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DROPLET DISPERSION ANGLE MEASUREMENTS ON A PEASE-ANTONY VENTURI SCRUBBER

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Abstract - A Pease-Anthony Venturi scrubber is a gas cleaning device that uses liquid, injected in the equipment as jets, to remove contaminants from the gas. The liquid jet is atomized into droplets, which are dispersed throughout the equipment due to the turbulence. The performance of the scrubber is affected by the spatial distribution of the droplets. Although CFD models have been used to predict the droplet dispersion, these models are expensive. Alternatively, the concept of "jet spreading angle" could be used as a simple and quick way to estimate droplet dispersion. The purpose of this paper is to measure the spreading angle of jets transversally injected into the throat of a Venturi scrubber and correlate it with both gas and jet velocities. The throat gas velocities varied between 59 and 74 m/s and the jet velocity between 3.18 and 19.1 m/s. The angles were measured through image analysis, obtained with high velocity photography. The spreading angle was found to be strongly dependent on jet velocity.

Keywords: Jet spreading angle; Venturi scrubber; Photographic images; Droplet dispersion; Jet penetration.

INTRODUCTION

Gas cleaning is an important operation in many industries, such as metallurgic, paper and cellulose, acids and alkalis, natural gas, insecticides, fertilizers, pigments, cement and others. This operation has many objectives, such as reduction of pollutant emissions, recovery of valuable products, purification of the gas and protection of downstream equipment.

A Venturi gas scrubber can have a circular or rectangular transversal section and is constituted of three different parts: converging section, throat and diverging section. The dust laden gas enters the Venturi scrubber through the converging section. It is accelerated due to the narrowing of the duct, flows at high velocity in the throat and suffers deceleration in the diverging section. The injected liquid is rapidly atomized by the high gas velocity, first being disintegrated into thin filaments and then into a large number of droplets of varied sizes. The droplets formed by the atomization of the liquid are responsible for collecting the particles, mainly through the inertial impacting mechanism.

The performance of a Venturi scrubber depends on the size (Fernández Alonso *et al*., 2001; Costa *et al*., 2003) and spatial distribution of the droplets in its interior. A poor distribution, characterized by the presence of high and low droplet concentration regions, allows the passage of many contaminants without hitting the droplets, decreasing considerably the efficiency of the equipment (Costa, 2002; Gonçalves *et al*., 2003b; Guerra *et al*., 2009). Since a major part of the operational expenses of a Venturi scrubber is associated with the usage of the liquid, more detailed studies on the distribution of droplets in the equipment, due to the characteristics of the injection system utilized, the mechanisms of atomization and the turbulence of the jets and the gas should generate knowledge by which it is possible to design a scrubber optimizing the distribution of droplets, maximizing the efficiency and minimizing

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*To whom correspondence should be addressed the usage of liquid. Such studies may result in a cost lowering of the gas washing technology and better control of industrial pollutant emission to the atmosphere (Costa, 2002; Gonçalves *et al*., 2003b).

Several models based on computational fluid dynamics are available to calculate droplet dispersion in Venturi scrubbers with a transversal injection (Taheri and Sheih, 1975; Fathikalajahi *et al*., 1995; Fathikalajahi *et al*., 1996; Viswanathan *et al*., 2005; Gonçalves *et al*., 2003a). Yoon (2005) used a Lagrangian simulation to study the dispersion and size distribution of droplets emerging from a jet that is parallel to the gas stream. However, those models are expensive and difficult to use by the design engineer. If it were possible to correlate a jet "spreading angle" parameter with gas and liquid properties and velocities and injection orifice diameter, then this parameter could be used as a cheap and quick method to design the spacing between the injection orifices.

It is not simple to give a rigorous definition of a liquid jet "spreading angle", for two main reasons. Firstly, the jet boundary is not sharply defined. While it is possible to delineate, through image analysis, a region in space where most of the droplets are located, a few droplets disperse very quickly, occupying positions far away from the higher droplet concentration region. Thus, a definition of jet spreading angle that would take into account all droplets may actually be useless. Secondly, the higher droplet concentration region that could be used to define a spray cone actually has curved boundaries, owing to the effects of air interaction with the spray. Although difficult to define rigorously, the simplified approximation of a liquid jet as a liquid dispersing in space in the form of a cone, with a single cone angle, has proved to be very useful in engineering (Lefebvre, 1989). Different ways to define and measure such a cone have been used. Lefebvre (1989), Ohrn *et al*. (1991) and Chen and Lefebvre (1994) defined the cone angle as the angle formed by two straight lines drawn from the discharge orifice that cut the spray contours at some specified distance from the atomizer face. Ruiz and Chigier (1991), using image analysis, defined the spray boundary as the line where the optical density reaches its peak gradient.

Abramovich (1963), Yokota and Matsuoka (1977) and Reitz and Bracco (1979) developed equations to express spray angle. In those works, the spray angle was correlated with liquid and gas flow rates, injection pressure, nozzle dimensions and the relevant air and liquid properties. The dimensionless numbers used are the Reynolds and Weber numbers, based on liquid flow rate and properties, and the injection orifice diameter. Direct application of those correlations to Venturi scrubbers is impaired because they were obtained for jets in quiescent air or jets parallel to the air stream. In Venturi scrubbers, the jets are usually transversal to the air stream.

Viswanathan *et al*. (1983) applied the concepts of jet penetration, jet maximum centerline penetration and jet atomization point to describe the liquid jet dynamics in Venturi scrubbers. These concepts are simplified models of reality in the sense that, strictly speaking, a jet does not have a single atomization point or a centerline. Nonetheless, these ideas proved to be very useful in Venturi scrubbers modeling and design (Fathikalajahi *et al*., 1995; Gonçalves *et al*., 2003a). By using these concepts, a designer is able to optimize the total area covered by liquid injection. This area is proportional to the number of injection orifices and the square of the diameter of the orifices ($A_{\text{orifices}} \propto N_{\text{orifices}} \times D^2_{\text{orifice}}$). At present, however, there is no simple method to optimize either of these quantities. The ability to predict the jet spreading angle (as a function of orifice diameter, among other quantities) could be used to design the distance between two consecutive injection orifices. Thus, the combination of Viswanathan's jet penetration correlation with the jet spreading angle correlation advocated in this paper should provide a complete design procedure. Although more robust and realistic design methods based on CFD are available, the simple method proposed here has the advantage of being quick and cheap, and can, at the minimum, provide a good starting point for CFD analysis.

The purpose of this paper is to measure the spreading angle of a jet transversally injected into a high velocity gas stream and to correlate it with both gas and jet velocities and properties. Images of the atomization process of liquid jets under different operational conditions were used for the measurements.

METHODS AND MATERIALS

A Venturi scrubber of rectangular geometry positioned horizontally was used, as shown in Fig. 1. The scrubber was mounted with independent sections to facilitate geometric modifications. The height of all pieces was 0.040 m and the inlet and outlet width was 0.075 m. The parts were built in acrylic, except for the special test section of the throat utilized for photography, which had a front wall made of glass with all the others painted black to facilitate image contrast. The dimensions of the transversal section of the throat were 0.040 x 0.027 m (Fig. 2). The throat contained three injection orifices, but only the orifice opposite to the glass front wall was used in the experiments. The orifice length to diameter ratio was fixed with a value of 2. The injection of liquid was carried out by a type MS helicoidal pump and the water flow rate was measured by a rotameter. The air flow was generated by a model Cr-8 radial blower.

The throat gas velocities (V_g) utilized were 59, 64, 69 and 74 m/s. The jet velocities (V_j) were 6.37, 9.59, 12.73, 15.98 and 19.10 m/s. In total, 20 different operational conditions were used. For each condition, two still pictures were taken for angle measurement purposes. The average of the two values obtained was accepted as the final result. The difference between Replicate I and Replicate II was very small in all cases.

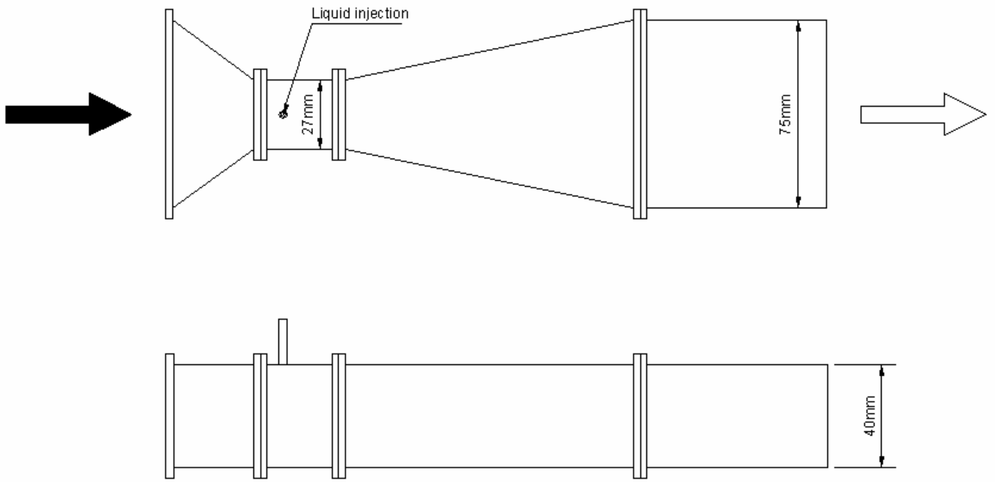


Figure 1: Scheme of the Venturi scrubber utilized in the present experiment.

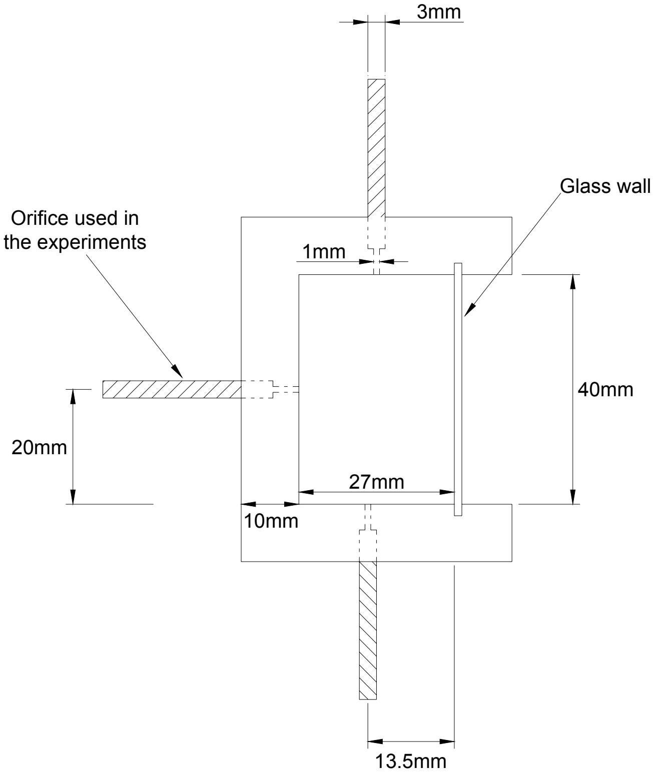


Figure 2: Frontal scheme of the throat and configuration for the injection of the liquid.

To obtain photographic images of the jet in the atomization process, the throat was illuminated with an electronic flash circuit using 100 white leds (approximately 10,000 candela), which was put on its top part (Fig. 3) and maintained triggered for a time period of 6.0μs±0.1μs, which was synchronized with a Sony model DCR-DVD 403 digital camcorder with a resolution of 3 megapixel and shutter velocity of 250μs±5μs. Details of the electronic flash can be found in Puentes *et al*. (2010). The camcorder was placed as close to the glass wall as possible. The distance between the camcorder and the center of the channel was 2 cm.

The images obtained were analyzed with the software AutoCAD 2006. The liquid spreading angle (θ) was determined using the definition and technique proposed by Ruiz and Chigier (1991). The spray boundary was considered to be represented by the two straight lines (one on each side) where the optical density reaches its peak gradient. These lines are usually not difficult to identify in photographs, although they are wavy. The lines were drawn, dividing the jet into two regions, one with high droplet concentration between the lines and another with a low droplet concentration outside the lines. Having drawn the lines, the spreading angle was measured.

The main source of angle measurement errors using the procedure delineated above is the subjective observation of the transition between the high and low concentration regions, which overshadows other possible error sources (for instance, due to optical aberrations). Three other subjects were asked to estimate the angles on randomly chosen photographs and a maximum error of 2.5 degrees due to human bias was estimated.

RESULTS AND DISCUSSION

In Fig. 4(a) and 4(b) the jet velocity was kept constant while the gas velocity was varied. Comparing the images 4(a) and 4(b), a nearly equal spreading angle is observed, suggesting that the gas velocity was not the main parameter affecting the angle. Fig. 5 shows the spreading angles of the jet maintaining the gas velocity constant and varying the jet velocity. The comparison between Fig. 5(a) and 5(b) demonstrates a greater spreading angle (θ) for a greater jet velocity (V_j). This result is in agreement with Varde *et al*. (1984), who found that, for small orifice length to diameter ratios, such as the one used in this work, the cone angle increased with increasing jet velocity. These findings can also be seen in the plot of the spreading angle as a function of the jet velocity for varying gas velocities shown in Fig. 6.

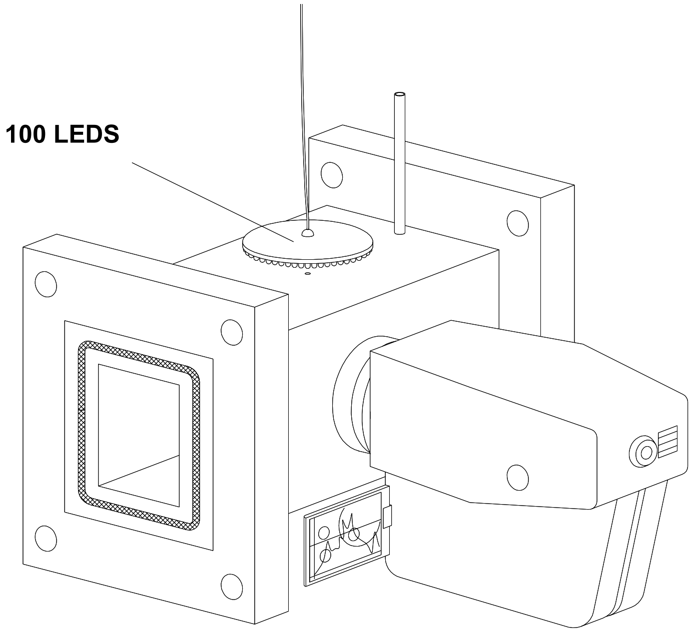
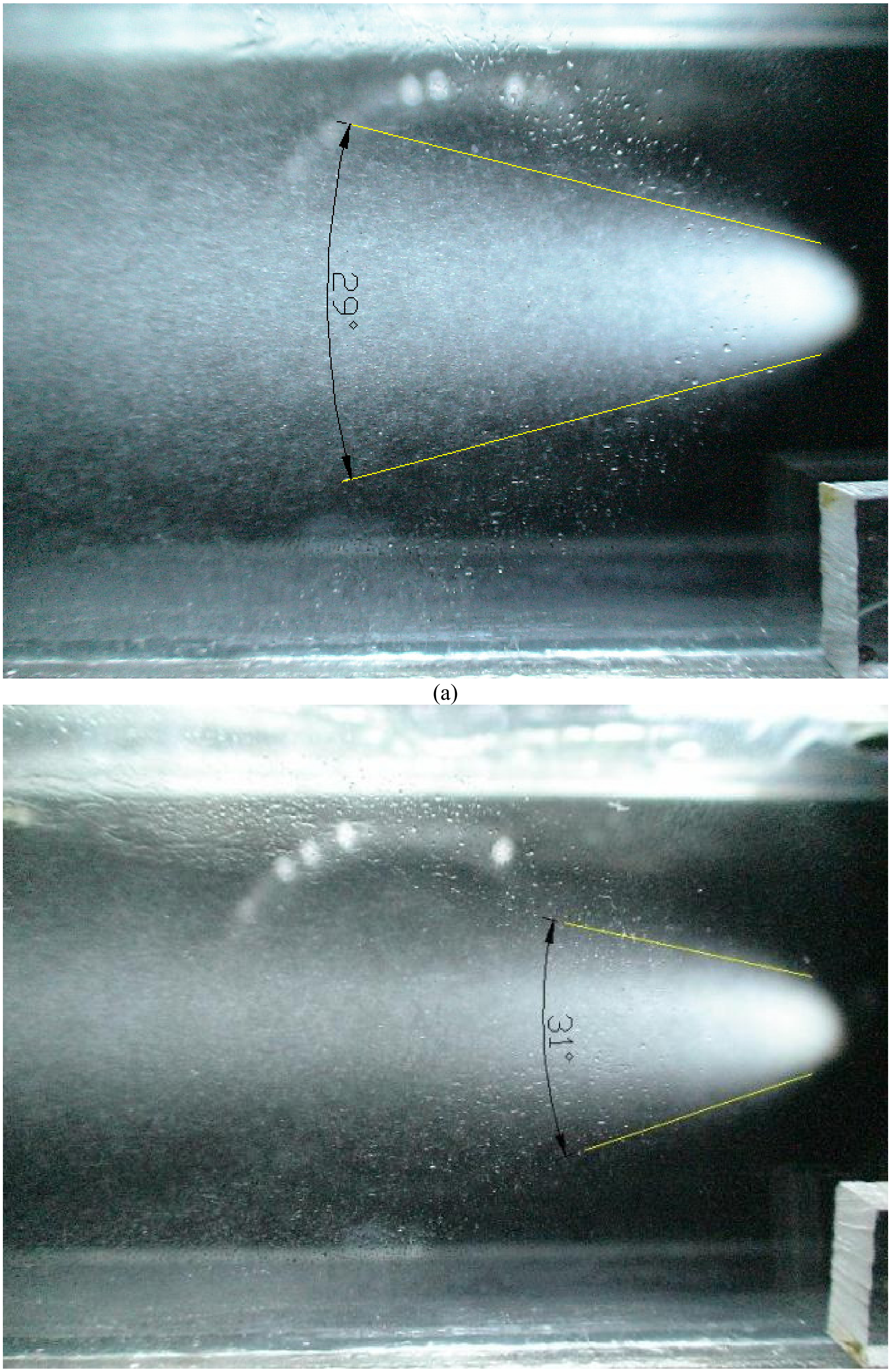


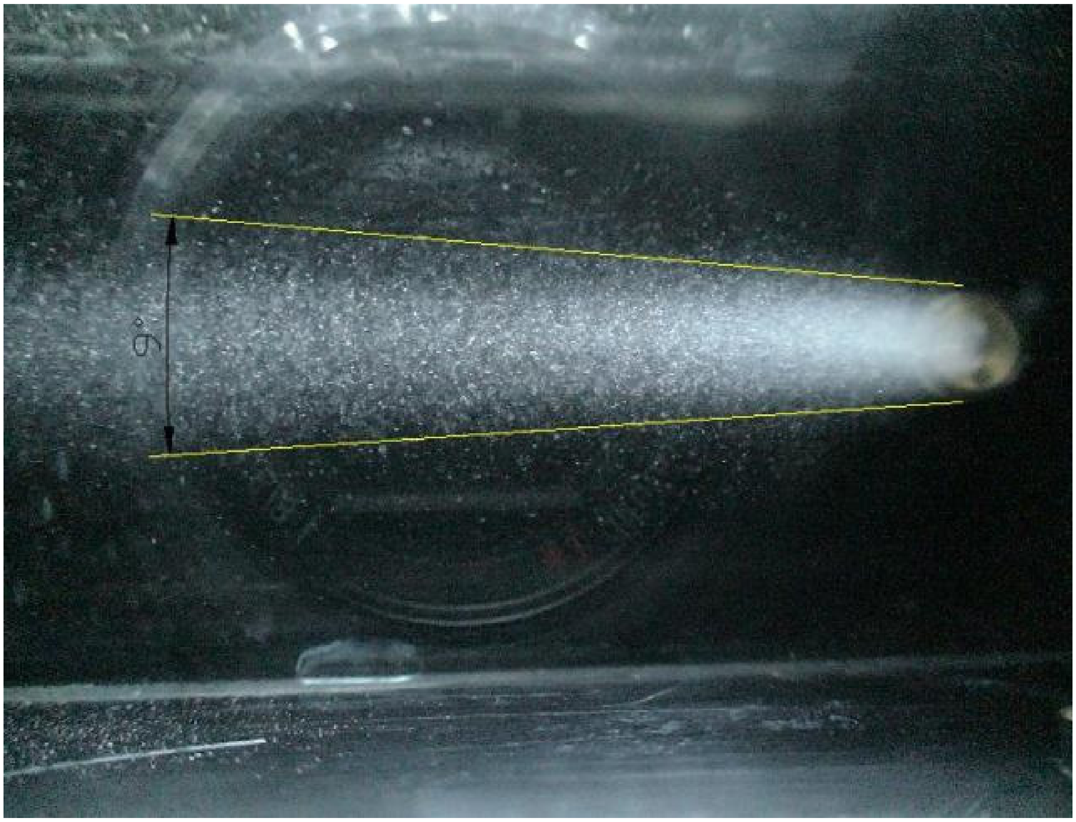
Figure 3: Camcorder and LED illumination positions with respect to the throat.



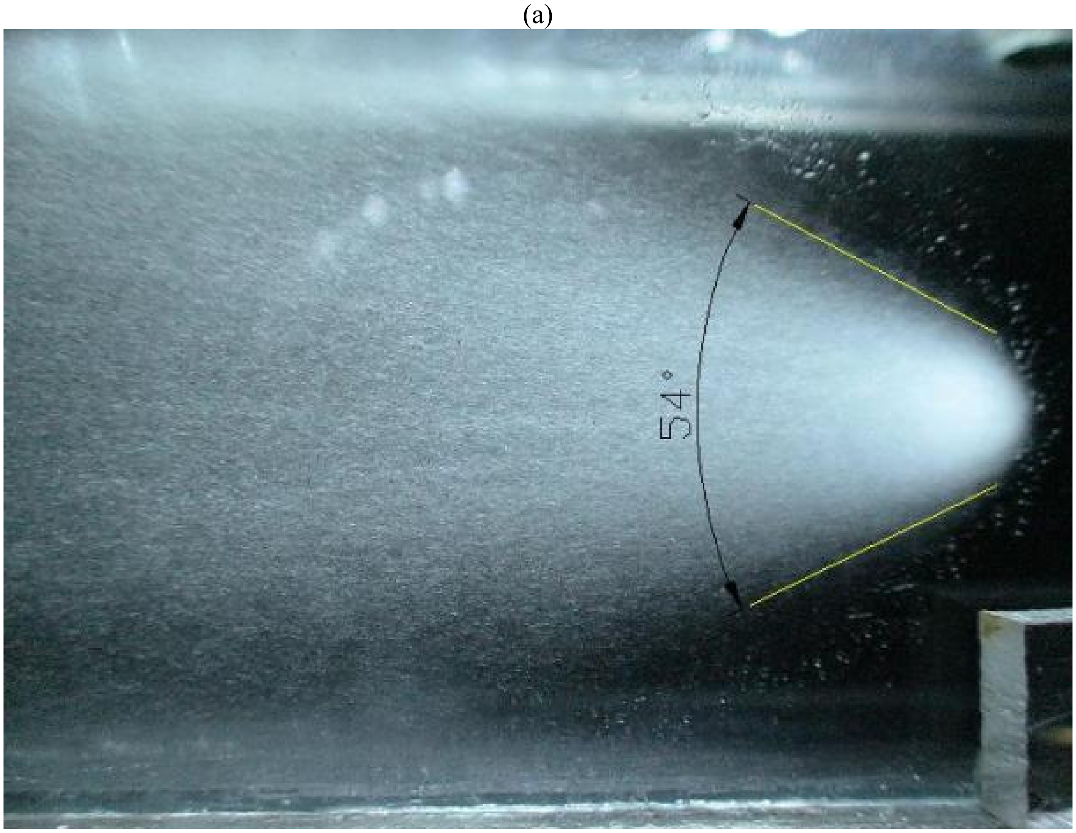
(a)

(b)

Figure 4: Images of the jets, V_j=12.73m/s and (a) V_g=59m/s; (b) V_g=74m/s.



(a)



(b)

Figure 5: Images of the jets, V_g=59m/s and (a) V_j=6.37m/s, (b) V_j=19.10m/s.

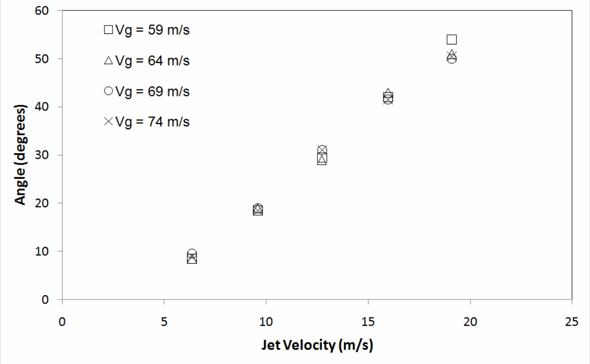


Figure 6: Experimental results of the spreading angle obtained for each one of the process conditions.

It is clear from Fig. 6 that a correlation to predict the spreading angle should be a strong function of liquid flux, increasing with jet velocity. In terms of dimensionless numbers, the ratio between the Reynolds and Weber numbers, both based on the liquid velocities and properties, when raised to a negative power, can provide the observed dependence of the angle with the liquid flux. Moreover, this ratio has been used in other equations for predicting spray cone angle (Reitz and Bracco, 1979; Yokota and Matsuoka, 1977). On the other hand, no clear trend can be perceived in Fig. 6 for the dependence of the spreading angle with the gas velocity, as the different angle values measured in this work for different gas velocities are within the experimental error. We found that Equation (1) correlates the date successfully, as shown in Fig. 7, where the predicted values are plotted against the experimental values. In the proposed correlation, both constants were obtained by least square fitting.

$$\theta = 370\left(\frac{\mathrm{Re}_L}{\mathrm{We}_L}\right)^{-1.47} \tag{1}$$

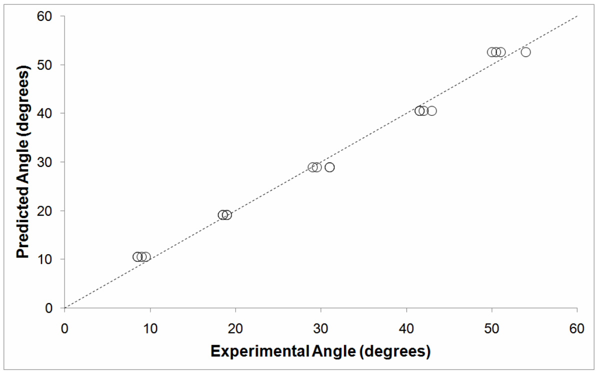


Figure 7: Performance of the proposed correlation (Equation (1)).

In the range of orifice length to orifice diameter used in this work, the proposed correlation is best compared to the correlation of Yokota and Matsuoka (1977). Apart from the gas and liquid properties, the main variable in the Reynolds to Weber number ratio is the liquid velocity. The proposed correlation suggests that the spreading angle is dependent on the liquid velocity raised to the power 1.47, whereas in the just mentioned correlation, which was obtained at quiescent high ambient air pressure, the liquid velocity is raised to the power 0.64. This result indicates that the influence of jet velocity is higher for jets that are typical of Venturi scrubbers, that is, transversal to a high velocity gas stream.

CONCLUSIONS

From the study of the photographic images of the transversal liquid jet in the process of atomization in the throat of the Venturi scrubber in the range of geometrical and operational conditions used in this study (V_g between 59 and 74 m/s; V_j between 6.37 and 19.10 m/s; orifice diameter equal to 1 mm, orifice length to diameter ratio equal to 2), it can be concluded:

- The gas velocity had little or no influence on the jet spreading angle;
- The jet spreading angle is a strong function of the jet velocity;
- The jet spreading angle increased with increasing jet velocity;
- The jet spreading angle was found to be proportional to the ratio of the Reynolds to the Weber number (both based on liquid properties and velocity) raised to the power of -1.47. The proportionality constant that best fitted the data was 370.

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NOMENCLATURE

$A_{orifices}$	Total area of orifices	m^2
$D_{orifice}$	Orifice diameter	m
$N_{orifices}$	Number of orifices	--
Re_L	Reynolds number $(= \rho_L V_j D_{orifice} / \mu_L)$	--
V_j	jet velocity	m/s
V_g	gas velocity	m/s
We_L	Weber number $(= \rho_L V_j^2 D_{orifice} / \sigma)$	--
μ_L	liquid viscosity	kg/(m.s)
θ	jet spreading angle	degrees
ρ_L	liquid density	kg/m^3
σ	surface tension	N/m

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