CONDENSATIONAL GROWTH ASSISTED WET SCRUBBING FOR MODEL COMBUSTION PARTICLES REMOVAL

La Motta F.*, Di Natale F.*, Carotenuto C., Lancia A.***
francesco.dinatale@unina.it

* Department of Chemical Engineering, Materials and Industrial Production, University "Federico II" of Naples, Piazzale V. Tecchio, 80 – 80125 Naples (Italy).
**Department of Information and Industrial Engineering, Università della Campania "Luigi Vanvitelli", via Roma 29 - 81031 Aversa, Caserta (Italy).

Abstract
This paper reports experimental findings on the condensational growth of water vapor over model combustion particles. The experimental campaign was performed at lab scale with a vertical growth tube exerted in laminar conditions: a film of hot water flowed along the internal walls of the tube and comes into contact with a cold gas running counter-currently. Two types of particles were considered: carbon black particles produced by a suspension of commercial nanoparticles and the particles produced by a paraffine candle combustion. The onset of condensational growth was detected by comparing the aerosol size distribution at the growth tube exit under different operating conditions. To quantify the potential improvements of condensational growth on the particle capture, a comparison between raw and enlarged particle capture in a Venturi Scrubber was shown. The experiments clearly indicated that condensational growth pretreatment allow significant improvement of the Venturi Scrubber efficiency, more pronounced for carbon black than for paraffine soot particles.

Introduction
This paper discusses how condensational growth can be effectively used as a pretreatment to generate coarser, easier to capture, particles, starting from particles in the Greenfield gap, which are the most complex to remove from flue gases.
Recently, Huang et al. [1] and Tsai et al. [2] showed that the coupling of a Venturi Scrubber and a growth chamber pretreatment allowed reaching significant improvement for particles in the range from 50 to 500 nm, which are well beyond the capacity of conventional Venturis. These tests were performed for NaCl and SiO_2 particles [1] as well as SiH_4 particles for semiconductors industry [2]. As far as we know, there is no experimental data concerning the treatment of soot particles with a condensational growth assisted Venturi scrubber, which are expected to be more complicated to growth. To this end, we performed a set of experiments in a growth tube, a glass tube whose internal walls are wet by a falling film of hot water at controlled temperature, which encounters an upflowing stream

of cold saturated gas. Two type of model particles were considered. The first ones are commercial carbon black particles (abbreviated as CB) feed by an aerosol generator. The lasts are the particles generated by a paraffine candle flame, named PS in the following. To quantify the potential improvements of condensational growth on the particle capture, we estimate the total number removal efficiency of raw and enlarged particle capture in a model Venturi scrubber, simulated according to the Yung model [3], which is particularly suitable for these applications.

Materials and methods.

The experimental setup was similar to that implemented in former studies [4-6] and was adapted to feed either the paraffine candle combustion particles (PS) or the carbon black (CB) particles. The same works also reports deeped details on the experimental procedures.
For the PS particles (see [5]), we burned a standard paraffinic white candles (Fatigati mod. 23945) in a combustion chamber having volume of about 9 L and operated with constant gas flow rate of 20 L/h. ULPA filtered air from the laboratory room (RH=50%; T=20°C; P=1atm) was used. The candle was burned in “sooting regime” [7-8], with the flame moving laterally thanks to the velocity field in the combustion chamber. Under this regime, soot particles are mainly composed by elemental carbon and their size distribution appeared either bimodal or trimodal with a peak in the nanometric range (<100 nm) and the others in the accumulation mode range (100-2000 nm). The particles in the accumulation range are superhydrophobic and superoleophilic [7-8] aggregates of elemental carbon (EC) [8] formed in a zone of the flame where the oxygen is insufficient [7]. The excess gas leaving the combustion chamber was purged in the open air through a hood, while the desired flow rate was kept in the rig and mixed with the by-pass air.
The CB test aerosol was produced with a commercial aerosol generator (TOPAS ATM 221) equipped with a Laskin nozzle, and fed with a carbon black (CB) suspension [4]. The generated aerosol passed through a diffusion dryer to remove the liquid water and produce a dry aerosol.
For both the PS and the CB particle laden gas, the gas streams passed through a water bubble saturator kept at 25°C, to achieve saturation humidity levels. The humid, particle-laden at desired flow rate and temperature, finally entered the growth tube where heterogeneous condensation took place over the particles.
This consisted in a glass cylinder with a length of 40 cm and an internal diameter of 1.5 cm. The tube size was designed by taking in account the diffusion rate of vapour from the cylinder walls to tube centreline and the need of minimizing the interferences between the gas and the liquid flows [6]. The liquid was fed to a bowl placed at the top of the cylinder and was filled up to the brim until a water film fell along the internal wall of the tube. The water was collected in a flask placed at the bottom of the cylinder. A gear pump guaranteed a uniform water circulation with a flow rate of 60 mL/min.

The film temperature and the gas velocity controlled the gas supersaturation level. In the growth tube, vapour condensation occurred until the temperature of the gas was lower than that one of the liquid film. To this aim, the liquid film was kept at a desired temperature, using a thermostatic bath and liquid temperature at the bottom of the growth tube was measured. The gas flow, monitored with a flowmeter, entered the growth tube from the bottom flask, so that the water and the gas were in counter-current flow. The liquid fed to the growth tube was distilled water (pH=6.5-6.7; conductivity 0.04-20 µS/cm).
In this work, the gas flow rate was kept constant at 48 L/h, corresponding to about 160 mm/s of gas velocity in the column, while the water temperature of the growth tube was fixed at 60°C.
Aerosol diagnostic methods include the measure of both cumulative and probability density distribution functions of the aerosol size and total aerosol concentration. Different units were used to tests the particles before the growth tube and the liquid-solid particles leaving the growth tube. In fact, while the aerosol entering the growth tube are only composed by solid particles (mostly below 500 nm), those leaving the growth tube include solid particles, water droplets and liquid-solid aerosol that can be larger than 2000 nm [6].
In particular, to investigate the size distribution of the raw PS and CB particles we performed tests with a TSI SMPS 3910 equipped with 1:100 diluters and a thermodenuder PALAS KHG10. This unit was also used to estimate the overall particle removal in the growth tube. To measure the aerosol size distribution at the growth tube exit and to have a better resolution of the PS and BC particles in the accumulation mode range, we selected the TSI LAS 3340 Laser Aerosol spectrometer operated with 50 bin logarithmically spaced in the range 90-2000 nm. This unit measures the intensity of light scattering and correlate it to the aerosol size using algorithms that require knowledge of the aerosol refractive index. In this device, the calibration was performed with traceable polystyrene latex (PSL) particles. Specific corrections should be adopted while using other materials [5] as well as to account for the presence of combustion particles enclosed in a shell of liquid water [5]. It is expected that the LAS 3340 overestimated the size of soot particles and underestimate that of water droplets, but in this work we did not apply any correction to its measurements. This is indeed a conservative measure both for particle enlargement and Venturi scrubber efficiency estimations.

Results and discussions

Figure 2 shows the aerosol size distribution of the PS and the CB at the inlet of growth tube as measured by the SMPS TSI 3910.

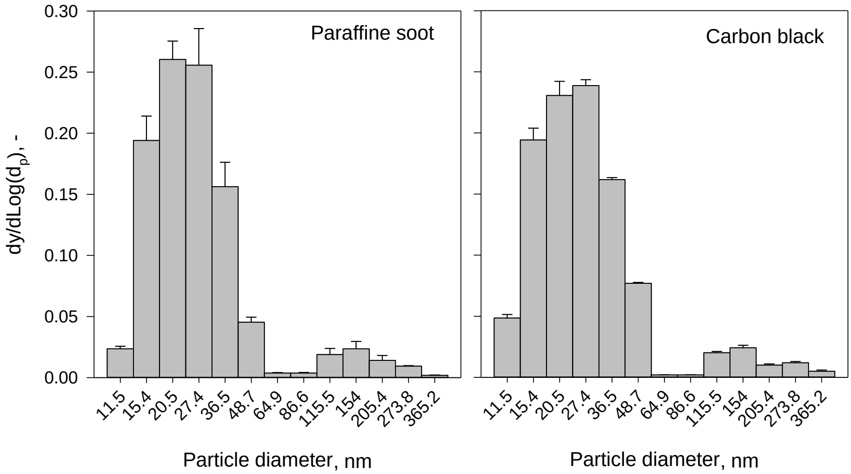

Figure 2. Aerosol Size Distribution (ASD) at inlet of growth tube of Paraffine soot and Carbon Black measured by the SMPS TSI 3910.

The particle size distributions of the PS particles had a bimodal distribution with one peak between 20 and 30 nm and another at about 150 nm. The CB particles had a primary distribution at nanometric scale ranging from 10 to 60 nm with a peak at 25 nm and a fraction of particles in the accumulation mode characterized by a peak at roughly 150 nm. The same measures, performed with the LAS TSI 3340 (data not shown) confirmed the presence of the second mode of the distribution in the accumulation size range and provided a peak at 143 nm for the paraffine soot and 110 nm for carbon black. The cumulative aerosol size distribution of the PS and CB, as measured by the TSI 3340, are show in Figure 3. This figure indicates that the 5th and 95th percentile of the accumulation mode particles were both around 90 nm and 265 nm (250 and 284 nm) for PS and CB.
Figure 4 compares the cumulative aerosol size distribution of PS and CB particles before and after the growth tube. Experiments showed that PS grew more than CB particles. Indeed, while the 50th percentiles of the enlarged particles are 240 nm and 270 nm for the PS and the CB respectively, the 95th percentiles are 520 nm and 391 nm. However, it is worth noticing a marked shift of the 5th percentile of the CB particles that passed from 90 to 145 nm against the 110 nm of the PS particles.
It is also worth mentioning that for both tests, the particles count detected by the LAS TSI 3340 at the exit of the growth tube are larger than entering the unit. The difference was, respectively, 71% for the PS and 40% for the CB. This indicated that part of the particles finer than 100 nm are enlarged as well and enter the accumulation mode range covered by the LAS 3340. On the other hand, the TSI 3910 reveal that the overall number of particles leaving the growth tube (including those finer than 100 nm) is about 31% less than those at the entrance. Besides, it was shown that the particle removal efficiency of the growth tube is almost

uniformly distributed over all the particles size and vary between 25 and 40%.
In conclusion, the passage through the growth tube provide a depletion of particles of all the sizes and the enlargement of particles not limited to those larger than 100 nm but also to those of finer size. The differences between PS and CB particles morphology led to a different condensational growth dynamics.

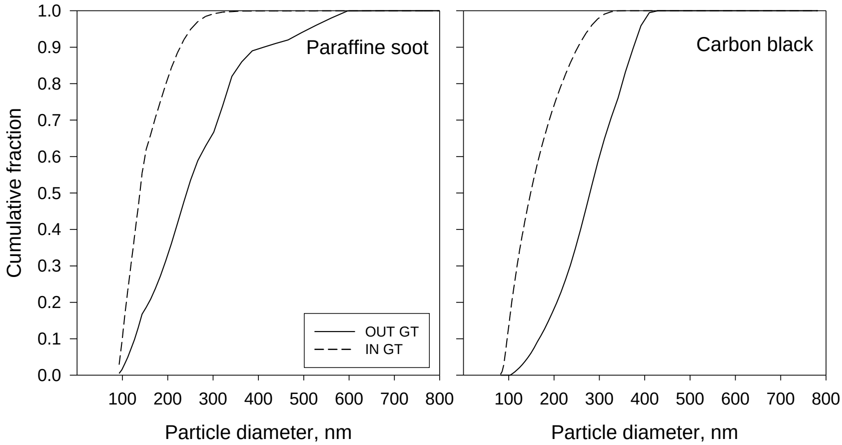

Figure 4. Cumulative aerosol size distribution of paraffine soot and carbon black before and after the growth tube.

Finally the Yung et al. [3] model was adopted to estimate the particle removal efficiency in a Venturi Scrubber operated with a gas-to-liquid velocity of 70 and 100 m/s and a throat length of 5 and 10 cm. The liquid to gas ratio was 1 L/m^3.

Table 1. Effect of the condensational growth on the total number removal efficiency of a Venturi scrubber operated with Liquid-to-gas ratio=1 L/m^3 and with different throat velocity and length.

Throat velocity, m/s	Throat length, cm	Paraffine soot		Carbon black	
		IN	OUT GT	IN	OUT GT
70	5	30%	53%	48%	82%
70	5	33%	57%	52%	86%
100	10	66%	84%	79%	96%
100	10	70%	86%	82%	97%

The model results were resumed in Table 1, which indicated a marked shift in the removal efficiency of particles pre-treated with the condensational growth. Unpredictably, these efficiencies were far more evident for the less grown CB particles than for the PS ones. However, the particle removal efficiency of a Venturi is mostly affected by the penetration of finer particles, and the observed results can be explained in light of the marked shift of the 5th percentile of the aerosol size distribution of the CB particles. It is worth noticing, however, that the larger tendency to enlargement shown by the PS particles, also testified by the marked increase in particles number at the exit of the growth tube, suggests the development of specific experiments to estimate the actual performances of a growth tube-Venturi scrubber sequence.

Conclusion

Results on the condensational growth of two model combustion particles (paraffine candle emission, PS and carbon black, CB) showed that both of them are effectively enlarged after 12 s exposure to a liquid film at 60°C in the growth tube. This condition corresponds to a water supersaturation field having a mean as low as 1.03 and a 95th percentile of 1.115 [5]. The particle enlargement was higher for PS, but for CB a larger shift of the particle size distribution is observed for the lower diameters. Condensational growth led to an effective improvement of the particle capture in a model Venturi scrubber, reducing up to six time the concentration of particles the skip the scrubbing capture. The assumption made for particle diagnostics suggest considering this a potentially conservative estimation.

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