Effect of Operational Parameters in the Droplet Size of a Venturi Scrubber With Multi-Orifice Injection

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Abstract: The Venturi scrubber is used for removing particulate matter from gaseous effluents and finds a large application in industry. The size of the droplet is of fundamental importance to the performance of the equipment. This work aims at studying the effect of some design parameters, namely liquid flow rate and liquid injection system in the droplet size and to correlate this with collection efficiency. A laser diffraction technique was used in order to measure droplet size in situ in a rectangular Venturi scrubber, with liquid injected through 1mm diameter orifices on the throat walls. Liquid flow rates of 600 and 900 cm³/min and number of orifices varying from 1 to 5 were used in the experiments. The throat gas velocity was kept at 69.3 m/s. It was found that all these variables significantly affected droplet size. The results of droplet size were compared with the particle capture (collection) efficiency measured in the same experimental conditions. It was observed that the collection efficiency was affected by the liquid atomizing conditions and by the droplet distribution in the Venturi throat.

Introduction

Scrubbers are gas cleaning devices that utilize liquid, in the form of droplets, to collect the particles. Among the many different scrubber types, the Venturi scrubber is the most efficient, although it also has the highest operational cost. Thus, it is very important to design properly these devices, aiming at maintaining the high efficiency at the minimal possible cost.

The collection efficiency of Venturi scrubbers depend on many variables, such as the droplet size, the size of the particles to be collected, the gas velocity, the liquid flow rate and the liquid injection system. The purpose of this paper is to study the influence of liquid flow rate and the number of liquid injection orifices on the collection efficiency of a Venturi scrubber.

The removal of particles in a Venturi scrubber

Particles are removed from gases in a Venturi scrubber by atomizing a liquid in the gas stream in the constricted region of the duct (referred to as throat), as seen in Figure 1. The liquid droplets act as particle collectors which incorporate the solid particles by inertial impaction. The particle laden droplets, normally one order of magnitude higher in size when compared to the solid particles, are then easily removed from the gas stream in a cyclone situated downstream. The classical correlation utilized in the prediction of the removal efficiency of a Venturi scrubber is due to Calvert et al. [1] and can be written as:

\[
E = 1 - \exp \left( \frac{2Q_L \nu_G \rho_L D}{55Q_G \mu_G} F(\psi) \right); \quad F(\psi) = \left[ -0.7 - 0.5\psi + 1.4\ln \left( \frac{0.5\psi + 0.7}{0.7} \right) + \left( \frac{0.49}{0.7 + 0.5\psi} \right) \right]
\] (1)
where $Q_L$ and $\rho_L$ are the liquid flow rate and density; $Q_G$, $v_G$ and $\mu_G$ are the gas flow rate, velocity and viscosity, respectively; $D$ is the droplet size; and $\psi$ is the inertial impaction parameter given by:

$$\psi = \frac{\rho_p d_p^2 v_G C}{18 \mu_G D}$$  \hspace{1cm} (2)

where $\rho_p$ and $d_p$ are the particle density and diameter, and $C$ the Cunningham slip factor.

**Figure 1 - Schematic representation of a Venturi scrubber**

It is apparent from equations 1 and 2 that the correct estimate of the droplet diameter is essential for the reliability of the scrubber performance. Two empirical correlations are often utilized: the one proposed by Nukiyama and Tanasawa [2], equation 3, and the one proposed by Boll et al. [3], equation 4. Both are expressed in SI units.

$$D = \frac{0.585}{v_G} \sqrt{\frac{\sigma}{\rho_L}} + 1.683 \times 10^{-3} \left( \frac{\mu_L}{\sqrt{\sigma \rho_L}} \right)^{0.45} \left( \frac{1000 Q_L}{Q_G} \right)^{1.5}$$  \hspace{1cm} (3)

$$D = \frac{4.22 \times 10^{-2} + 5.77 \times 10^{-3} \left(1000 Q_L/Q_G\right)^{0.932}}{v_G^{1.602}}$$  \hspace{1cm} (4)

where $\mu_L$ and $\sigma$ are the liquid viscosity and surface tension, respectively.

Nukiyama and Tanasawa expression was derived from experiments with a liquid jet transversally fed in a free gas stream. Boll et al. measured the droplets inside a Venturi. Both expressions are widely utilized, and no pre-eminence of any of them is clear to date. The Boll et al. correlation predicts droplet diameters somewhat smaller than Nukiyama and Tanasawa’s.

Another important feature regarding the scrubber performance is the jet atomization. It is well known (see [4]) that a liquid jet, when entering the throat, describes an inclined trajectory and generates a relatively small amount of droplets. After some penetration, the liquid jet ‘bursts-out’ completely, and forms a droplet cloud that flows parallel to the duct walls, as shown in Figure 2a. The ideal condition for the scrubber is when this ‘bursting’ occurs in the central region of the throat cross-section, as can be seen in Figure 2b. An expression utilized for calculating the jet penetration till bursting was proposed by Viswanathan et al. [5] and is given by:

$$\frac{1^{**}}{D_{or}} = 0.1145 \frac{\rho_L v_J}{\rho_G v_G}$$  \hspace{1cm} (5)

where $1^{**}$ is the jet penetration, $D_{or}$ is the orifice diameter and $v_J$ is the jet velocity.

This work presents *in situ* measurements of the droplets and particle collection efficiency, with different injection configurations, and compares them with the predicted droplet size (equations 3 and 4) and collection efficiency (equation 1).
Experimental procedures

All tests were performed in a rectangular Venturi scrubber, with a throat of 35mm by 24mm of cross sectional area and 65mm in length. The liquid was injected through 1mm orifices situated in the throat wall. The number of orifices could be varied between 1 and 5, and the general view of their disposition is shown in Figure 3.

<table>
<thead>
<tr>
<th>Total number of active orifices</th>
<th>Location (see figure)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>1, 2, 3 — config 1</td>
</tr>
<tr>
<td>5</td>
<td>1, 4, 5 — config 2</td>
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Figure 3– Schematic view of the throat and injection orifices.

The gas velocity in the throat was kept constant in all tests in 69.3 m/s. Two liquid flow rates were tested: 600 and 900 cm³/min (1.0×10⁻⁵ and 1.5×10⁻⁵ m³/s).

The droplet size (Sauter Mean Diameter) was measured in situ utilizing a Spray Tech® Aerosol Analyzer, a non-intrusive laser diffraction technique in which a naked laser beam crosses the Venturi throat. The diffracted beam angle, which is inversely proportional to the droplet size, is captured and analyzed, and the droplet size distribution is calculated.

The collection efficiency was measured by collecting (with a cyclone), filtrating and weighing the particles in the liquid after the scrubber. Once the inlet particle concentration was known, a mass balance provided the percentage of particles removed by the droplets.

A more detailed description of the experimental procedure can be found elsewhere [6,7].

Results and discussion

The measured values of the Sauter Mean Diameter in the throat of the Venturi scrubber for the different experimental conditions utilized are reported in Figures 4 and 5, where the predictions of two extensively used correlations are included for comparison purposes. Although the values predicted by Boll [3] and Nukiyama and Tanasawa [2] differ widely one from another,
both correlation predict only a slight influence of liquid charging on drop sizes. This trend, also found experimentally by Teixeira et al. [8] and Fernandez Alonso et al. [9], was generally confirmed in the present study (Figures 4a and 4b) with an important exception to this rule shown in Figure 4c. With one orifice, the jet velocity for the highest liquid flow rate ($1.5 \times 10^{-5}$ m) was 19m/s and the jet penetrated excessively (about 70% of the distance to the opposite wall as shown in Figure 6). Under these conditions, one can expect that the larger drops formed during the jet’s atomization would travel towards the opposite wall, with a majority of small drops remaining in the center of the flow, where the laser beam performed the measurements.

The measured drop sizes were sensitive to the number as well as position of the injection orifices. For example, with 3 orifices, the second configuration produced drop sizes approximately 7% smaller than those for the first configuration. With 5 orifices the sizes were still smaller (about 13% to 16% in comparison to the first configuration with 3 orifices). None of the available correlations to predict drop sizes in Venturi scrubber account for variables such as number, size and position of the injection orifices. The results reported here suggest that these variables are important and that therefore new correlations for drop sizes should be sought.

The actual drop size values reported here are higher than both those predicted by Nukiyama and Tanasawa (average 20% higher) and Boll (average 73% higher).

Figure 5 (a) to (c) report experimental results of overall collection efficiency for the several operational conditions utilized in this study, as functions of both liquid charging and number of injection orifices. For comparison purposes, the values of efficiency predicted by the classical Calvert model [1] were also included in the Figure. As that model utilizes drop sizes when calculating the efficiency, Figures 5(a) to 5(c) present three model results, each using a different value for the drop sizes, namely the sizes actually measured and those predicted by Boll and Nukiyama and Tanasawa.

Figures 5(a) to 5(c) also show that the model of Calvert performed poorly. Using the model with the actual drop sizes produced the worst results, while using the same model with the drop sizes calculated according to Boll yielded the best agreement, with an average of 10% of the measured value. Overall collection efficiency increased with liquid charging in all situations, although not as much as predicted by the model of Calvert. This was expected: an increase in the liquid flow rate means usually (but not necessarily) that more drops will be available for dust collection.

For the same liquid charging, the efficiency was very sensitive to the number and position of injection orifices used, as clearly seen in Figure 6. These variables are actually responsible for jet velocity, jet penetration and liquid throat coverage. For instance, with three injection orifices, configuration 2 led to an efficiency 6 to 8% higher than configuration 1. These results allow us to conclude that the injection system needs to be designed properly, and that the methods for predicting liquid throat coverage as a function of the number, position and diameter of the injection orifices would permit the designer to optimize liquid usage in Venturi scrubbers, that is, to maintain the desired efficiency with the minimum total liquid charging.

**Conclusions**

Both total liquid charge and the number and position of the liquid injection orifices in a Venturi Scrubber affect drop sizes and collection efficiencies. Increasing the liquid charge for a same injection system led to an increase in the collection efficiency. For the same liquid charge and jet velocities, a better throat liquid coverage also increased the efficiency. The available correlations cannot account for differences in the liquid injection system. New design methods that would allow more effective liquid usage in Venturi scrubbers are needed.
Figure 4- Comparison of the experimental droplet diameters with those estimated by Nukiyama and Tanasawa (NT) and by Boll et al. (Boll): (a) 1 orifice; (b) 3 orifices; (c) 5 orifices.

Figure 5- Comparison of the experimental collection efficiency with those estimated utilizing the droplet diameter calculated by Nukiyama and Tanasawa (NT) and by Boll et al. (Boll): (a) 1 orifice; (b) 3 orifices; (c) 5 orifices.
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**References**