermal conductivity (W/mK)
Kn	Knudsen number
k_p	particle thermal conductivity (W/mK)
$\langle LI \rangle$	average jet projection length (m)
M_g	gas molecular weight (g/mol)
M_w	water molecular weight (g/mol)
n	numerical particle concentration ($1/m^3$)
n_0	initial value of numerical particle concentration ($1/m^3$)
n'	instantaneous scavenging rate ($1/m^3$ s)
n'_D	instantaneous scavenging rate for a single drop with diameter D ($1/m^3$ s)
N	numerical droplet concentration ($1/m^3$)
P	pressure (KPa)
P_w°	water vapor pressure (KPa)
P_a	water atomization pressure at nozzle (bar)
Pr	Prandtl number
q	droplet electric charge (C)
q_p	particle electric charge (C)
q_R	Rayleigh limit charge (C)
Q	gas flow rate (Nm^3/h)
Q_w	water flow rate (l/h)
R	scrubber characteristic radius (m)
Re	droplet Reynolds number
RH	relative humidity
Sc	particle Schmidt number
Sc_w	droplet Schmidt number
St	stokes number
St^*	critical Stokes number in Slinn Eq. (2)
t	time (s)
T	gas temperature (K)
T_{as}	adiabatic saturation temperature (K)
U	droplet/gas relative velocity (m/s)
V	electric potential (kV)

Greek symbols

α	water packing factor in Eq. (6) – Jung and Lee model
γ	fraction of the effective water flow rate
δ	dirac distribution function
ϕ	volumtric drop fraction
ε	air dielectric constant (F/m)
Γ_{w}	water superficial tension (N/m)
η	collection efficiency
θ	characteristic spray angle of the nozzle (°)
Λ	scavenging coefficient
μ	gas viscosity (kg/ms)
μ_{w}	water viscosity (kg/ms)
$\Psi(D)$	droplet size distribution
ρ	gas density (kg/m^3)
ρ_{p}	particle density (kg/m^3)
ρ_{w}	water density (kg/m^3)
ω	ratio between water and gas viscosity

tal regulations have gradually reduced the cut-off particle size for industrial flue gases from 10 μm (PM10) to 2.5 μm (PM2.5) until 1 μm (PM1). Similarly, restrictive regulations have been applied to diesel engines (e.g. Euro 4 and Euro 5 regulations for cars; USA Tiers 2 standards for diesel locomotives). In the last years, several countries required a revision of MARPOL VI standards for marine engines to introduce specific limits to particulate matter emissions for new and existing ships. Recently, on August 2009, the US-EPA announced the introduction of "emission control areas" near United States coast, aimed to reduce the emitted particulate matter up to 85%.

Albeit this scenario, the traditional particle abatement devices are mainly designed and optimized to treat particles with sizes above or around 1 μm, and they are far less effective towards the submicronic dimensions. Usually, for process industry and combustion units, complex systems including trains of consecutive abatements devices (water scrubber, WS; fabric filters, FF; cyclones, CYC; Venturi scrubbers, VS; electrostatic precipitators, ESP) are employed. For diesel engines, the typical retrofit system is the DPF (Diesel Particulate Filtration) coupled with EGR (Exhaust Gas Recirculation). These aftertreatment units allow high removal efficiency for nanometric particles and they are commonly adopted on cars, but the high pressure drops and the catalyst costs reduce their applicability for heavy duty diesel engines as those of trucks, trains or vessels.

Wet electrostatic scrubbing (WES), proposed for the first time in 1944 by Penney [16], could be a reliable method to achieve very high particle removal efficiency with reduced costs. The basic idea of this process has been suggested by two simple observations: (i) the particles emitted by industrial processes and diesel engines are generally bipolarly charged; (ii) water droplets can be easily charged and sprayed in a polluted gas in order to attract the particles charged with opposite sign. This electrostatic phenomenon is at the basis of particle scavenging during thunderstorms, when the highest removal of atmospheric aerosols is achieved.

WES reactor is an upgrade of traditional water scrubbers and it inherits all its advantages as the low pressure drops, the reduced process costs and the simultaneous ability to capture gaseous pollutants (SO_x, NO_x, HCl, soluble VOCs). In particular, the spray electrification can be used to improve the wet scrubber efficiency towards submicronic particles, with special attention to the capture of particles in the so-called Greenfield gap, i.e. for particle diameters ranging from 0.1 to 1 μm. In fact, the main particle scavenging mechanisms in a typical (non-electrified) wet scrubber are related to particle/drop collisions driven by hydrodynamic forces – mainly due to the Brownian diffusion for ultrafine particles and to the inertial impactions and hydrodynamic interceptions for micrometric ones – which are far less effective right in the Greenfield gap [17–21]. Consequently, typical particle collection efficiencies of industrial WS are higher than 90% for particle diameters coarser than 1 μm and finer than 0.1 μm, similarly to the typical values obtained with ESP and FF. On the contrary, the WS efficiency falls down below 60% in the Greenfield gap, resulting less effective than ESP and FF.

Theoretical results [17–24] and proofs-of-concept [25–34] of the potentialities of the wet electrostatic scrubbing can be found in literature mainly for the case of micrometric size particles.

Several investigators [26–33] have developed different kinds of lab-scale WES reactors founding that, by working with a water fraction between 50 and 200 ml/m^3, collection efficiencies for 1 μm particles are around 35–45% for water scrubbing and increase to 60–90% by charging the water spray. In some cases, to further improve the electrostatic interactions, also the particles are pre-charged. Metzler et al. [26], Cross et al. [29] and Krupa et al. [31] pointed out that the wet electrostatic scrubbing leads to 20% increase of the capture efficiency for particles coarser than 1 μm. It was also found that the particle collection efficiency is reduced by higher gas velocities [29,31] and water flow rates [29]. Fewer studies are directly related to submicronic particles. Pilat et al. [32] studied a two chambers scrubber with and without electrification; by charging both drops and particles oppositely they observed an increase of collection efficiency from 35% to 87% for 300 nm and from 70% to 95% for 700 nm particles. Balachandran et al. [28] and Jaworek et al. [30] obtained similar results by scrubbing a cigarette smoke with charged water.

It is worth noticing that, in all these experiments, the particle concentration has been determined either with gravimetric [26,29,32] or infrared light scattering [28,30] techniques. In both cases, the measure is in mg/m^3 and it is highly affected by the fraction of coarser particles. A more correct measure of particle concentration and collection efficiency has to be derived from the actual numerical concentration of particles, but these measures require more sophisticated methods (e.g. [13–15]) and are currently unavailable for WES experiments.

Recently, Zhao and Zheng [34] presented a Monte Carlo method for particle population balance in gravitational wet scrubbers with and without droplet electrification. The model results show that the numerical collection efficiency of submicronic particles dramatically increases from about 5% in WS to 99% circa in opposite-charged WES. Furthermore, the particle collection efficiency increases for faster gas velocity, slower droplet velocity, larger liquid-to-gas flow ratio, larger charge-to-mass ratio of droplets and smaller droplet size.

Further information should derive from computational fluid dynamics models but, at the moment, the applications to wet electrostatic scrubbing are still at a pioneering level. CFD simulation is made complex by the necessity of adding electromagnetic forces to the momentum and energy balance for the charged particles and droplets. Several attempts to model the fluid dynamic and electric field exist [35,36] as well as examples of numerical models to describe the particle scavenging in classical water scrubbers [37,38], but until now, there are no available studies on the wet electrostatic scavenging.

To sum up, pertinent literature presents a variegated and sometime conflicting description of the effect of the different process parameters on the WES collection efficiency. Therefore, a generalization of results is unreliable at the moment since each investigator referred to specific type of experimental apparatus equipped with very different kinds of electrified water spray systems and, finally, using different types of aerosols. Nevertheless, some general conclusions can be stated. Both the modeling and the experimental studies are in agreement regarding the improvement of collection efficiency with droplet charge levels, water loadings and with contact time. However, it is also clear that the main process costs are proportional to the electricity and the water consumptions [39–41] and that the investment costs are proportional to the treatment time, i.e. to the reactor volume. As regard the effect of other process parameters, such as droplet size distribution and relative water/gas velocity, different results have been reported in literature.

This scenario suggests that the definition of general rules to estimate optimal values of the process parameters for a correct design and operation of a WES is only partially accomplished.

This paper presents a model for wet electrostatic scrubbing derived by the coupling of classical equations for particle scavenging with a simplified model for the description of average properties of the electrified water spray. The model has been tested on some experimental studies reported in literature both for micronic and submicronic particles and for charged and uncharged droplets. Then, the model has been applied to a reference case study to allow a systematic and more general evaluation of the actual effect of each process parameter. In conjunction with the available information about the droplet charging and the spray generation systems, the model results allow the definition of preliminary guidelines for the design of WES reactors as well as a first estimation of optimal working conditions to minimize the energy and water consumptions.

2. Theoretical framework

The theory of particles capture by one water droplet is mainly derived from studies on atmospheric aerosol scavenging during rains [17–21]. The instantaneous rate of the scavenging, $n'_D(d_p, t)$, of particles with diameter d_p at time t, due to the fall of a single drop with diameter D can be written as:

$$n'_D(d_p, t) = n(d_p, t) \cdot \left[\frac{\pi}{4}(D + d_p)^2\, U \right] \cdot E \tag{1}$$

where $n(d_p, t)$ is the numerical concentration of particles, U is the water/gas relative velocity and E stands for collision efficiency. The term between squared brackets in the right hand side of Eq. (1) represents the so-called impact cylinder, i.e. the volume swept by a falling droplet in the unit time. The droplet is considered a rigid sphere without internal liquid circulation [29,42]. The product of $n(d_p, t)$ and the impact cylinder gives the number of particles that should come in contact with the droplet. Among these particles, the quantity effectively captured by the drop depends on the collision efficiency, E. Usually, E is lower than 1, so only a fraction of particles inside the impact cylinder will be englobed in the drop; values of E larger than 1 are also possible and indicate that particles can be also captured outside the impact cylinder.

In Eq. (1), the overall collision efficiency, E, resumes all the features of droplet–particle interactions [17–21,43–46]. In particular, E is usually considered the sum of the collision efficiencies deriving from different contributions due to different capture mechanisms: inertial impaction, E_{In} [43–45]; directional interception, E_{DI} [44–46]; Brownian diffusion, E_{BD} [43]; electrostatic interactions, E_{Es} [20,25–28]; thermophoresis, E_{Th} [17,20]; and diffusiophoresis, E_{Dph} [17,20]. Mathematical expressions for the collision efficiencies available in literature are listed in Table 1. Among them, the model of Licht [44] is the only one specifically designed for water scrubbers while all the others are well-established theoretical models for atmospheric scavenging. It is worth noticing that the expression of Davenport and Peters [20] for the droplet–particle electrostatic interactions includes Coulomb forces while neglects mutual electrical induction phenomena (the so-called image charge forces). Indeed, Jaworek et al. [27] showed that the effect of image charge forces are relevant only for particles coarser than about 3 μm, and for particles and droplets with few elementary charges, while for typical WES systems the only Coulomb forces can be considered.

The electrostatic contribution can be determined once the charge on droplet and particle is known. The charge, q, generated on a droplet depends on the electrical charging system and can be considered as a fraction of the so-called Rayleigh limit, q_R, which is the highest electrical charge that can be present on a droplet of a given diameter, D, without making it unstable and eventually tearing it apart. The value of q_R is given by [47]:

$$q_R = 2\,\pi \sqrt{2\,\varepsilon\, \Gamma_W D^3} \tag{11}$$

Table 1
Models for collisional efficiencies.

Inertial impaction, E_{In}		
(2)	$E_{In}=\left[\frac{St-St^{*}}{St-St{*}+2/3}\right]^{3/2}\left(\frac{\rho_p}{\rho_w}\right)^{1/2}$ $St=\frac{C_c\rho_p {d_p}^2 U}{18\,\mu\,D}$ $St{*}=\frac{1/2+1/12\cdot\ln[1+Re]}{1+\ln[1+Re]}$	Slinn [43]
(3)	$E_{In}=\left[\frac{St}{St+0.35}\right]^2$	Licht [44]
(4)	$E_{In}=3.4St^{9/5}\quad \text{at}\quad St\le 0.5$ $E_{In}=1\quad \text{at}\quad St>0.5$	Kim et al. [45]
Directional interception, E_{DI}		
(5)	$E_{DI}=4H[\omega^{-1}+(1+2Re^{1/2})H]$ $\omega=\frac{\mu_w}{\mu}\quad H=\frac{d_p}{D}$	Slinn [43]
(6)	$E_{DI}=\frac{(1-\alpha)}{(J+\omega K)}\left[\left(\frac{H}{1+H}\right)+\frac{1}{2}\left(\frac{H}{1+H}\right)^2(3\omega+4)\right]$ $J=1-\frac{6}{5}\alpha^{1/3}+\frac{1}{5}\alpha^2\quad \omega=\frac{\mu_w}{\mu}$ $K=1-\frac{9}{5}\alpha^{1/3}+\alpha+\frac{1}{5}\alpha^2\quad H=\frac{d_p}{D}$	Jung and Lee [45]
Brownian diffusion, E_{BD}		
(7)	$E_{BD}=\frac{4}{ReSc}[1+0.4Re^{1/2}\,Sc^{1/3}+0.16Re^{1/2}\,Sc^{1/2}]$ $Sc=\frac{\mu}{\rho\,D_{BR}}\quad D_{BR}=\frac{k_B C_c T_{as}}{3\,\pi\,\mu\,d_p}$	Slinn [43]
Electrostatic interactions, E_{Es}		
(8)	$E_{Es}=\frac{16K_c C_c q\cdot q_p}{3\,\pi\,\mu\,UD^2 d_p}$	Davenport and Peters [20]
Thermophoresis, E_{Th}		
(9)	$E_{Th}=\frac{4a(2+0.6Re^{1/2}Pr^{1/3})(T-T_{as})}{UD}$ $a=\frac{2C_c(k_g+5Kn\cdot k_p)k_g}{5P(1+6Kn)(2k_g+k_p+10Kn\cdot k_g)}$	Davenport and Peters [20]
Diffusiophoresis, E_{Dph}		
(10)	$E_{Dph}=\frac{4b(2+0.6Re^{1/2}Sc_w^{1/3})\left(\frac{P_w^{\circ}(T)}{T}-\frac{P_w^{\circ}(T_{as})}{T_{as}}RH\right)}{UD}$ $b=\frac{T\,D_w}{P}\sqrt{\frac{M_w}{M_g}}$	Davenport and Peters [20]

where ε is the air permittivity and Γ_w is the droplet surface tension. For a 400 μm water droplet the Rayleigh charge is $q_R = 5.8\times10^{-11}$ C $\cong 10^8\,e$. In this work, the dimensionless charge q/q_R is adopted.

The charge q_p naturally present on a particle mainly depends on its chemical–physical properties and its diameter and is usually related to the occurrence of triboelectric phenomena. Detailed studies have been reported by Johnston et al. [48] and Rodrigues et al. [49], who related the particle charge to its diameter for different aerosol types. Typical levels range from 0.1 to 1 mC/kg.

The value of particle charge naturally present on coal dust, q_p, can be calculated according to the formula reported by Rodriguez et al. [49] as:

$$|q_p| = A d_p^B\cdot e \tag{12}$$

where $A = 36.8$, $B = 1.17$ and d_p is measured in microns. This formula was used to fit experimental data on coal particles in a range between 600 μm and 7.5 mm, but it also allows to calculate the charge of particles above 100 μm, as shown by the comparison with the experimental data on charge-to-mass ratio of coal particles reported by Prem and Pilat [50].

Particles can also be pre-charged with corona discharge systems [27], leading to an increase of their charge up to ten times their natural values.

The instantaneous scavenging rate for a real scrubber, due to N droplets per cubic meter with size distribution $\Psi(D)$, is given by the addition of the contribution of each droplet throughout this expression [19]:

$$\begin{aligned} n'(d_p,t) &= \int_0^\infty n'_D(d_p,t)\cdot N\,\Psi(D)dD = n(d_p,t) \\ &\quad \int_0^\infty \left[\frac{\pi}{4}(D+d_p)^2U\right]\cdot E\cdot N\,\Psi(D)dD \\ &= n(d_p,t)\cdot\Lambda(d_p) \end{aligned} \tag{13}$$

The integral, named scavenging coefficient, $\Lambda(d_p)$, represents the inverse of the characteristic time for particle scavenging. Eq. (13) is valid for volumetric drop fractions sufficiently low ($\phi = N{\cdot}\pi{\cdot}D^3/6 < 10\%$) to assure negligible droplet–droplet interactions. Usually, this is a well-posed assumption for industrial water scrubbers. Low values of ϕ also avoid coalescence phenomena, leading to a constant numerical droplet concentration [42].

The numerical concentration over time of particles with diameter d_p, $n(d_p,t)$, is described by the following population balance:

$$\begin{aligned} &\frac{d}{dt}n(d_p,t) = -n'(d_p,t) \\ &n(d_p,t=0) = n_0 \end{aligned} \tag{14}$$

The solution of Eq. (14) is:

$$n(d_p, t) = n_0 \cdot \exp[-\Lambda(d_p)t] \quad (15)$$

showing a linear dependence of the particle concentration on its initial concentration value and an exponential reduction with time. Finally, the collection efficiency for the particle diameter d_p can be written as:

$$\eta(d_p) = \frac{n_0 - n(d_p, t)}{n_0} = 1 - \exp[-\Lambda(d_p)t]. \quad (16)$$

3. Model validation

The validation of the model was performed by comparing the theoretical predictions with the experimental data of four different works present in the literature [28,29,32,51]. These four works report sufficient experimental details to allow a reliable estimation of all the variables needed in Eqs. (13)–(16). These works are representative of quite different operating conditions with different types of particulate, different levels of droplet charge and/or dimensions, and different scrubber configurations. Therefore, they can be considered a significant benchmark for the validation of the model. The details of the experimental conditions of each work are all listed in Table 2. Finally, with reference to the expressions used for the evaluation of collisional efficiencies, E_{In} is calculated using the Licht equation [44], E_{DI} and E_{BD} with Slinn equations [43] and E_{Es} with Davenport and Peters equation [20]. Indeed, as verified by preliminary tests, all the models for E_{In} and E_{DI} give very similar results. For E_{In}, the Licht equation was adopted since it is conceptually more suitable, being directly derived from experiments on wet scrubber rather than on atmospheric scavenging. The Slinn model for E_{DI} [43] was preferred to that of Jung and Lee [46], thanks to its simplicity.

Some of the process parameters required by the model equations (n_0, d_p, $\Psi(D)$, q_p, q), are explicitly reported in the articles (see also Table 2), while the average values of droplet concentration, ϕ, and of the water/gas contact time, t, have to be properly derived.

In an unconfined system, the volumetric fraction ϕ can be calculated with the ratio: $Q_w/(Q_w + Q)$ where Q_w and Q are, respectively, the water and the gas flow rates. Differently, in a confined system, part of the droplets can collide with the perimetric walls and do not contribute to the scavenging anymore. So, only a fraction of the water flow rate, γ, is effectively "active" for the scrubbing process. In this confined case, ϕ, results:

$$\phi = \frac{\gamma \cdot Q_w}{\gamma \cdot Q_w + Q_{gas}} \quad (17)$$

For a tubular scrubber, γ can be calculated with the geometric formula suggested by Cheng [52]:

$$\gamma = \frac{3R/\langle L_i \rangle - 2\cot(\theta/2)}{2(R/\langle L_i \rangle)^3 \cdot \left[1 - \cos(\theta/2)\right]} \quad (18)$$

where R is the radius of the tubular scrubber, θ is the characteristic spray angle of the nozzle, $\langle L_i \rangle$ is the so-called average jet projection length that represents the average distance covered by a droplet inside the scrubber, from the nozzle to the perimetric walls. Cheng [52] estimated the projection length in function of the initial injection velocity, the gas velocity, the droplet size and the characteristic spray angle of the nozzle, by using the classical momentum balance equations for the motion of a single rigid sphere in a fluid (e.g. in Seinfeld and Pandis [19] and in Hesketh [53]). The same equations can be used to calculate the average contact time as the ratio of $\langle L_i \rangle$ and the average water/gas relative velocity, U [52].

The first work adopted to test the model is referred to the uncharged water scrubber studied by Tomb et al. [51]. The authors performed scrubbing tests in a tubular counter-current device, equipped with one nozzle. A wide range of operating conditions was explored. Four different types of nozzles, operated at different jet velocities and atomization pressures, were worked out to produce droplets with diameters between 225 and 950 μm for the scrubbing of coal particles with size from 0.68 to 6 μm. Fig. 1 compares the values of the collection efficiency reported by Tomb et al. [51] with those obtained by the scavenging model for two exemplar cases. The model shows a good consistency with experimental data for $d_p > 1$ μm, while it tends to underestimate the collection efficiency for smaller particles by 15% *circa*.

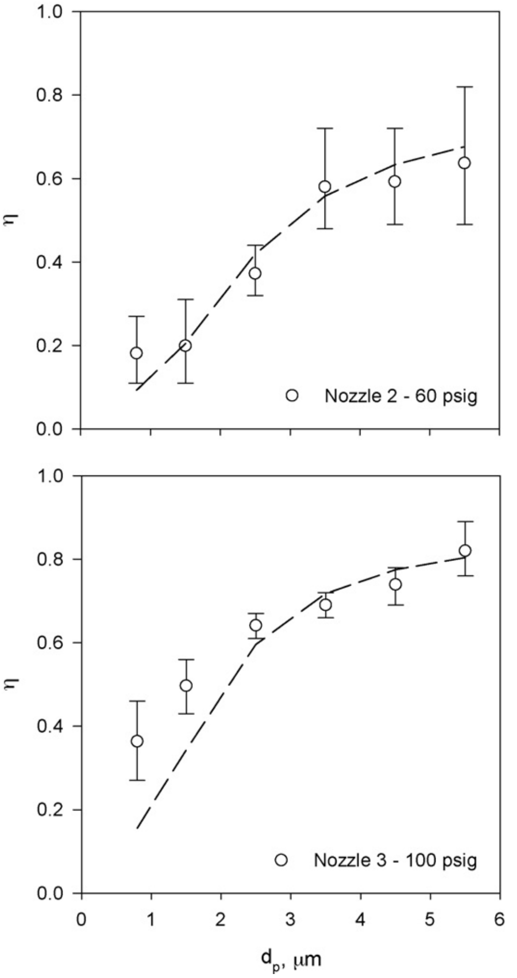

Fig. 1. Collection efficiency as a function of particle size for two kinds of spraying nozzles and atomization pressures. Comparison between experimental data (*empty symbols*) by Tomb et al. [51] and model predictions (*broken line*).

Cross et al. [29] described experimental results on a WES reactor treating two different streams of coal dust polluted gas: the first one contained fine particles with averaged size around 4 μm (named respirable dust), the other one was made by coarse particles of 25 μm average diameter (inspirable dust). The experimental apparatus consisted in a cross-flow tubular reactor equipped with an ad hoc charging system for the sprayed water. Experimental tests were conducted by varying the water and gas flow rates, the dust concentration, the atomizing pressure and the droplet charge. The average collection efficiency spanning over the entire particle size distribution were determined. Experimental results and model predictions are both reported in Fig. 2 as a function of electrical potential difference for droplet charging, gas and water flow rates. The model allows a good prediction of the effect of charging potential on the collection efficiency for both the respirable and the inspirable dusts, while its consistency with the experi-

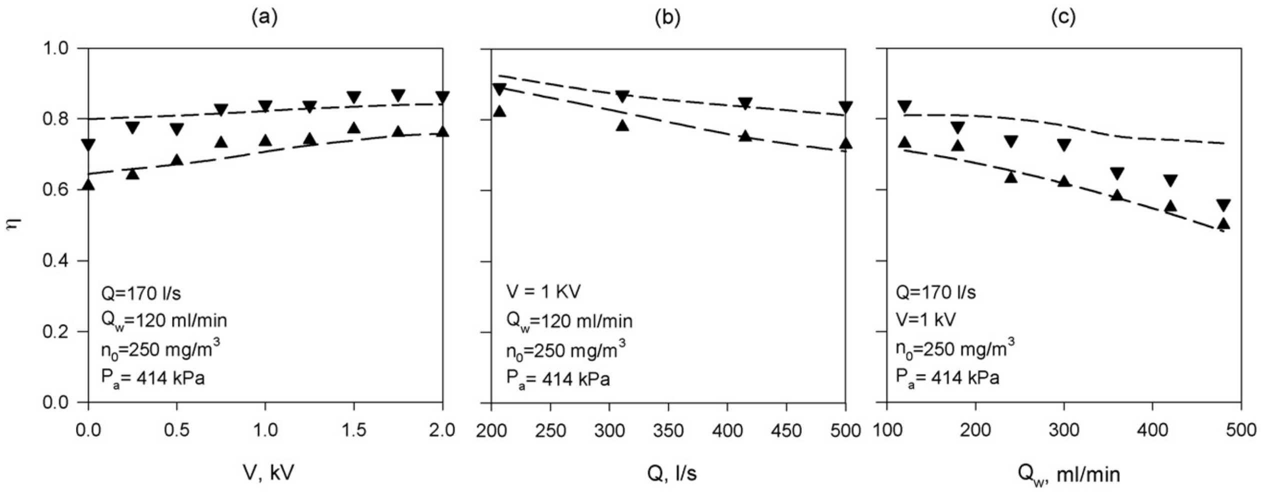

Fig. 2. Collection efficiency as a function of electric potential for droplet charging (a), gas flow rate (b) and water flow rate (c). Comparison between our model predictions and experimental data obtained by Cross et al. [29] for two characteristic particle sizes: (▲) respirable dust, d_p ~4 μm; (▼) inspirable dust, d_p ~ 25 μm.

mental data at different gas and water flow rates is less accurate. Finally, it is worth noticing that, by increasing the charging potential from 0 to 2 kV, collection efficiency for the two gas streams increases of about a 10%, although the particle diameters are in the range typically dominated by inertial impaction phenomena. Furthermore, according to the model predictions, the experimental data assure that the collection efficiency remains almost constant if dust loading varies from 50 to 500 mg/m^3 (not reported in Fig. 2).

Pilat et al. [32] reported experimental data for the wet electrostatic scrubbing of dioctilftalate particles with $d_p \in [0.05–5]$ μm in a pilot scale two-stages scrubber. The first stage was constituted by a counter-current scrubber of rectangular cross-section equipped with 12 nozzles (Spraying Systems 7N4) while the second one was a cylindrical co-current scrubber equipped with 10 nozzles of the same type used for the first scrubber. Experimental tests were carried out at constant gas and water flow rates (1700 Nm^3/h and 500 l/h, respectively) both with uncharged and charged droplets and particles. As expected, the overall collection efficiency increased by passing from the uncharged to the charged case, with impressive relevance right inside the Greenfield gap: for d_p = 0.3 μm the value of η rises from 35% to 87%. Fig. 3 reports the collection efficiency as a function of the particles size for the experimental data and the theoretical predictions showing a satisfactory agreement.

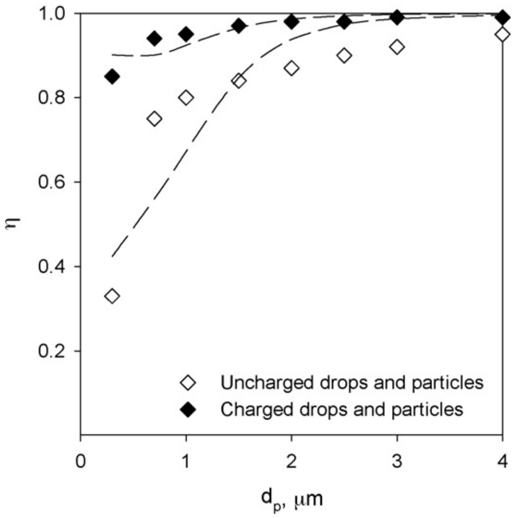

Fig. 3. Collection efficiency as a function of particle size. Comparison between experimental data (*symbols*) by Pilat et al. [32] and our model predictions (*broken line*).

Finally, the experiments of Balachandran et al. [28] have been considered. In this case, the experimental rig consisted in a wide chamber, 1.8 × 2 m^2 of base area and 1.8 m height, equipped with a single rotary atomizing nozzle (Newland Electrics) and with additional lateral fans used to mix the gas and the particle phases. The chamber acted as a batch system. A known amount of cigarette smoke was emitted in the chamber for a given time (around 500 s) and then 10 l/h of water were sprayed for different times (from

Table 2
Summary of working conditions for the experimental studies used for model validation.

	Tomb et al. [51]	Cross et al. [29]	Pilat et al. [32]	Balachandran et al. [28]
Scrubber type	Counter-current WS	Cross-flow WES	Double chamber (counter and co-current) WS and WES	Rectangular chamber WS and WES
Nozzle type	Described in the paper	Spraying system SU22®	Spraying system Fogjet 7N4®	Newland Electric rotary atomizer®
Droplet charging systems	–	Induction electrode: d.o.p. < 3 kV	Induction electrode: d.o.p. = 5 kV	Induction electrode: d.o.p. = 8 kV
Chamber volume	1.25 m^3	1.1 m^3	0.56 + 0.23 m^3	6.5 m^3
Air flow rate	300 m^3/h	720–1800 m^3/h	1700 m^3/h	(Batch system)
Water flow rate	100–750 l/h	7.2–28.8 l/h	500 l/h	10 l/h
Droplet charge	Uncharged	–	0.56 mC/kg	9 mC/kg
Droplet size	225–950 μm	20 μm	50 μm	80 μm
Particle type	Coal dust	Coal dust	Dioctylphtalate	Cygarette smoke
Particle charging system	Uncharged	Uncharged	Corona needle 53 mC/kg	Corona needle
Particle size	0.68–6 μm	Respirable dust: VMD = 4 μm inspirable dust: VMD = 25 μm	0.05–5 μm	0.3–4.0 μm
Particle concetration	–	30–500 mg/m^3	5.3 g/m^3	12 mg/m^3

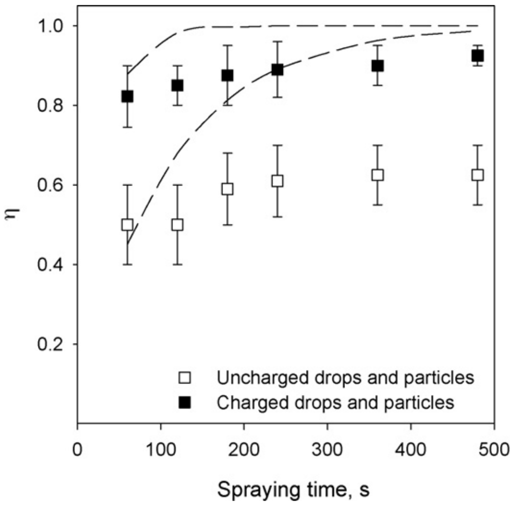

Fig. 4. Collection efficiency as a function of the time of water spraying in the scrubbing chamber. Comparison among experimental data (*symbol*) obtained by Balachandran et al. [28] and our model predictions (*broken lines*).

60 to 480 s). The smoke particle concentration within the chamber was measured by means of light beam extinction method using a homemade optical system. The light extinction profile given by suspended aerosols (particles + droplets) was measured over time at different distances from the chamber ceiling. The collection efficiency was evaluated 400 s after the end of the water spraying in order to allow even the finer droplets to settle at the bottom of the chamber. However, this technique has an intrinsic limitation since it does not allow the estimation of the collection efficiencies for a specific particle size and tends to amplify the effects of coarser aerosols respect to the finer ones. The experimental results, in terms of average collection efficiency as a function of the water spray time, are reported in Fig. 4; η results almost constant with the spraying time both for charged and uncharged systems. In addition, the particle concentration varied within the chamber height in a non-monotonic way, giving a 10% variation of aerosol concentration in about 1 m of sampling height. The addition of charges on the droplets and on the particles allowed a strong reduction of the particle concentration. Model predictions are also reported in Fig. 4, which shows how the model gives a reliable description of collection efficiency for the lowest spraying time, but it predicts higher values for longer spraying times. This incongruence should be explained by considering the existence of dead volumes in the reactor chamber where the water cannot scrub the particles. This area can be easily found close to the lateral parts of the chamber ceiling, far from the nozzle section. As a confirmation, in another paper [30], the same authors repeated the same experiments with a multi-nozzle system that intrinsically minimize dead volume issues. In this case, the expected monotonic increase of particle collection efficiency with spraying time was actually observed.

The four works discussed above cover very different conditions and, in all cases, the model is able to describe consistently the experimental data. This is showed also in Fig. 5, where the particle collection efficiency for all the available experimental studies are plotted as a function of the corresponding model predictions. It is evident that almost all data are scattered around the bisector of the graph. Apart for the data of Balachandran et al. [28], that are affected by the aforementioned dead volume issue, the WES data are predicted with a maximum error around 5%. On the other hand, data for wet scrubbers are usually underestimated by a 15% for submicronic particles (represented by the collection efficiency ranges below 0.4), while the model predictions gives only a small overestimation of the collection efficiency for micrometric particles.

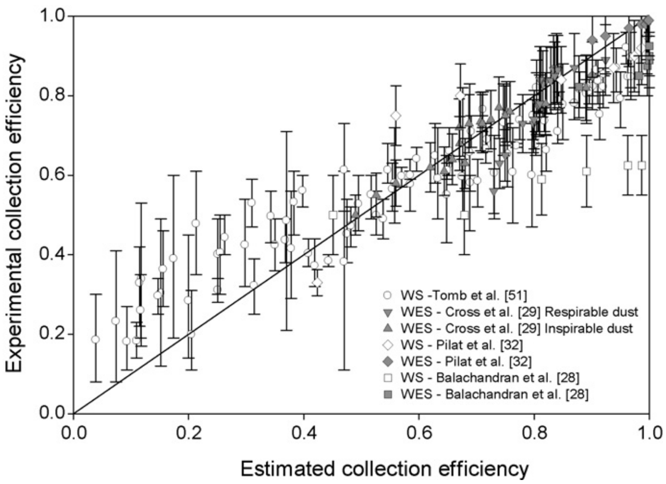

Fig. 5. Comparison between experimental and predicted values of the particle collection efficiency for WS (*empty symbols*) and WES (*filled symbols*).

This scatter between model and experiment can find a possible explanation not only in a partial lack of accuracy of the model equations for submicronic particles, but also in the large experimental errors affecting particle concentration measurement in this range.

4. Effect of the main process parameters on the particle collection efficiency of a WES unit

The focus of this paper is to provide general indications on the specific effect of each of the main process parameters on the WES particle collection efficiency. In particular, the effects of water concentration, liquid–gas contact time, electrified water spray properties (droplet charging level, droplet size and water/gas relative velocity) have been studied in details. To allow a more general analysis of these effects, the model is applied to the ideal case of an open unconfined water spray in contact with a polluted gas stream for a given time. By this way, it is possible to analyze separately the effect of each process parameter without the intrinsic constraints imposed by the choice of specific scrubber geometry, as it happens, for example, for the study of Zhao and Zheng [34].

The case study simulates the treatment of an air stream at ambient pressure and temperature, that contains coal dust, at initial concentration, n_0, made by monodisperse particles with diameter d_p. An electrified water spray is injected in the scrubber at 25 °C and it is composed by identical non-deformable spherical droplets ($\Psi(D) = \delta(D)$), with a dimensionless charge level, q/q_R, moving with relative velocity U respect to the gas flow. The aforementioned process parameters are varied over wide ranges, covering the typical working conditions of real industrial processes. The effect of each variable on the collection efficiency is considered separately by keeping a constant reference value for all the others. Both these reference values and the parameters ranges of variation are summarized in Table 3. The collection efficiency is calculated through the Eq. (16) where E_{In} is calculated using the Licht [44] equation, E_{DI} and E_{BD} with Slinn [43] equations and E_{Es} with Davenport and Peters [20] equation. The working conditions ($T = 25\,^\circ$C and $P = 100$ kPa) allow to assume that thermophoretic and diffusiophoretic phenomena, as well as droplet evaporation rates, are negligible.

Three particles diameters are chosen in the following as reference dimensions:

Table 3
Reference conditions for the investigated case study.

Parameter	Reference value	Investigated range
Particle type	Coal dust	–
T (°C)	25	–
P (kPa)	100	–
d_p (μm)	–	10^{-1} to 10
q/q_R	–	0–0.5
D (μm)	400	50–600
t (s)	3	0.1–1000
U (m/s)	Terminal velocity	0–8
ϕ	2×10^{-4}	10^{-5} to 10^{-2}

(a) $d_p = 0.1$ μm: the lower limit of the Greenfield gap;
(b) $d_p = 1$ μm: the upper limit of the Greenfield gap;
(c) $d_p = 5$ μm: a particle size for which inertial impaction is the dominant mechanism in water scrubbers.

Fig. 6 reports the collection efficiency as a function of particle size for different droplet charge levels ranging from 1% to 30% of the Rayleigh limit ($q/q_R = 0.01$–0.3). The collection efficiency for uncharged droplet ($q/q_R = 0$) is also reported for comparison. These curves show a minimum of the collection efficiency in the Greenfield gap that slightly reduces and shifts toward higher particle diameter by increasing the droplet charge. A charge level equal to $q/q_R = 0.3$ allows to obtain collection efficiencies greater than 95% in the entire Greenfield gap.

The dependence of the collection efficiency on the water volumetric fraction, ϕ, the relative water/gas velocity, U, and droplet diameter, D, for the three reference diameters are described in Figs. 7–9, parametrically with the droplet charge level. The case of uncharged droplets is plotted with empty symbols, while for charged droplets solid symbols are used.

Fig. 7 reports the value of collection efficiency for water volumetric fractions ranging from 10^{-5} to 10^{-2}. As expected, the collection efficiency increases with ϕ, i.e. with the water consumption per unit volume of treated gas. It is interesting to observe that the efficiency increases with a S-shaped curve, reaching unity at lower water fractions for higher droplet charge levels.

Before considering the effect of relative velocity and droplet size upon collection efficiency, it is worth remembering that the particle capture mechanism depends, in the first instance, on the probability that the particles come into contact with the droplets. This is proportional to two terms: the volume swept by each flowing droplet in the unit time (i.e. the impact cylinder reported in Eqs. (1) and (13)) and the droplet concentration (i.e. the symbol N in Eq. (13)). The former term is proportional to the square of droplet diameter, D, and to the relative droplet-gas velocity, U; the latter, at a given water flow rate, is inversely proportional to the cube of particle diameter. However, it is also worth noticing that the sprayed droplets rapidly achieve their terminal velocity, indeed, for droplet size from 100 to 500 μm the relaxation time varies from 0.03 to 0.1 s circa [54]. Consequently, as already stated, we assumed that droplets moves steadily respect to the gas phase at their terminal velocity, $U = U_T$. Since U_T is almost proportional to the square of the droplet diameter, the overall result is that the probability of particle–droplet contact increases linearly with D. Particle–droplet contact probability together with collisional efficiency contributes to define the overall effect of D and U on η.

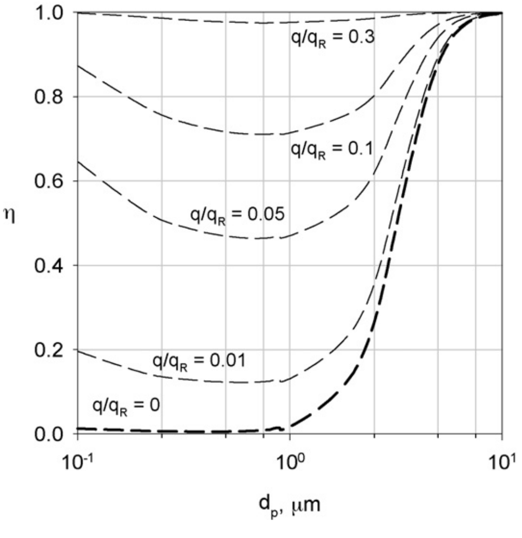

Fig. 6. Collection efficiency as a function of particle diameter for different levels of dimensionless droplet charge. Reference conditions are reported in Table 3.

Fig. 8 shows the effect of droplet size on the particle collection efficiency. In this case, the model predictions show that the value of η decreases with droplet size, but this effect becomes less pronounced by increasing the droplet charge. This behaviour is totally reversed for 5 μm uncharged particles where η increases with D as shown in Fig. 8(c). Indeed, at constant water consumption, by increasing droplet size in uncharged scrubbers and for inertial impaction controlled regime, where $E \cong E_{In} \propto D^{1.8}$, both the collisional efficiency and the droplet–particle contact probability are increased and an enhancement of collection efficiency is observed. On the contrary, where Coulomb forces are dominant ($E \cong E_{Es} \propto D^{-3}$), the effect of a lower collisional efficiency overwhelms the increase of droplet–particle contact probability leading to lower collection efficiency. Finally, for uncharged scrubbing of submicronic particles (Fig. 8(a) and (b)), the observed reduction of collection efficiency for larger droplet size mirrored the dependence on D of directional interception and Brownian diffusion capture mechanisms (Table 1).

For a given droplet size, the effect of water/gas relative velocity on the collection efficiency is shown in Fig. 9. For coarser particles (Fig. 9(c)), the collection efficiency increases both with the relative velocity and with the droplet charge level. On the contrary, for particle finer than 1 μm (Fig. 9(a) and (b)), the collection efficiency sharply increases with the droplet charge with a negligible dependence on the relative water/gas velocity.

The effect of gas velocity on particle capture efficiency can also be analyzed in light of the results reported in the numerical study of Adamiak et al. [22] on the particle trajectories close to a fixed spherical collector at different gas velocities. The authors showed that, when the droplets move faster in the polluted gas, the particle streamlines become closer to the droplet surface, thus enhancing the inertial impactions. This result is actually mirrored by the dependence of E_{In} on U (roughly E_{In} is proportional to $U^{1.8}$ - see Table 1). Differently, the particle–droplet interactions, in presence of electrical forces, are improved by lower velocity, since in this case the electrical attractive forces are more effective in deviating particle streamlines toward the droplet surface at larger distances. This is also consistent with the expression of electrostatic collisional efficiency provided by Davenport and Peters [20] adopted in this paper.

In a wet electrostatic scrubbing of micrometric particles, both the contribution of the inertial impaction and the electrostatic interaction are significant for particle capture (Fig. 9(c)). Until the inertial impaction gives the most relevant contribution to collection efficiency, the increase of gas velocity allows an overall increase of both the collisional efficiency and the probability of particle–droplet contact. Therefore the particle collection efficiency increases, as observed for the case of a single fixed collector shown by Adamiak et al. [22]. On the contrary, for submicronic particles, the model results are quite different from that obtained by Adamiak et al. [22]. In this case, the negligible dependence of the collection

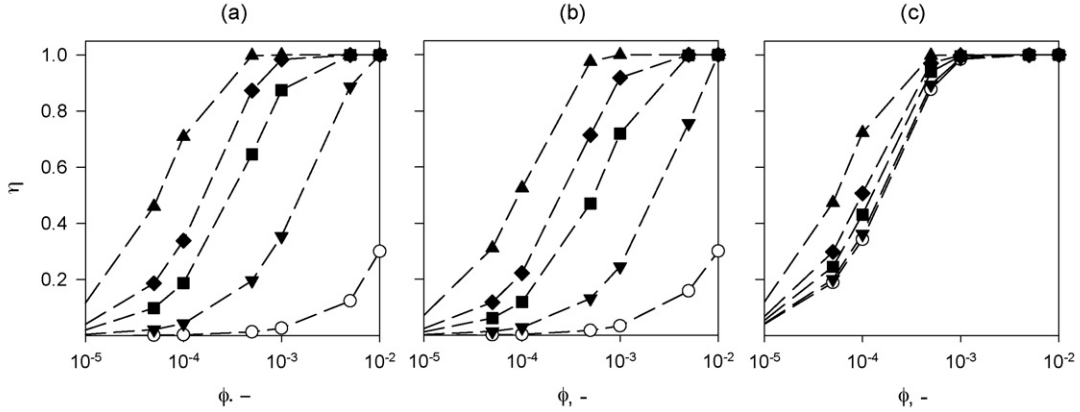

Fig. 7. Collection efficiency as a function of volumetric water fraction for three particle diameters, (a) 100 nm, (b) 1 μm, (c) 5 μm, and different droplet charge levels: (○) $q/q_R = 0$, (▼) $q/q_R = 0.01$, (■) $q/q_R = 0.05$, (◆) $q/q_R = 0.1$, (▲) $q/q_R = 0.3$. Reference conditions are reported in Table 3.

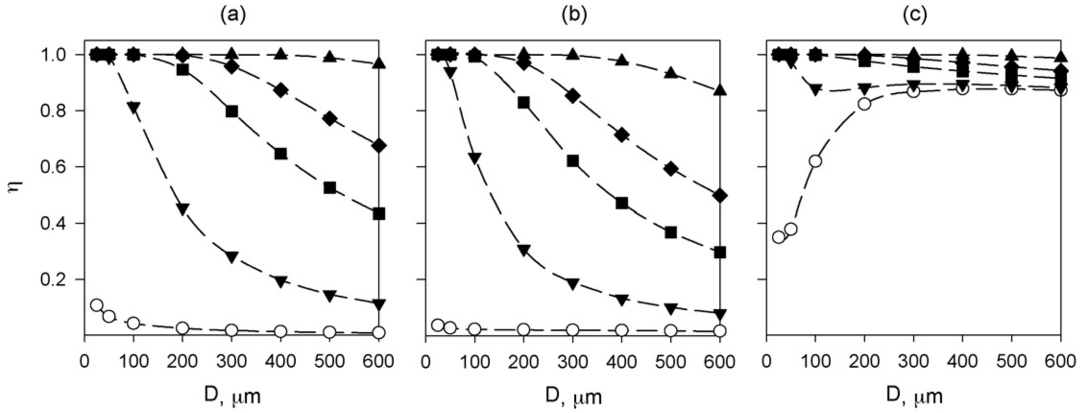

Fig. 8. Collection efficiency as a function of droplet size for three particle diameters, (a) 100 nm, (b) 1 μm, (c) 5 μm, and different droplet charge levels: (○) $q/q_R = 0$, (▼) $q/q_R = 0.01$, (■) $q/q_R = 0.05$, (◆) $q/q_R = 0.1$, (▲) $q/q_R = 0.3$. Reference conditions are reported in Table 3.

efficiency on water/gas relative velocity (Fig. 9(a) and (b)) derives from the counterbalancing of the droplet–particle contact probability (that increases with U) and the electrostatic collisional efficiency (that decrease with U). The practical consequence of this result is that to enhance the collection efficiency of micrometric particles higher water/gas relative velocity are necessary, while for submicronic particles, this parameter is almost insignificant.

From an overall comparison of at the three graphs in Figs. 7–9, it is evident that the plots for $d_p = 5\,\mu m$ always show a behaviour different from the other two, by highlighting the different influence of the process parameters on micronic and on submicronic particles. In addition, the effect of electrostatic forces results much more relevant for particles belonging to the Greenfield gap. It is also evident that the process efficiency is mainly determined by the value of droplets size and charge and by the amount of sprayed water, while only marginal effects of water/gas relative velocity can be observed.

These results may be used to evaluate preliminary guidelines for the optimal operational ranges of the process parameters. For example, Fig. 10 reports a series of curves representing the

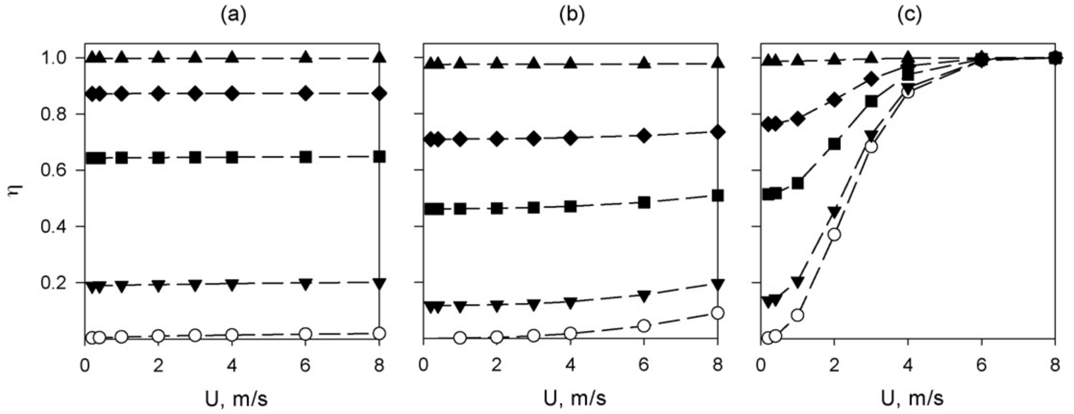

Fig. 9. Collection efficiency as a function of water/gas relative velocity for three particle diameters, (a) 100 nm, (b) 1 μm, (c) 5 μm, and different droplet charge levels: (○) $q/q_R = 0$, (▼) $q/q_R = 0.01$, (■) $q/q_R = 0.05$, (◆) $q/q_R = 0.1$, (▲) $q/q_R = 0.3$. Reference conditions are reported in Table 3.

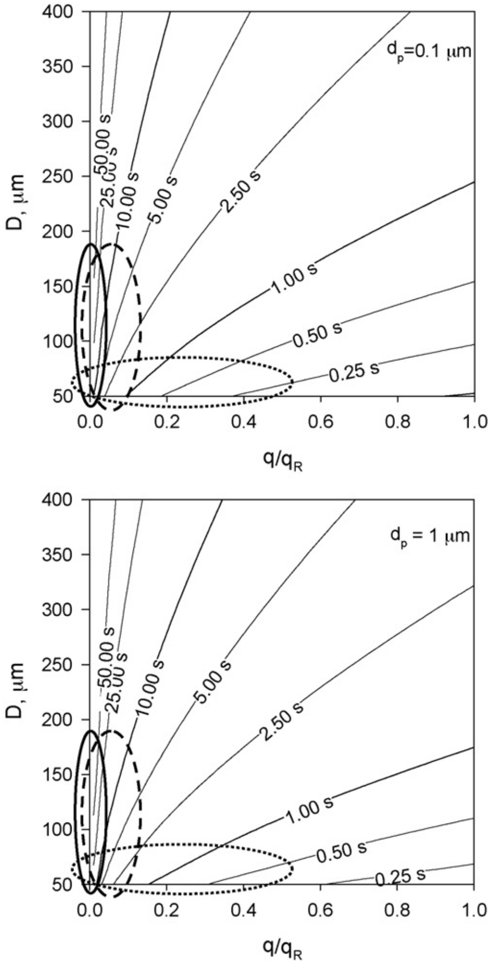

Fig. 10. Required contact time for $\eta = 99.5\%$ in function of droplet size and charge, at $\phi = 0.1‰$, for two different particle sizes. The highlighted regions represent the typical operational range of: (——) air-atomizing nozzles with corona charging system [19,41], (– – –) air-atomizing nozzles with induction charging [17,27,29,32,40,41], (···) electrospraying systems [27,28,30].

contact time required to get a 99.5% collection efficiency with sprayed droplets of diameter D and relative charges q/q_R, with a water consumption $\phi = 0.1‰$ (i.e. 100 ml/m^3). This water consumption is comparable with typical values ($\phi = 0.05–0.2‰$) reported in literature [26–34]. A relative water/gas velocity equal to the droplet terminal velocity has been adopted for calculations. The data reported in Fig. 10 refers to the lower ($d_p = 100$ nm) and the upper ($d_p = 1$ µm) limit of the Greenfield gap. The iso-time curves confirm that the WES process is much more effective when finer droplets and higher charge levels are used. Furthermore the contact time is reduced to a greater extent by increasing the droplet charge rather than reducing the droplet size. In particular, this effect is much more pronounced for the case of 100 nm particles, where the electrostatic phenomena are more effective. For both particle sizes, a droplet diameter ranging between 50 and 200 µm and a charge level around 10–20% of the Rayleigh limit charge allow to reduce the treatment time to few seconds, resulting in a good compromise between collection efficiency and charging costs [27,39–41]. As shown in Fig. 10, the suggested droplet size and charge levels are commonly obtained with commercially available atomizing nozzles equipped with induction charging systems or with electrospraying devices, while atomizing nozzles with corona discharge systems are quite less effective [25–33,39–41].

5. Final remarks

This paper reports a modeling study of the wet electrostatic scrubbing, an innovative method to remove submicronic particulate from polluted gases. The study aims to describe the functional dependencies of the collection efficiency on the main WES process parameters by using a simplified model for particle scavenging via an electrified spray of water. The model has been tested on several experimental results, proving its reliability in describe the wet electrostatic scrubbing phenomena in a wide range of working conditions. Then, the model has been applied to evaluate the theoretical collection efficiency of the wet electrostatic scrubbing of an air stream, at ambient pressure and temperature, polluted with coal dust particles with diameters ranging from 100 nm to 5 µm.

A general result of this study is that one of the main benefits of wet electrostatic scrubbing is the enhancement of collection efficiency right in the Greenfield gap region, i.e. $d_p = 0.1–1$ µm. Furthermore, model results highlight the central role of droplets size and charge and the marginal influence of water/gas relative velocity. This condition leads to a peculiar result. For the capture of micronic particles, where inertial impaction is the leading scavenging mechanism, high water/gas relative velocities have to be assured and usually the water is sprayed in counter-current flow respect to the gas or, in advanced systems, Venturi scrubbers are adopted. On the contrary, in case of submicronic particles captured by wet electrostatic scrubbing, the model shows that the water/gas relative velocity has a negligible effect on the particle collection efficiency. Therefore, the use of co-current, counter-current or cross-flows injection of water in the gas stream is conceptually irrelevant and the Venturi scrubbing is unnecessary.

With reference to the investigated case study, the model shows that reliable optimal working conditions for the WES system consider the use of charged spray of fine droplets with $D = 50–200$ µm and $q/q_R > 10\%$. By this way, spraying 100 ml/m^3 of charged water in the polluted gas stream, a removal efficiency of 99.5% should be achieved in around 3 s for all the particles in the Greenfield gap. These conditions can be reliably obtained by commercially available air-atomizing nozzle with induction charging systems or with electrospraying nozzles.

Acknowledgments

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