COMBUSTION OFF-GAS CLEANING BY WET ELECTROSTATIC SCRUBBING: PRELIMINARY EXPERIMENTAL RESULTS

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Abstract
This paper reports preliminary experimental results on wet electrostatic scrubbing of model submicron particles in controlled hydrodynamic conditions based on the use of an electrospray exerted in dripping mode. The experimental results were successfully compared with the predictions of classical particle scavenging models.

Introduction
Submicron particles are receiving a growing attention in the past few years due to the recent toxicological and environmental studies that have demonstrated their correlation with both health [1] and climate control [2] problems. Wet electrostatic scrubbing (WES) is a valuable technique to remove particles from polluted gas streams. This process was firstly patented in the middle of 20th century [3] but received greater attention in the last couple of decades. The process entails scrubbing the particle-laden gas with electrically charged water spray. The gas stream is sometime pre-treated in order to charge the particles and modify its temperature and humidity levels [4].
The physics that governs the wet electrostatic scrubbing can be only partially deduced from the experimental works available in the pertinent literature, due to the complex electrohydrodynamics interaction between the charged particles and the spray droplets [4-6]. This lack of knowledge is far more relevant for submicron particles, for which only a few experiments are available (e.g. [5, 6]).
This paper reports the experimental results of wet electrostatic scrubbing tests of submicron particles generated by a combustion process. To minimize the side effects of spray dynamics, the tests were carried out in a controlled fluid dynamic condition by operating on lab-scale with a train of charged droplets in place of a continuous charged spray. The tests were carried out in "benchmark" conditions, i.e. ambient pressure, temperature and humidity levels. In these conditions, the classical assumptions of particle scavenging models were well suited and should allow a reliable comparison with experimental results.

Methodology
The experimental approach used in this study is based on the use of one electrospray nozzle operating in dripping mode to produce a train of droplets, with controlled size

and charge, which scrubs the gas contained in a closed vessel. The gas is entrained with particles that can be charged to a desired polarity and level by corona discharge before entering the closed chamber. The experimental rig used in this work is described in Figure 1. This consists of three main sections; i) the WES Chamber; ii) the particle generation and charging section and iii) the drops generation and charging section. The detail of each section is described in D'Addio et al. [7]

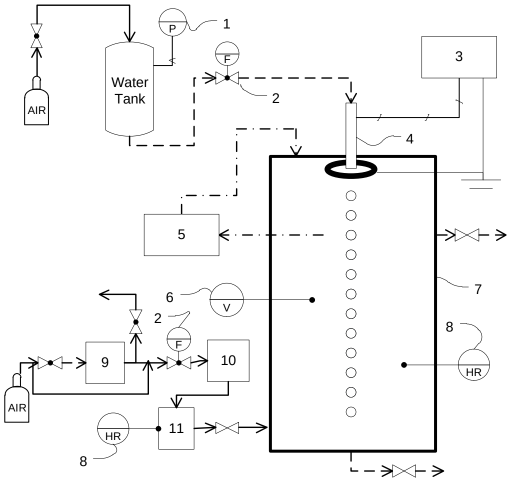

Figure 1. Layout of the experimental system for wet electrostatic scrubbing tests. 1: Digital Pressure transducer; 2: Flowmeter; 3: High voltage power supply; 4: Electrospray Nozzle; 5: LAS 3340; 6. Hot wire anemometer; 7: Wet electrostatic scrubber; 8: Hygrometer; 9: Washer for incense stick combustion; 10: Particle charging unit; 11: Quiet tube.

The wet electrostatic scrubber is the core of the experimental system. This device is designed to be operated batchwise similarly to the large scale experimental system developed by Balachandran et al. [8].
The particle-laden gas is produced by burning an incense stick placed in a modified washer using compressed air as oxidant. The combustion off-gas is diluted with air and sent through the charging unit, whose electric potential and active length are suitably adjusted at the desired level. The gas stream flows through the quiet tube and enters the scrubber, where the gas outflow valve is fully opened. The particle size distribution, pdf(d_p) and particle concentration are measured over time in the scrubber until they reach a stationary level. At this moment, the intake and the outflow valves are simultaneously closed and the electrospray is switched on. This is considered the reference time zero of the scrubbing experiment. The pdf(d_p)and particle concentrations are measured over time until the lower detection limit of the instrument is reached. In particular, the pdf(d_p) is determined in the range 90-700 nm with 50 linear bins, with 10 seconds samplings by using a Laser Aerosol Spectrometer (TSI LAS 3340).

Preliminary tests showed that particle abatement was relevant also when the electrospray is switched off. This is due to the adhesion of particles to the scrubber walls, sampling tubes and electrospray surfaces. Therefore, during scrubbing experiments, the particle abatement should be considered as the resultant of both the charged scrubbing droplet and the equipment. In the following sections, this will be referred as “baseline” abatement. Specific precautions are taken to consider this phenomenon in the experimental procedure.

Results and discussion

Experimental tests were carried out in the following conditions: gas flow rate was 2.4 m^3/h; water flow rate was 1.85 ml/min; electrospray potential was +3.70 kV; particle charging unit potential was -9.30 kV, temperature was 25°C and relative humidity was 20%. It is worth noticing that the overall test duration is 400 s, but the water spray works only for the first 200 s, while during the remaining time only the baseline contributions are effective.

Figure 2a shows the stationary pdf(d_p) of the particles in the vessel at time zero. All the particles produced by the incense stick combustion are below 500 nm. The overall number concentration of the particles, n_0, was about $2 \cdot 10^9$ particles/m^{-3}. Figure 2b describes the charge achieved by each particle of size d_p as estimated with an accuracy of 75%, according to D’Addio [7].

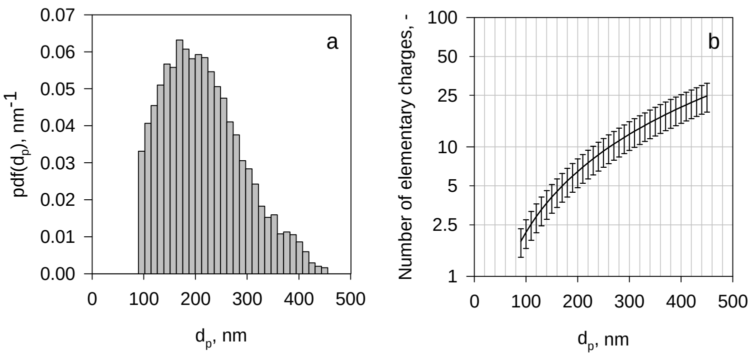

Figure 2. Particle size distribution at t = 0.

The droplets present a narrow size distribution and have a mean diameter equal to 0.9 mm. Droplet charge to mass ratio in the investigated condition was 0.21 mC/kg, equivalent to 41% of the Rayleigh limit charge.

Experimental results are reported in Figure 3, in terms of values of the dimensionless particle concentration n/n_0 versus time for two selected particle diameters. Experimental results show that the logarithm value of the ratio between actual particle concentration and the initial concentration decreases linearly with time, showing that the scrubbing rate follows a first order mechanism, according to the theoretical models (e.g. [9, 10]), so that particle scrubbing rate of particles of a given size is expressed as:

$$\frac{dn(d_p,t)}{dt} = -\Lambda\left(d_p\right)\cdot n(d_p,t)\,. \tag{1}$$

In Eq.(1) $\Lambda(d_p)$ represents the so called scavenging coefficient, which resumes all the features of single particle-droplet interactions. The value of $\Lambda(d_p)$ is the slope of the $\ln(n/n_0)$ Vs time. During the experiments, the effect of falling droplets and of the baseline can be easily distinguished: when the electrospray is switched off at 200 s, the value of $\Lambda(d_p)$ changes abruptly (i.e. passing from $4.7\cdot10^{-3}$ s^{-1} to $0.95\cdot10^{-3}$ s^{-1} for d_p = 150 nm). In particular, the slope of the $\ln(n/n_0)$ Vs time at $t > 200$ s is representative of the baseline contribution $\Lambda_b(d_p)$, while for $t < 200$ s the overall scavenging coefficient $\Lambda(d_p)$, is the sum of the scrubbing, $\Lambda_s(d_p)$, and the baseline contribution.

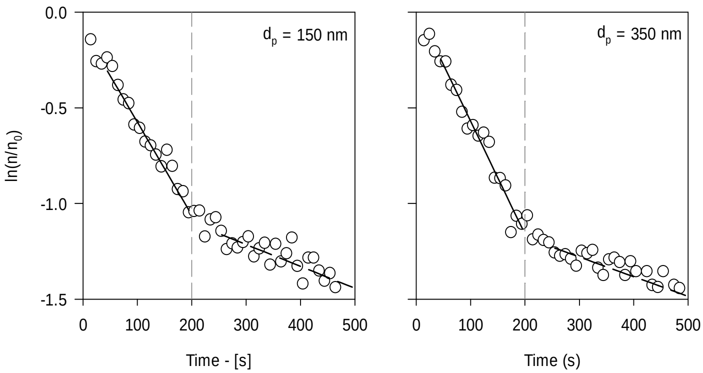

Figure 3. Dimensionless particle number concentration versus time for WES test for different particle diameters.

The scavenging coefficient due to the wet electrostatic scrubbing is reported in Figure 4 as a function of the particle diameter. In this figure, the value of the scavenging coefficient calculated from theoretical model is also shown for comparison. Error bars in theoretical model predictions reflect the uncertainties on the particle charge estimation as shown in Figure 2b and explained in D'Addio et al. [7]. Figure 4 shows that experimental results and model predictions are quite consistent. This result is important due to the limited number of comparison between experimental and modelling results for submicron particles currently available. In addition, it is worth noticing that the theoretical model shows that the scrubbing efficiency is mainly related to the electrostatic collision mechanisms, determining more than 99% of the scavenging coefficient [9]. The good matching between model predictions and experiments is even more evident by comparing the pdf(d_p) at different times (t = 30 s and 50 s), as reported in Figure 5.

Conclusion

A new experimental methodology was used to perform tests on wet electrostatic scrubbing of submicron particles generated by a combustion process. The new methodology allows studying the wet electrostatic scrubbing process while avoiding the complications deriving from the use of a spray of charged water. Experimental tests reveal that in the investigated conditions, the particle scrubbing rate can be well described by a first order model, as expected from theoretical studies. The experimental set up and procedure allow an estimation of the scavenging coefficient, a fundamental parameter of scrubbing processes.

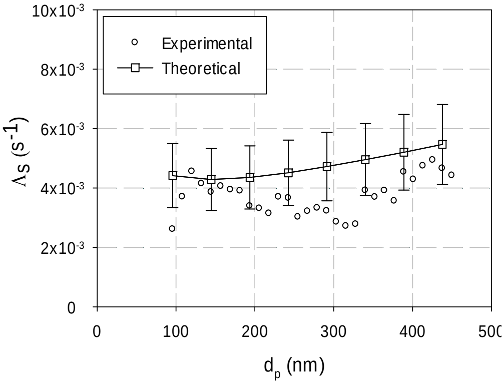

Figure 4. Theoretical and experimental scavenging coefficient for the WES test as a function of the particle diameter.

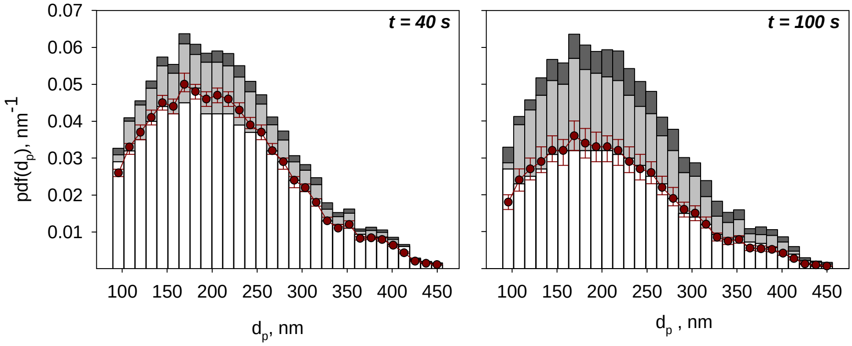

Figure 5. Modelled (red symbols) and experimental (white histogram bars) pdf(d_p) during WES test at two different times. The light and the dark grey boxes are the contribution to particle abatement due to scrubbing and baseline effects, respectively. The upper histogram level is the initial pdf(d_p).

Experimental results are in good agreement with results of well-established theoretical model available in the literature, extending its validity also to submicron particles. This model allows a good description of the values of the scavenging coefficient and an accurate reconstruction of the pdf(d_p) as a function of the scrubbing time. The theoretical model also point out that the particle abatement is mainly related to the Coulomb forces, while hydrodynamics and image-charge interactions were negligible in the investigated conditions.

Acknowledgment
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