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Research article

Condensational growth assisted Venturi scrubber for soot particles emissions control

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ABSTRACT

This paper aims to evaluate how condensational growth may be used to improve the performances of a Venturi scrubber in removing soot particles, which are among the most relevant air pollutants emitted in industrial and power plants exhaust gases. Former studies on this system, called Condensational Growth assisted Venturi scrubbers (CGVS), suggested that the most relevant step to address their efficiency is the assessment of the amount of water that condense on the soot particles, which determines the actual aerosol size distribution entering the Venturi. Unfortunately, a definite physical mathematical model to predict the actual condensational growth of an ensemble of non-spherical particles is not yet available and experimental investigation is better suited to assess this point. This study reports experimental data on the size distribution achieved by exposing model soot particles to a water supersaturated gas for different residence times. The obtained size distributions are used to estimate the efficiency of a Venturi scrubber in removing the water-soot aerosols, allowing a comparison with the removal of parent soot particles. The experiments were carried out at lab scale by using a laminar-flow growth tube, a simple device to perform a controlled condensational growth. The experiments indicated that, even for a hydrophobic material as soot, condensational growth is effective even at supersaturation levels as low as 1.02. Liquid-solid aerosols from nearly 2 to > 3 times larger than the parent particles are produced with a supersaturation level lower than 1.15. Finally, the analysis of experimental data indicated that the fraction of particles subjected to condensational growth is relevant. Indeed, calling as ψ the fraction of particles that become larger than the 98% percentile of the original particle size distribution, we found that ψ can be as high as 78%. The analysis of data indicated that an appreciable linear correlation exits among ψ and the 95th percentile of the supersaturation level, S_{95}, while not being dependent on the exposure time. The experimental evidences suggest that the adsorption of water molecules over the soot surface overcome the effects of hydrophobicity and of line tension effects, favouring condensation of water over the soot surface and leading to a higher nucleation rate even at low supersaturation.

Application of the Venturi scrubber model to the water-soot aerosol leaving the growth tube indicate that the CGVS may remove particles with an efficiency far higher than that achieved by the stand alone Venturi.

For a given Venturi's throat length and velocity and a given liquid-to-gas ratio, the CGVS efficiency depends almost linearly on ψ and, in turns on S_{95}.

Experimental and model results suggested that the CGVS can be a valuable and effective device to capture soot particles and that condensational growth can be used as a retrofit method for existing units.

1. Introduction

Condensational growth, also known as heterogeneous condensation, is a natural phenomenon involved in the formation of clouds [1–4], which is also used in particles diagnostic as a mean to enlarge nanometric particles and count them optically [5–11].

Condensational growth is also contemplated as a way to generate a liquid-solid aerosol easier to treat by conventional techniques [12–17] rather than the parent solid particles. Recently Niklas et al. [18] presented a new membrane-based process to improve separation efficiency of airborne particles by condensational growth of water vapour, which showed promising experimental results.

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In industrial flue gas cleaning processes, the condensational growth is expected to take place in some sections of conventional desulphurization scrubbers due to the large liquid flow rate and the temperature gradients inside the scrubber. The process was so effective that several authors [12,16,19–26] proposed the use of condensation scrubbers to remove fine particles and especially those belonging to the Greenfield gap (100–2000 nm), for which the conventional depuration techniques have the minimum capture efficiency.

The condensational growth process generates a stream of liquid-solid aerosols together with some entrained water droplets. Therefore, we think that the condensational growth can be better couples with wet processes as Impactors [27,28], Venturi scrubbers [29], Wet Electrostatic Scrubbers [13,30–35] Wet Electrostatic Precipitators [36–38] rather than fabric filters or Electrostatic precipitators [39]. Recently, our group successfully applied condensational growth to enhance the removal of ultrafine polystyrene particles in bubble columns [40], obtaining improvement of the total particle removal from 20 to 95%.

Venturi scrubbing is one of the processes that can benefit more for a condensational growth pre-treatment. This process, in fact, has removal efficiencies that swiftly increase with particle size [41–44] and, provided for the appreciable pressure drop, can also remove particles as fine as 100 nm [29]. Several models were developed in the past to estimate the particle removal efficiency in a Venturi scrubber. Most of them were tested on particles coarser than 500 nm, but some of them were used to predict the capture of finer particles, even as fine as 50 nm [41,43,44]. Apart from the physical properties of the gas, the liquid and the particles, the particle removal efficiency of a Venturi scrubber mainly depends on the value of liquid-to-gas dosage, throat length, L_t, and gas velocity inside it, v_t.

In particular, the model of Yung et al. [42] was successfully tested and recommended by several authors in the past [41,43,45] to effectively estimate the particle removal efficiency in a Venturi scrubber. In this paper we followed the Yung et al. [42] model as presented by Huang et al. [43]. The particle removal efficiency was calculated as:

$$\ln(1-\eta(d_p)) = \frac{B}{K_{p0}(1-u_{d1})+0.7}\cdot \left[4K_{p0}(1-u_{d1})^{1.5}+4.2(1-u_{d1})^{0.5} - 5.02K_{p0}^{\;0.5}\left(1-u_{d1}+\frac{0.7}{K_{p0}}\right)\tan^{-1}\left(\frac{(1-u_{d1})K_{p0}}{0.7}\right)^{0.5}\right] + -\frac{1}{0.7+K_{p0}}\cdot\left[4K_{p0}+4.2-5.02K_{p0}^{\;0.5}\left(1+\frac{0.7}{K_{p0}}\right)\cdot\tan^{-1}\left(\frac{K_{p0}}{0.7}\right)^{0.5}\right] \quad (1)$$

where:

$$B = \frac{L\cdot\rho_L}{G\cdot\rho_G\cdot C_{D0}} \quad (2)$$

$$K_{p0} = \frac{\rho_p C_c d_p^2 v_t}{9\mu D} \quad (3)$$

$$u_{d1} = 2[1-x^2+\sqrt{x^4-x^2}] \quad (4)$$

$$x = 1+\frac{3L_t C_{D0}\rho_G}{16D\rho_L} \quad (5)$$

$$D = \frac{4.22\cdot 10^{-2}+5.77\cdot 10^{-3}\cdot\left(\frac{1000L}{G}\right)^{1.922}}{v_t^{1.602}} \quad (6)$$

In these equations L and G are the water and the gas flow rate, ρ_G, ρ_L and ρ_P are the densities of gas, liquid and particles, L_t is the throat length, v_t is the relative particles-drop velocities inside the Venturi throat, μ is the gas viscosity and D is the Sauter mean droplet diameter, as estimated by Boll et al. [46] and later successfully applied by Alonso et al. [47] in operating conditions similar to those adopted therein. Besides, C_{D0} is the droplets drag coefficient [48] at the throat entrance and C_C is the particles Cunningham correction factor [49]. Fig. 1 shows the application of the Yung et al. [42] model for an air stream at 25 °C and 1 atm containing spherical particles having the same density of water (about 1000 kg/m^3) scrubbed with water at 25 °C. Other operating conditions include: throat velocity of 70 m/s; L/G ratio of 2 L/m^3; throat length of 100 mm. The figure shows that particles removal efficiencies higher than 90% can be achieved only if the particle size is higher than 450 nm while the Venturi cut diameter, $d_{50,VS}$, for which the removal efficiency is 50%, is around 220 nm.

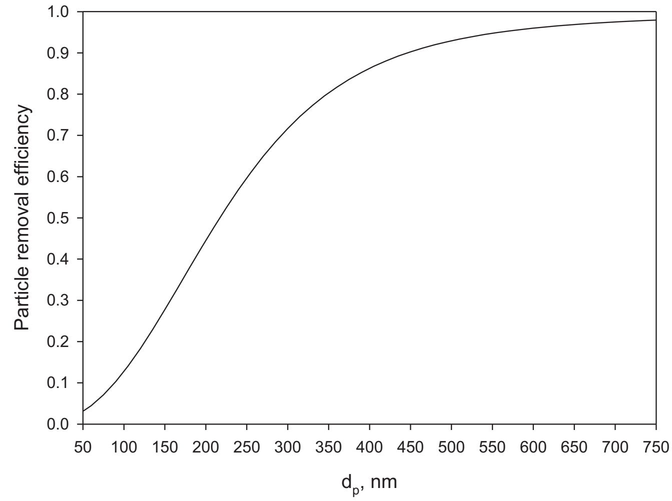

Fig. 1. Particle removal efficiency as a function of particle diameter for particles of density 1000 kg/m^3 as predicted by the Yung et al. model [42] with $L/G = 2$ L/m^3, throat length of 100 mm and throat velocity of 70 m/s.

Recently, Huang et al. [43] and Tsai et al. [44] showed that the coupling of Venturi scrubbers and a growth chamber operated with a supersaturation level up to 2.9 allowed reaching significant improvement for particles in the range from 50 to 500 nm. The removal of these particles is well beyond the capacity of conventional Venturis. These tests were performed on NaCl and SiO_2 particles [43] and SiH_4 particles for semiconductors industry [44]. However, this experimental setup is not able to provide a reliable correlation between supersaturation levels, treatment time and aerosol growth.

As far as we know, there is no experimental data concerning the treatment of submicron carbonaceous particles with a CGVS. These particles are among the most critical pollutants both for its toxicity and for the number of exposed people, with severe effects on the quality of life [50] especially in densely polluted areas, as for large cities or, for example, the Italian region of Pianura Padana, which have some of the highest concentrations of $PM_{2.5}$ particle concentration in the atmosphere of Europe. The macroscopic physical chemical properties of carbonaceous particles classify them as strongly hydrophobic, i.e. not prone to be covered by a liquid water embryo. However, hydrophobicity is not the only property to consider at nanoscale, as shown by a series of experiments suggesting that condensational growth may take place at supersaturation levels well below expectations (e.g. [51–59]) thanks to the onset of adsorption phenomena.

In view of the good understanding on the Venturi scrubber modelling, the focus of this study was given to the condensational growth of soot particles, with the aim of establishing feasible and minimal operating conditions to achieve an appreciable improvement of the removal efficiency of the subsequent Venturi scrubber.

Experiments were performed over soot particles produced by combustion of paraffin candles, which contain high molecular weight condensed phase waxes. Candle flames are used as model soot sources because they produce appreciable amounts of hydrophobic particles in