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An analytical model-based assessment of Wet Electrostatic Scrubbing for mitigating fine and ultrafine particles emissions in domestic biomass boilers

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ABSTRACT

This paper proposes the general design of a Wet Electrostatic Scrubber aimed at mitigating fine and ultrafine particles emissions from domestic heating boilers. The design is based on particle capture modelling supported by specific experiments and technical literature information. Results indicate up to 96.6% removal efficiency, consuming 1.2 kg/h of water and 0.3 W per 1 m^3/h of gas treated. Comparative analysis highlights the balanced performance of Wet Electrostatic Scrubber in particle capture, energy and water usage, pressure drop, and space occupancy, with the additional benefit of more efficient absorption of gas pollutants.

1. Introduction

Biomass boilers are largely used for domestic heating in Europe: most of the units have potentialities from a few to tens of kWh. The produced exhaust gases are around 2 kg/kWh and contain several pollutants [1,2], either in the form of gas species, such as SO_2, NO_x, CO and volatile organic compounds (VOCs), or as particulate matter of different sizes, from a few nanometers to tens of micrometres. The emission profile includes substantial amounts of particulate matter, both in the form of large fly ash fragments (deriving from comminution and attrition of pellets), and ultrafine particles deriving from flame nucleation and growth processes. While the toxicity of gas compounds is well-known and is independent of the specific source, particulate matter is a fingerprint of the process and its toxicity depends on the chemical composition of the fuel, the combustion conditions, and the final size distribution that the particles acquire at the end of the stack. Besides, particles may exploit further toxic effects related to the content of heavy metals, which derives from their presence in the parent fuels and their transfer to the particulate matter. The toxicity of aerosols also depends on their physical state: liquid-like and soluble solid components of the emissions are likely to exploit their toxicity proportionally to their mass since they can be dissolved and absorbed at a molecular scale; insoluble solid particles, instead, act on the cells mostly through their surface area. Finally, the toxicity of emitted particles also depends on their size: solid particles finer than 300 nm are proven to penetrate the lung membranes, passing to the blood circulation, and reaching other target organs, thus increasing the toxic effect [3]. Several studies on the toxicity of biomass boilers emitted particles are reported in the pertinent literature [4–7]. The particle size distribution produced from biomass boilers is highly dependent on the fuel type and the boiler design. Some examples are shown in Fig. 1.

As with all other process plants, also the exhausts of domestic biomass boilers need to be treated to reduce their impacts on both the outdoor and the indoor environment. One of the most complex problems in the assessment of an after-treatment unit aimed to treat such gases is the need to eliminate ultrafine combustion particles: Although the toxicity of ultrafine particles is well known, the difficulties in assuring reasonable treatments for this class of pollutants still devoid from introducing specific regulations. Despite this, the WHO has recently introduced the particle number concentration, PN, in the list of Air Quality Indices, fostering the introduction of new regulations to contain ultrafine particles emissions, which give far higher contributions to PN rather than to particles mass, PM, measurements.

Techniques to remove fine and ultrafine particles are based on three main approaches: water scrubbing, filtration, and electrostatic field-driven separations [10,11]. Water scrubbing is based on the hydrodynamic interactions between the particles carried by the gas and the water distributed either in the form of sprayed droplets, liquid film flowing over packings or bulk liquid through which the gas breaks up into bubbles. Filtration is largely diffused and involves the use of specific non-woven textiles (sometimes properly modified to carry out an electric charge) or metallic or ceramic porous materials to block the particles on their surface. Intrinsically, the filters clog after a certain operating time and the treated gas experiences an increasing pressure drop. When

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a critical pressure drop is achieved, the filter must be regenerated. For industrial applications involving large particles ($PM_{2.5}$, PM_{10}) and textile materials, the regeneration is often physical and involves compressed air jets or mechanical shaking. For the filtration of ultrafine particles on ceramic filters, the physical regeneration is more complex, strongly limiting the applicability of these units. For soot particles produced by LNG, LPG, gasoline or car diesel, a chemical regeneration can be proficiently carried out, so this method is the best available technology for the automotive sector. In large-scale units, the formation of cakes of deposited particles on the filtration medium promotes the removal of particles much finer than the pore size, assuring high PN removal efficiency at the price of high pressure drops [12].

Conventional electric field-driven technologies involve dry (ESP) and wet (WESP) electrostatic precipitators, which mostly use corona

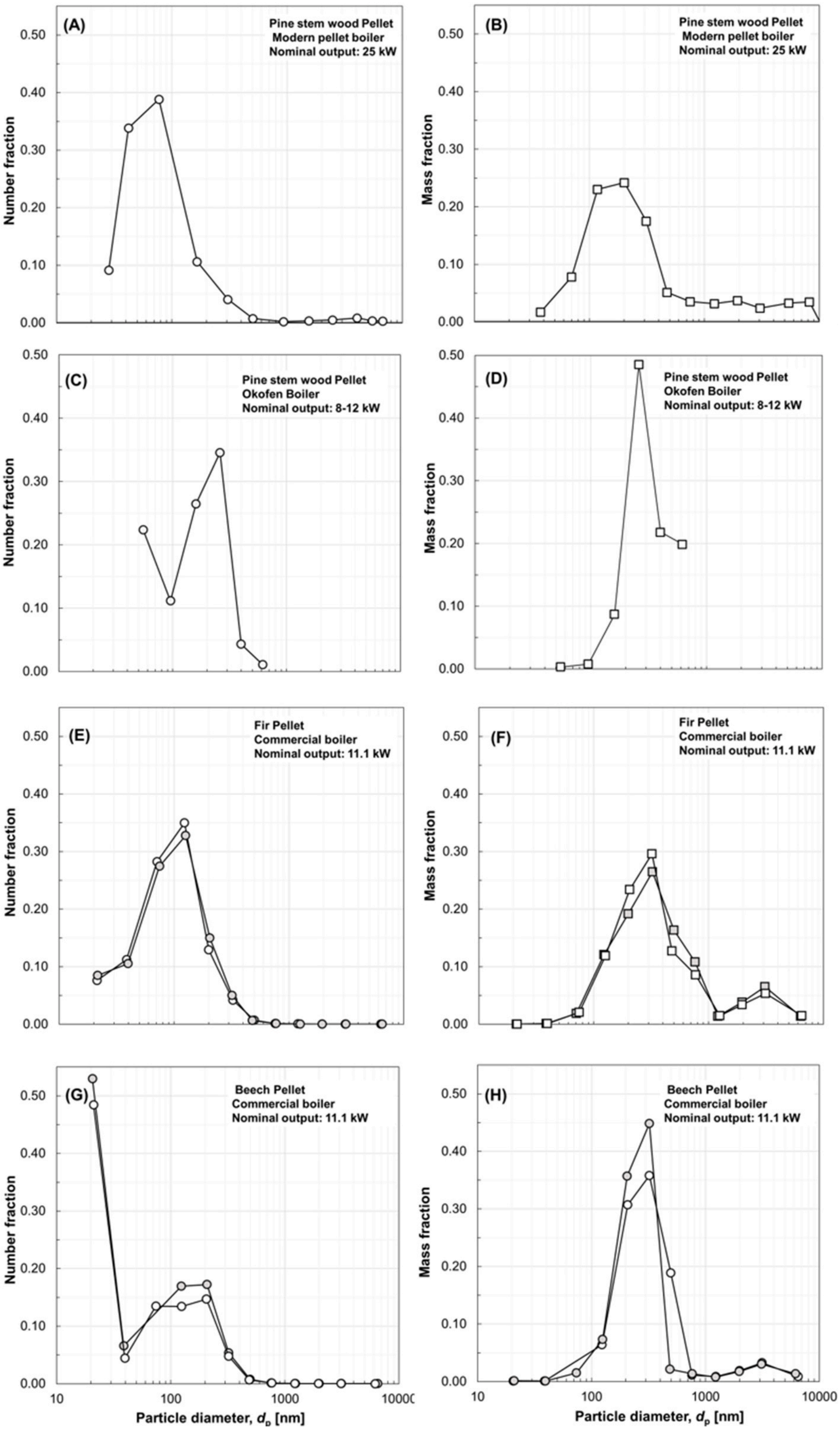

Fig. 1. Particle size distribution in number (left) and mass (right). A-B Lamberg et al. [8] - C-D Limousy et al. [9] - E-F-G-H Ozgen et al. [2].

discharge to unipolarly charge particles and remove them by deposition on grounded (dry or wet) surfaces. Compared to filtration, WESPs have the advantage of low-pressure drops, but to achieve a high efficiency for ultrafine particles they need high potentials and require longer residence times with respect to filters [13]. Among the innovative approaches aimed at improving the performances of electric field-driven processes, some of the most interesting ones involve the use of agglomerators [14–16], electrets [17–20] and wet electrostatic scrubbers [21–26].

Wet electrostatic scrubbers are spray chambers modified to be operated with charged sprays produced by electrospraying nozzles (ES). Optionally, the gas entering the unit is subjected to an ionization process to produce charged ions and particles with a sign opposite to that of the sprayed droplets. In the contact chamber, the intimate contact between oppositely charged droplets and particles favors their electrostatically driven attraction: this couples with the conventional hydrodynamic interactions to promote the effective removal of particles from the gas stream. The electrostatic interactions mostly contribute to the capture of submicronic particles, while they scarcely affect the capture of particles larger than several microns. Therefore, wet electrostatic scrubbing has found application in those fields when the removal of fine and ultrafine particles is required, as in the control of combustion off-gases [23–27] or for the process industry [28,29]. Besides, it was explored as a process for indoor air cleaning and bioaerosol removal [30]. Among the points of strength of WES units, we must recall the low-pressure drop [26,30,31], similar to that of conventional scrubbers, the low energy consumption [24–26,32] and the capability to remove particles and gas pollutants simultaneously [24,33–36].

While the basic physics of a wet electrostatic scrubbing process is well understood [23,26], the design of a wet electrostatic scrubber requires specialistic modelling and field testing. In particular, large-scale unipolar gas ionization units, spray units and contact vessels must be designed to ensure a uniform charging of the gas and the liquid and a uniform treatment of the gas stream. Besides, detailed information on particles properties and size distribution is needed. To develop the detailed engineering of WES units and fine-tune their operation, it is needed an accurate hydrodynamic tracing of the particles and droplets trajectories and residence time distribution both for the gas ionization unit and the contact chamber. Nevertheless, for the WES general design, a reasonable estimation of the overall particle removal efficiency can be achieved using simplified models that consider averaged value of the charged particles and spray properties and assume ideal particles residence time distribution in the chamber (*e.g.* a Dirac or an Exponential one) and simplified spray fluid dynamics. This is the same approach used to design conventional spray scrubbers [24,37,38].

To the best of our knowledge, wet electrostatic scrubbing has not been proposed so far for the depuration of biomass combustion off-gases except for a single work related to the development of a laboratory-scale WES for the control of particle emissions from poultry facilities [39].

In this work, we will present a first assessment of the main characteristics and the potential performances of wet electrostatic scrubbing (WES) processes applied to the removal of particles from the exhaust gases produced by small biomass boilers. The study consists of developing the general concept design of the unit for a reference pellet boiler size and includes considerations on space requirements, pressure drops, energy consumption, and water consumption. To accomplish this task, we used a renowned semiempirical stochastic model for particle capture, which - after suitable coupling with experimental data on particles charging and electrified droplets characterization - provides robust enough indications for a preliminary design of the WES unit. Experimental results and technical literature data have been used to estimate pressure drops and energy consumption. A comparison with other technologies has been reported considering selected sustainability indicators, such as the fractional water consumption (FWC – the water requirements per unit mass of filtered particles) and the specific energy intensity (SEI – the energy duty per unit mass of filtered particles).

2. Methodologies

The conceptual layout of the WES system is that of a downward unit that, following the classification adopted by Jaworek et al. [13], can either be a chimney-top or a boiler-attached unit operating on cold gas, close to the dew point. In chimney top applications, the WES unit is part of the chimney stack and can be mounted outside the building either on its top or on a lateral wall. When space is not available, the boiler-attached configuration should be used, with the WES placed aside of the boiler itself before the chimney stack. Fig. 2 shows a sketch of the complete process, including a modular combustion unit with its chimney stack and the WES unit.

The preliminary design of the WES unit for biomass combustion is based on the combination of experimental and numerical modelling activities coupled with data deriving from former experimental activities.

In particular, in order to design the WES chamber, we used a semiempirical stochastic particles capture model that has been successfully adopted to describe former experiments [23,24]. The stochastic model, whose mathematical and physical characteristics were thoroughly discussed in the papers of Carotenuto et al. [23], D'Addio et al. [27] and Di Natale et al. [40], is derived from models of atmospheric scavenging and its semiempirical nature mostly resides in the need for specific input that can be effectively retrieved only through experimental analyses. The advantage of using this model resides in its robustness and simplicity which makes it suitable for general design purposes. It possesses the capability to estimate overall particle removal efficiency without necessitating a detailed mechanical design. Following a well consolidated engineering practice for pollution control technology, after this general design, a subsequent mechanical design can be formulated. In this subsequent stage, rating models can be applied to simulate the WES unit's performance with increased precision. These models facilitate the fine-tuning of equipment design and operation, ensuring optimal efficiency and effectiveness. The equation to calculate the removal efficiency $\eta(d_{pi})$ of charged particles having a size d_{pi} scrubbed for t seconds by an ensemble of droplets of different sizes, D_j, each of which has a number concentration $N(D_j)$ is [23,24]:

$$ln\left[1-\eta\left(d_{pi}\right)\right] = -\Lambda\left(d_{pi}\right) \bullet t = -\sum_{j=1}^{+\infty} \lambda\left(d_{pi}, D_j\right) \bullet N\left(D_j\right) \bullet t \tag{1}$$

Where $\Lambda(d_{pi})$ is the scavenging coefficient of the entire spray and $\lambda(d_{pi})$ is the scavenging coefficient of each droplet size D_j.

One of the main characteristics of the stochastic model is the assumption of linear superimposition of collisional mechanisms. When considered individually, the impact of each force on particle collection can be characterized as a probability of collision, or collisional efficiency. This efficiency reaches 100% when all particles within the impact cylinder, swept in unit time by a moving droplet, are successfully captured.

In the atmospheric scavenging model employed, it is posited that the overall collisional probability is the linear sum of the collisional efficiency attributed to each interaction force. Synergistic effects, although present, are neglected in this assumption.

The single droplet scavenging coefficient, $\lambda(d_{pi})$, is directly proportional to the overall collisional efficiency, E_i:

$$\lambda\left(d_{pi}, D_j\right) = \frac{\pi}{4} \bullet U_r \bullet \left(d_{pi}, +D_j\right)^2 \bullet E_t = \frac{\pi}{4} \bullet U_r \bullet \left(d_{pi}, +D_j\right)^2 \bullet \left(E_{hyd} + E_{ph} + E_{Es}\right) \tag{2}$$

In Eq. (2) E_{hyd} resumes all the hydrodynamic (inertial impaction, directional collision and Brownian diffusion) collisional mechanisms, E_{ph} indicates the phoretic (thermophoretic, diffusiophoretic and dielectrophoretic) contribution and E_{Es} includes the contribution of Coulomb force, image charge forces and electrophoretic effects.

In this work, we neglected image charge force, electrophoretic and

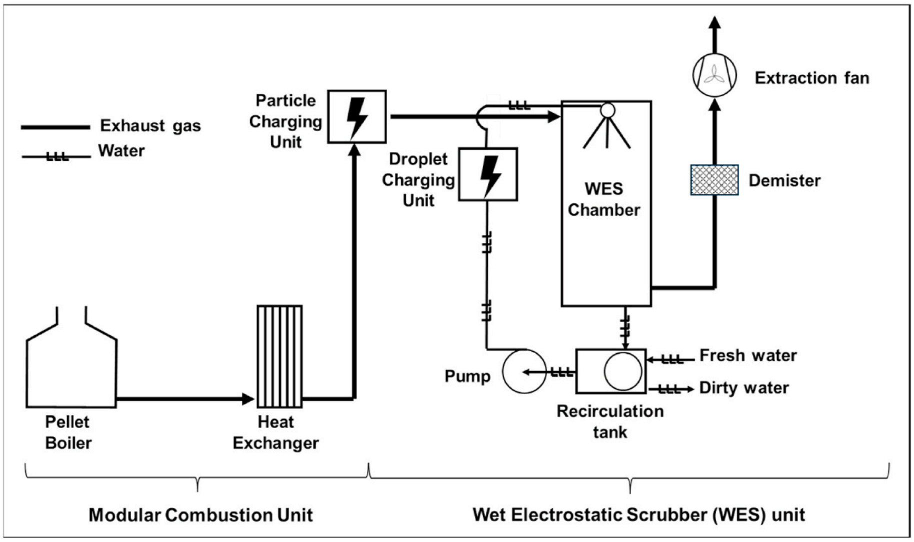

Fig. 2. Sketch of the overall process, including the modular combustion unit and the Wet electrostatic scrubber unit.

dielectrophoretic interactions, and we reduced electrostatic interactions to the sole Coulomb force effect, providing, on the one hand, a simplification of the model and, on the other hand, a cautious estimation of the particle removal efficiency. Furthermore, the model neglects the interconnections between thermo-/diffusio-phoretic and electrostatic forces that, in the experimental conditions, are likely to give rise to an increase in the collection efficiency [40].

For the topic of the paper, it is useful to report the contribution of electrostatic forces to the scavenging coefficient, which is given by Refs. [23,24]:

$$\Lambda_{Es}\left(d_{pi}\right)=\frac{\pi}{4}\bullet U_r\bullet\left(d_{pi}+D_j\right)^2\bullet E_{Es}\bullet N\left(D_j\right)=\left(\sum_{j=1}^{+\infty}\frac{4k_c}{3\mu}\bullet\frac{q_{pi}C_{ci}}{d_{pi}}\bullet N\left(D_j\right)q_{Dj}\right) \tag{3}$$

where k_c is the Coulomb constant; C_{ci} is the Cunnigham factor for the i-th particle; μ is the gas viscosity; q_{DJ} is the charge of each *j-th* droplet.

The semi-empirical nature of the adopted stochastic model resides in two aspects. First, some of the equations used to estimate the hydrodynamic collisional efficiency are descriptive equations with fitting parameters valid in specific fields of application. Second, the model itself requires detailed experimental data (*e.g.* on spray properties and trajectories, gas fluid dynamic fields and droplets and particles charge), to be properly applied. As regards the expression of $\Lambda_{Es}(d_{pi})$, experiments are needed to provide information on the charge level acquired by the particles in the gas ionization unit, q_{pi}, the spray concentration, $N(D_j)$, and the charge acquired by the droplets in the electrified spray unit, q_{Dj}.

To this end, we performed experimental studies on new prototypes of a gas ionization unit and an electrified spray, whose details are omitted for intellectual property protection. The gas ionization unit is based on corona charging and uses a needle plate configuration. The electrified spray unit is based on induction charging: the liquid jet emitted by a spray nozzle is exposed to the electric field produced by a high-voltage electrode. The electric field acting on the surface of the liquid sheet generates an accumulation of charge over this surface and, following the leaky dielectric liquid approach (*e.g.* Ref. [41]), once the liquid sheet breaks, two currents are produced: (i) a spray current related to the droplets, which contains a charge proportional to that deposited on the surface of the liquid sheet at the breakup point; (ii) a dispersion current, having the same value but opposite sign than the spray current, which flows into the liquid core, reaching the ground. Trichel pulses and corona discharges can appear at a certain critical potential, above which pure induction charging is no longer maintained and the spray and the dispersion current are no more equal.

Information on particles charging, based on corona and aerosol charging currents, has been retrieved from tests performed with the same approach adopted by D'Addio et al. [27,42] and Esposito et al. [43], using the exhaust of an open gasoline flame as the source of particles entering the gas ionization unit with a temperature around 80–100 °C. The tests indicated a mean charging efficiency of 40% when operated at 18 kV. Accordingly, for a given particle size, the charge is assumed equal to 40% of the corresponding theoretical value, calculated according to the consolidated models which consider this value as the sum of field and diffusional charging phenomena (*e.g.,* Refs. [27,42,44]).

The induction charging electrified spray unit formerly adopted by Di Natale et al. [24] has been modified to operate with a flat spray, using a plane electrode, placed 30 mm below the nozzle tip. Three flat nozzles manufactured by Spraying Systems Co (USA) of the same series (Unijet Tip Type 25-015-SS, 25-03-SS, 25-04-SS, named in the following Type 1, Type 2 and Type 3 respectively), have been characterized using the same procedures of Manna et al. [45] and Di Natale et al. [24]. These are capable of covering water flow rates between 0.5 and 1.5 L/min by operating between 3 and 4 bar. Each nozzle has been operated under three induction potentials, corresponding to three droplets charging levels: these are indicated as low-, mid- and high-performance conditions. The mid-performance (MP) mode is considered as a stable working conditions of the electrospray, the high-performance (HP) mode is close (90% of the critical potential) to the onset of electric discharges and corresponds to +30% of the current produced in MP condition. The low-performance (LP) mode simulates a lack of efficiency, or a malfunctioning, of the spray unit and its spray current is −30% of that in MP condition. The LP mode is also representative of the current achieved when the spray is used with heavily dirty water during closed-loop tests with combustion particles.

The main parameters that characterize the charged water sprays are: flow rate, *L*, frontal and lateral spray angles, spray current, *I*, average droplet charge to mass ratio (*i.e.* the ratio between spray current and mass flow rate), *D-CMR*, and average droplet charge to surface ratio (*e.g.* the ratio between spray current and surface area produced by the spray in the unit time), *D-CSR*. This last can be calculated as the ratio between six times the D-CMR and the droplet spray average Sauter diameter D_{32}.

A resume of the spray parameters are reported in Table 1:

Optical analyses indicate a modest alteration of spray size distribution with the applied potential and that the three nozzles have a similar average droplet Sauter Diameter D_{32}, in the range 325 ± 30 μm. The

Table 1
Main characteristics of the electrified spray nozzles.

Nozzle		Type 1	Type 2	Type 3
Reference Flow rate, L/min		0.5	1	1.5
Spray angle at operating potential, degs	Frontal	25	25	26
	Lateral	7	7	8
D-CSR, C/m^2	LP	6277	3877	2954
	MP	9046	5538	4246
	HP	11815	7200	5538

droplet size distribution, $\varphi(D_j)$ is well described by the model proposed by Kooij et al. [46] for flat sprays.

The values of droplet charges can be calculated assuming that the droplet surface charge density, *D-CSR*, is the same regardless of their size: this assumes that the charge deposited on the liquid sheet is transferred on the droplets, proportionally to their surface area. The charge for a droplet size D_j can be calculated as:

$$q_{Dj} = D - CSR \bullet \pi D_j^2 = \frac{I}{L} \bullet \frac{D_{32}}{6} \bullet \pi D_j^2 \tag{4}$$

The preliminary design of the WES considers a reference boiler size having a nominal power of 30 kW and a corresponding exhaust gas flow rate of 61.41 kg/h.

The WES is assumed to be operated in co-current flow, with the spray and the gas fed at the top of the unit and moving downward. Under co-current flow conditions, the droplet concentration per size D_j is calculated as [23,24]:

$$\begin{aligned} N(D_j) &= \frac{\psi(D_j)L}{U_D(D_j)+U_G} \bullet \left(\frac{G}{U_G} + \frac{\psi(D_j)L}{U_D(D_j)+U_G}\right)^{-1} \bullet \frac{6}{\pi D_j^3} \\ &\cong \psi(D_j) \bullet \frac{L}{G} \bullet \frac{U_G}{U_D(D_j)+U_G} \bullet \frac{6}{\pi D_j^3} \end{aligned} \tag{5}$$

Being $\psi(D_j)$ the volumetric size distribution of the spray, calculated from the corresponding value of the droplet size distribution $\varphi(D_j)$. It is here assumed that the droplets velocity evolves as an isolated sphere ejected at the jet velocity,u_j, until reaching its terminal velocity $U_T(D_j)$ following the gas trajectory.

With this information, it is now possible to provide a preliminary design of a WES unit sized for the reference boiler size. The main process parameters considered in this work are:

- The liquid-to-gas mass flow rate, *L/G*.
- The height of the WES, *Z*.
- The gas velocity, U_G.
- The gas residence time, *t*.

To analyze the effects of process parameters and identify how the performances of the WES may change under different design conditions, we considered twenty-seven operating conditions starting from a reference condition (indicated with the acronym RC in the following), with the electrified spray operated in LP, MP an HP modes. Starting from the reference condition, two additional values of *L/G* ratio (one *L/G* ratio per nozzle), three gas velocities and three WES heights have been considered. The variation of the two last parameters also corresponds to a variation of the residence times. To simplify the following discussions, the tests are thereinafter indicated with the value of the variable that characterizes its difference with respect to the reference condition, *e.g.,* $Z = 1$ m indicates the test carried out under the same conditions of the RC case but with a different *Z* value, equal to 1 m.

A resume of the investigated conditions is reported in Table 2. For the gas phase, we assumed that it enters the WES unit at a temperature, *T*, of 80 °C, water-saturated, thanks to the natural cooling of the gas along the pipeline from the boiler exchanger's outlet to the chimney top. The presence of hot gas further increases the capture of particles due to the onset of thermophoretic and diffusiophoretic phenomena [40], but these contributions are neglected here for the sake of simplicity and to grant model robustness. Table 2 also reports the values of the residence time and the required cross-sectional area of the WES, *S*.

To estimate the pressure drops of the WES-based gas cleaning system, which is not related to the main WES unit, but rather to its own auxiliaries, we used reference data from technical handbooks and specialistic papers. The same has been done for the pump and for an optional extraction fan. The energy duty required for particles and droplets charging is instead directly retrieved from the experimental data.

The performances of the WES unit are compared with those of other techniques reported in the pertinent literature, in terms of expected removal efficiency, pressure drop and energy duty, by considering the following sustainability indicators:

- Fractional water intensity (FWC): The ratio between the water flow rate used for gas cleaning to the mass of particles captured.
- Specific Energy Intensity (SEI): The ratio between the total energy consumption and the amount of particles captured.

3. Results

In the first part of this paragraph, we present results for spray nozzles operated under MP mode.

The first process parameter considered is the gas velocity. Theoretically, its effect on particle capture can be easily predicted: by increasing the U_G (while keeping constant the WES height *Z*) the residence time lowers, and the removal efficiency is bound to decrease according to Eq. (1). Nevertheless, other non-linear effects exist since, for a given flow rate, the gas velocity is inversely proportional to the WES cross-sectional area, *S*. The section plays an important role in the system design, especially for small WES sizes as those considered here, because it determines the amount of water lost on the WES walls and defines the actual fluid-dynamic field inside the scrubber chamber.

To minimize the water losses at the scrubber walls, flat sprays are more effective than conical ones: it is possible to contain the dispersion of the droplets in the direction parallel to the flat spray sheet, whose spray angle is a few degs. It is worth noticing that, due to their size, it is unlikely that droplets may attend a pure vertical motion inside the WES chamber. To account for water losses, we thus used the same simplified estimation based on the spray coverage experimental data at different distances from the nozzle recorded from open-air experiments [24,38]. Given the small value of the lateral spray angle, we estimated that a WES chamber having a rectangular cross-section, with a width of 100 mm, is sufficient to assume a negligible loss of water on two faces of the WES unit parallel to the flat spray sheet, while assuring a good distribution of

Table 2
Resume of the experimental conditions.

	RC	L/G = 0.5	L/G = 1.5	$U_G = 0.25$ m/s	$U_G = 0.75$ m/s	$U_G = 1.00$ m/s	Z = 0.75 m	Z = 1 m	Z = 2 m
L, L/min	1	0.5	1.5	1	1	1	1	1	1
U_G, m/s	0.50	0.50	0.50	0.25	0.75	1	0.50	0.50	0.50
Z, m	1.5	1.5	1.5	1.5	1.5	1.5	0.75	1	2
L/G, kg/kg	1	0.5	1.5	1	1	1	1	1	1
t, s	3	3	3	6	2	1.5	1.5	2	4
S, m^2	0.028	0.028	0.028	0.056	0.019	0.014	0.028	0.028	0.028

water droplets, within the RC height of 1.5 m, Given this lateral size and the frontal spray angle, which for the charged sprays is at most 25 degs, the water loss model indicates that operation at the RC velocity, 0.5 m/s, which corresponds to a length of 280 mm, allows containing water losses within 33% at Z = 1.5 m. Operation at higher spray velocities and smaller cross-sectional areas imply higher water losses, which depress the efficiency: the water lost at 0.75 m/s along the chamber in RC conditions is nearly 51%, while at 1.0 m/s it approaches 62%. Under RC conditions, the water loss within the first meter of the WES unit is negligible. Higher WES heights also increase water losses.

By computing these effects in the particle removal model, the particle removal efficiency parametric with the gas velocity is described by the curves in Fig. 3. It is worth mentioning that the electrostatic contributions are dominant, but Brownian contributions affect the capture below 20 nm. Inertial impact and directional interception effects become appreciable above 500 nm. Consequently, to better exploit the contribution of electrostatic forces, only the particles removal efficiency in the range 20–500 nm is reported here.

The model results indicate that the gas velocity has a significant effect on the removal efficiency. If a larger cross-sectional area is geometrically reliable for the boiler design, a velocity as low as 0.25 m/s, which allows both a higher residence time and a negligible (<2%) water loss, makes possible to achieve very high removal efficiency, above 96% for all particles size. The model results indicate that the removal efficiency of the WES unit in the RC operation is mostly higher than 90%, with a minimum of nearly 87% occurring for a particle size around 80 nm. The efficiency increases above 90% for particles finer than 20 nm thanks to the Brownian efficiency contribution and to the higher particles mobility, which gives higher values of $q_{pi}C_{ci}/d_{pi}$ ratio and for particles larger than 200 nm for which particles charge increases due to the higher contribution of field charging mechanisms. Above 400 nm the efficiency passes 95%.

The size-dependent particles removal efficiency as a function of the L/G ratio is shown in Fig. 4. The differences in the spray angle values have been accounted for in the model calculations.

By altering the L/G ratio (*e.g.,* by changing the nozzle type) the removal efficiency varied, having minima between 81% at $L/G = 0.5$ and 90% at $L/G = 1.5$. The L/G ratio has a non-trivial effect on the removal efficiency: In fact, while, on the one hand, the droplets concentration increases by spraying more liquid, on the other hand, the droplet charge is lower because of the lower *D-CSR* value of the electrified spray. Since the size distributions of the three nozzles are similar, the effect of L/G on droplet concentration prevails, providing higher removal efficiency.

Finally, the effect of WES height is considered in Fig. 5.

Increasing the WES height has a trivial, direct, effect on the gas residence time and the efficiency increases accordingly. Nevertheless, higher WES units also imply higher water losses. For the reference gas velocity $U_G = 0.50$ m/s and the corresponding cross-sectional area, an increase in the value of Z from 1.5 to 2 m corresponds to an increase in water losses from 33% to 46%. This effect depresses the increase of gas residence time, making the elevation of the WES column less effective than the theoretical expectations. Moreover, it should be discussed that larger heights may not be feasible when referring to residential applications: in a boiler-attached configuration, the unit must not be higher than the roof height; in a chimney-top configuration, such a high unit can be mounted only on some rooftops or on the building side [51–53].

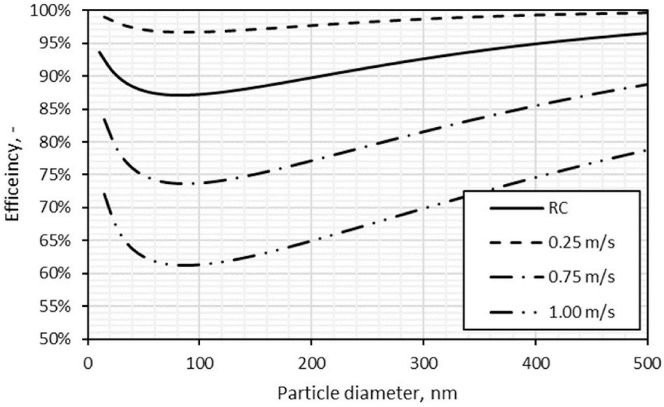

Fig. 3. Size-dependent particles removal efficiency as a function of the gas velocity, U_G, considering water losses. Spray nozzle operated in MP mode.

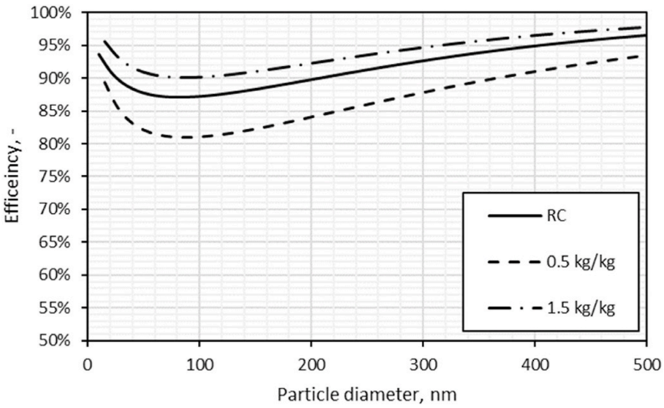

Fig. 4. Size-dependent particles removal efficiency as a function of the L/G ratio. Spray nozzle operated in MP mode.

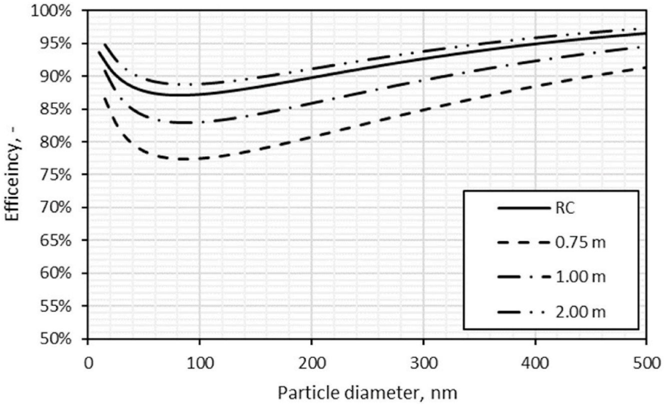

Fig. 5. Size-dependent particles removal efficiency as a function of the WES height, Z, considering water losses. Spray nozzle operated in MP mode.

When the spray is operated under LP or HP modes, the particles removal efficiency related to the hydrodynamic effects is not altered, since the droplets characteristics are not sensibly affected by the induction charging, while the electrostatic contributions scaled linearly with the spray current values. The electrostatic effects are dominant for particles within 20 and 500 nm. In this range, operations of the WES unit under LP and HP modes indicate that the size-dependent particle removal efficiency curves preserve their shapes, and all the process parameters have the same effect, scaling almost proportionally to the new values of the spray current. For the sake of brevity, only the minimum value of the removal efficiency for the RC condition is reported, as a reference, in Table 3.

The model simulations indicate that the highest efficiency (with a minimum close to 99%) can be achieved with a gas velocity of 0.25 m/s and with the nozzle operated in HP conditions. Operation under reference condition (RC) ranks in the middle range of efficiency.

Finally, the total numerical, η_N, and the volumetric, η_V, removal efficiency for the particle size distribution reported in Fig. 1 are shown in

Table 3

Minimum value of the removal efficiency for the investigated conditions.

	Low performances	Mid-performances	High-performances
RC	74.4%	87.1%	93.5%
$L/G = 0.5$	67.0%	81.0%	89.1%
$L/G = 1.5$	78.6%	90.1%	95.4%
$U_G = 0.25$ m/s	89.6%	96.6%	98.9%
$U_G = 0.75$ m/s	58.9%	73.6%	83.1%
$U_G = 1.00$ m/s	46.8%	61.2%	71.7%
$Z = 0.75$ m	63.0%	77.5%	86.3%
$Z = 1$ m	69.2%	82.9%	90.5%
$Z = 2$ m	76.7%	88.7%	94.6%

Table 4

Total numerical and volumetric removal efficiency for the size distribution functions shown in Fig. 1. Reference conditions (RC): $U_G = 0.5$ m/s, $Z = 1.5$ m, and $L/G = 1$.

	LP η_N	LP η_V	MP η_N	MP η_V	HP η_N	HP η_V
Lamberg et al. [8] - Pine stem wood pellet	76.1%	91.9%	88.2%	91.9%	94.2%	99.3%
Limousy et al. [9] - Pine stem wood pellet	75.9%	81.7%	88.1%	91.9%	94.1%	96.3%
Ozgen et al. [2] - Fir pellet	76.2%	89.6%	88.4%	96.4%	94.3%	98.7%
Ozgen et al. [2]- Beech pellet	78.1%	89.2%	89.7%	96.2%	95.1%	98.6%

Table 4. In light of the aforementioned considerations, only the RC case is shown.

The model results indicate a high removal efficiency (>90%) in terms of reduction of particles volumetric emissions (and thus mass emissions) while being able to grant, in the worst scenario, a 76% reduction in the number of emitted particles. When properly maintained to grant HP conditions, efficiencies as high as 96.6% for η_N, and up to 99% η_V could be achieved. Comparison with Table 3 data further suggests that if the gas velocity $U_G = 0.25$ m/s is feasible, this is by far the preferred choice since the efficiency can be dramatically increased.

As regards the estimation of other key performance indicators, such as energy duty and pressure drop, it must be considered that the WES unit requires a few auxiliaries. In particular, apart from the control electronics and the high-voltage generators, a turn-key WES unit must include a demister (to eliminate spray droplets entrained in the gas stream leaving the chamber), a water tank and a pump.

The chimney-top positioning of the WES proposed here is meant to help the natural cooling of the gas stream but, due to the actual temperature of the gas leaving the boiler heat exchanger and in consideration of different pipeline lengths, the temperature reaching the WES may be too high, reducing the effectiveness of the process due to droplets evaporation. We estimated that if the gas temperature reaching the WES is above 110 °C, it may be useful to place an additional preconditioning unit, such as a water spray quenching unit or an additional exhaust gas heat exchanger, before the gas ionization unit. This last can be preferred to improve heat recovery and, to this end, it is more convenient to place it closer to the main boiler exchanger. Needless to say, in case the WES is designed as a boiler-attached unit, the auxiliary heat exchanger is mandatory.

In terms of energy consumption, the use of an auxiliary exhaust gas heat exchanger implies extra pressure drops and an auxiliary fan might be included in the WES setup. In the following, we refer to full-optional WES unit (w.e.) to indicate the unit equipped with an auxiliary heat exchanger, while simple WES unit (s) indicates the exchanger is not adopted.

All the auxiliary units considered here can be easily found in commerce and will not be designed in this work. However, their performances contribute to the actual capital, operational and maintenance costs of the unit. At this stage, only the operational costs are considered.

In particular, the experimental data provided direct information on the energy requirements of the high-voltage generators for the gas ionizing unit and the induction sprays. The induction spray nozzle has a negligible energy consumption, as low as $8 \cdot 10^{-5}$ W per m^3/h of treated gas. For the Particle Charging Unit, the experimental value found here for the treatment of model combustion particles from open gasoline flames is 0.05 W per m^3/h of treated gas, which is consistent with the values found in former experiments [25]. The energy consumption of the water pump (assuming an efficiency of 70% and a prevalence of 40 m), corresponds to 0.15 W per m^3/h of treated gas.

The backpressure exerted by the unit on the boiler, which can be eventually overcome with an extraction fan, mostly depends on the pressure drops of the demister and, if present, of the auxiliary heat exchangers. In fact, the WES chamber and the piping have negligible pressure drops as confirmed by the works of Di Natale et al. [25]. Despite the additional costs, the extraction fan may be also useful to improve combustion efficiency by assuring proper dosage of airflow with no fuel penalty with respect to the untreated boiler.

As regards the demister, several options are available in the market. Brunazzi and Paglianti have studied knit demisters in detail, providing robust equations for sizing this kind of equipment [47–50]. The knit demisters grant efficiency above 95% for 10 μm particles with pressure drops below 1 mbar. As regards the heat exchanger, in light of the small size of the equipment, we consider the use of a plate-plate unit. Commercial units of this kind are reported to have a pressure drop lower than 2 mbar.

With these pressure-drop values, the auxiliary extraction fan should grant a nominal overpressure of nearly 1 mbar for a simple WES and 3 mbar for a WES unit with an auxiliary heat exchanger. Considering an overall fan efficiency of 30%, the fan power requirement is nearly 0.09 W per m^3/h of treated gas for the simple WES and 0.278 Wh/m^3 for the WES unit with an auxiliary heat exchanger.

Summing up, the specific energy duty for the simple WES (1 mbar pressure drop) is around 0.30 Wh/m^3, while the WES unit with an auxiliary heat exchanger (3 mbar pressure drop) requires around 0.48 Wh/m^3.

Comparison of the WES with other possible solutions reported in the pertinent literature as dry filters [51–53], ESP [13], hydrodynamic-water-based processes [54,55] and WESP [56]. From these papers, data on particle removal efficiency and, when available, pressure drops can be gathered. For scrubbing processes, these data are not reported in the cited papers but other references (*e.g.* Ref. [52]) allow estimating values varying between 2.5 and 10 mbar for this simple counter-current flow washing tower, between 5 and 80 mbar for a Venturi scrubber [57–59] and above the liquid hold up value (e.g. >25 mbar for a 250 mm water column) for a bubble column [60,61]. For WES and WESP units, the pressure drops reside in the gas distribution system and, for the WESP, also in the demister. They should be accounted to be in the range of 0.5–1.2 mbar [34].

Table 5 resumes the average efficiency, the Fractional Water Consumption (FWC), the Specific Energy Intensity (SEI) and the pressure drop for the proposed WES design and other technologies. To allow a reasonable comparison, we refer to a unique reference value of particle mass concentration of 100 mg/m^3.

It is interesting to revise these data in terms of relative performances. The FWC, the SEI, the efficiency and the pressure drops are calculated as:

$$y_r = \frac{y - y_{worst}}{y_{best} - y_{worst}} \tag{5}$$

Where y is one of the four aforementioned variables and the subscript "best" and "worst" stands for the best and worst values of y reported in

Table 5
Resume of performance indicators for WES and other particle capture technologies. (s) Indicate simple WES and (w.e.) indicate WES unit with auxiliary heat exchanger.

Equipment	Avg. $PM_{2.5}$ efficiency	FWC, kg/mg (c_0 = 100 mg/m^3)	SEI, W/mg (c_0 = 100 mg/m^3)	Pressure drop, mbar	Reference
WES $LP_{(s)}$	88.9%	0.0110	0.0033	1	This work
WES $MP_{(s)}$	93.6%	0.0104	0.0032	1	This work
WES $HP_{(s)}$	98.5%	0.0099	0.0030	1	This work
WES $LP_{(w.e.)}$	88.9%	0.0110	0,0054	3	This work
WES $MP_{(w.e.)}$	93.6%	0.0104	0,0051	3	This work
WES $HP_{(w.e.)}$	98.5%	0.0099	0,0049	3	This work
ESP	70–95%	0.0000	0.0059	0.5–1.2	Deduced from Jaworek et al. [13]
WESP	70–95%	0.0066	0.0064	0.5–1.2	Kim et al. [56]
Washing tower	28.2%	1.1439	0.3759	n.a.	Bianchini et al. [55]
Bubble column	58.6%	0.1651	0.1945	n.a.	Bianchini et al. [55]
Venturi scrubber	60.4%	0.1602	0.9073	n.a.	Bianchini et al. [55]
Combined Venturi/ Bubble column 250 mm	89.7%	0.1079	0.6990	>25	Bianchini et al. [55]
Combined Venturi/ Bubble column 360 mm	94.8%	0.1021	0.6983	>36	Bianchini et al. [55]
Packed tower	99.9%	0.0323	0.0970	14	Bianchini et al. [54]
Fabric Filters	90.0%	0/100	0.0255	25	Estimated - pressure drop 25 mbar, Eff 90%
Metallic filter	90.0%	0/100	0.0102	9.9	Schott et al. [56]

Table 5.

The relative values for the two WES options (simple and with auxiliary exchanger) are:

- η_r = 84.60% (MP) – 98.00% (HP).
- FWCr = 0.96% (MP) – 0.87% (HP)
- SEI_r = 0.0% (Best case – $HP_{(s)}$) – 0.27% (LP $_{(w.e.)}$).
- ΔP_r = 1.03% ($WES_{(s)}$) – 9.28% ($WES_{(w.e.)}$)

These relative values indicate that the WES unit performs well compared to the existing technologies for biomass particles removal, resulting in a useful option for this application.

4. Conclusions

In this study, we present a preliminary assessment of wet electrostatic scrubbing as a particle removal technique in domestic boilers, leveraging a combination of experimental data and model-derived results. The efficacy of the Wet Electrostatic Scrubbing (WES) system is primarily constrained by water losses, a consequence of the limited cross-sectional area of the chamber. Notably, water loss significantly impacts the minimum size-dependent removal efficiency, reducing it from a potential value exceeding 95% to an average of approximately 87% under reference conditions. The numerical process efficiency experiences substantial enhancement (5–15 percent points) when operating at lower gas velocities, contributing to increased residence time and reduced water losses.

Enhancing water flow rates exhibits a limited effect on efficiency, yielding an increase from 2 to 4 percent points with an elevation of water consumption from 1 to 1.5 L/min. Moreover, elevating the scrubber height above the reference condition offers marginal advantages, with efficiency increasing by less than 2% points when transitioning from 1.5 to 2 m.

It is imperative to acknowledge that the reported WES sizing reflects the net size required for optimal removal efficiency. The actual WES size should encompass top and bottom sections, including the top height for spray and gas feeding, as well as the bottom height for gas and liquid disengagement. These extra heights are omitted here, since in practice, they derive from specific, proprietary, design concepts.

Comparative analysis of WES performance with other exhaust gas cleaning systems reveals that, while WES may not surpass high-efficiency dry filters or wet systems in removal efficiency, it demonstrates competitive performance. Despite being less efficient in water consumption than Electrostatic Precipitators (ESP), dry filters, or certain Wet Electrostatic Precipitators (WESP), WES proves advantageous in terms of energy consumption when heat exchangers and energy recovery are not considered. If WES with a heat exchanger is employed, the Specific Energy Consumption Index (SEI) is less favourable compared to dry filters, ESP, and WESP, but it remains superior to other wet techniques. Overall, WES units exhibit promising performance with high efficiency, limited water and energy consumption, and low-pressure drops, suggesting the need for further exploration of this technology.

A noteworthy strength of the WES unit lies in its ability to achieve high efficiency in reducing water-soluble pollutants, a facet not expounded upon in this paper [24,33–36]. Previous experiments indicate that a co-current WES unit can attain nearly 97% fractional equilibrium, surpassing the 87% achievable with an equivalent uncharged water scrubber at the same Liquid-to-Gas (L/G) ratio [24].

Finally, as is the case with all water-based systems such as scrubbers and WES, meticulous consideration must be given to handling washwater. The preferred choice is washwater recirculation, a method extensively experimented with during laboratory and bench tests. Further steps, including water skimming, sludge removal, dedicated wastewater equipment clarification, pH adjustment, and/or treatment for dissolved solids removal, should be considered to achieve viable washwater recirculation. Additional experimental studies are warranted to investigate this matter, drawing upon the experience gained from wet and Venturi scrubbers and WESP units as a valuable starting point for assessment.

CRediT authorship contribution statement

Arianna Parisi: Software, Data curation, Conceptualization. **Francesco Di Natale:** Writing – original draft, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

List of Symbols and Abbreviations

Symbols

c_0	Reference value for the initial particle mass concentration
C_{ci}	Particle Cunningham factor

D_j	Droplet size
D_{32}	Sauter Mean Diameter
d_{pi}	Particle size
I	Spray current
G	Gas mass flow rate
E_{Es}	Electrostatic collisional efficiency
E_{hyd}	Hydrodynamic (inertial impaction, directional collision and Brownian diffusion) collisional mechanisms, n and
E_{ph} i	Phoretic (thermophoretic, diffusiophoretic and dielectrophoretic) collisional efficiency
k_c	Coulomb constant
L	Liquid mass flow rate
$N(D_j)$	Droplet concentration in a number
q_{DJ}	Charge of each j-th droplet
qi	Charge for each droplet size d_{pi}
r	Subscript to refer to a relative value
S	Cross-sectional area of the WES
t	Gas residence time
$U_D(D_J)$	Droplet velocity
U_G	Gas velocity
u_j	Liquid jet velocity
$U_T(D_j)$	Droplet terminal velocity
y	Generic variable chosen to compare the WES unit to other particle capture technologies
y_{best}	Best value for the generic variable chosen to compare the WES unit to other particle capture technologies
y_{worst}	Worst value for the generic variable chosen to compare the WES unit to other particle capture technologies
Z	Height of the WES

Greek symbols

ΔP	Pressure drops
$\varphi(D_j)$	Droplet size distribution
$\eta(d_{pi})$	Removal efficiency for a particle of diameter d_{pi}
$\Lambda(d_{pi})$	Scavenging coefficient of the entire spray
$\Lambda_{ES}(d_{pi})$	Contribution of electrostatic forces to the scavenging coefficient
$\lambda(d_{pi})$	Scavenging coefficient of each droplet size D_j
$\psi(D_j)$	Volumetric size distribution of the spray
μ	Gas viscosity

Abbreviations

D-CSR	Droplet surface charge density
ESP	Dry electrostatic precipitator
FWC	Water requirements per unit mass of filtered particles
HP	High-performance conditions in terms of potential applied to the induction electrode
LP	Low-performance conditions in terms of potential applied to the induction electrode
MP	Mid-performance conditions in terms of potential applied to the induction electrode
PM	Particle mass
PN	Particle number
RC	Reference condition for the WES operation
s	Simple WES configuration
SEI	Energy duty per unit mass of filtered particles
VOC	Volatile Organic Compound
w.e.	WES unit with auxiliary heat exchanger
WES	Wet electrostatic scrubber
WESP	Wet electrostatic precipitator

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