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Experimental investigation on the effect of liquid injection by multiple orifices in the formation of droplets in a Venturi scrubber

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ABSTRACT

Venturi scrubbers are widely utilized in gas cleaning. The cleansing elements in these scrubbers are droplets formed from the atomization of a liquid into a dust-laden gas. In industrial scrubbers, this liquid is injected through several orifices so that the cloud of droplets can be evenly distributed throughout the duct. The interaction between droplets when injected through many orifices, where opposite clouds of atomized liquid can reach each other, is to be expected. This work presents experimental measurements of droplet size measured *in situ* and the evidence of cloud interaction within a Venturi scrubber operating with multi-orifice jet injection. The influence of gas velocity, liquid flow rate and droplet size variation in the axial position after the point of the injection of the liquid were also evaluated for the different injection configurations. The experimental results showed that an increase in the liquid flow rate generated greater interaction between jets. The number of orifices had a significant influence on droplet size. In general, the increase in the velocity of the liquid jet and in the gas velocity favored the atomization process by reducing the size of the droplets.

1. Introduction

Scrubbers are gas-cleaning devices that utilize liquid, in the form of droplets, to collect particles and/or absorb gases. Among the many different scrubber types, the Venturi scrubber is one of the most efficient. On the other hand, this device has relatively high-energy consumption, most of it spent in the atomization process. Thus, it is very important to design properly these devices, aiming at maintaining the high efficiency at the minimal possible cost.

This type of scrubber has three distinct parts: convergence section, throat and diffuser, as shown in Fig. 1. The air flow through the throat is a high velocity forced flow and then decelerates in the diffuser section. The liquid, usually injected into the throat of the Venturi scrubber, is atomized by the high velocity air flow to form a cloud of droplets. These droplets, dispersed in the dust-laden gas, act as particle collectors. Particle collection in the Venturi scrubber is the result of simultaneous collection mechanisms: inertial impaction, direct interception and diffusion. The contribution of each mechanism depends on the diameter of the particle, the size of the droplet and their relative velocities. Existing correlations for the prediction of particle collection in a Venturi scrubber involve other phenomena such as liquid to gas ratio (L/G), penetration of liquid jet, droplet distribution throughout the throat, liquid film fraction, throat length, droplet size and the geometric configuration of the scrubber [1–4].

Droplet size is an important parameter that affects the performance of a Venturi scrubber. However, existing experimental data about this parameter in Venturi scrubbers is scarce [4–11]. Aside from this, existing studies do not take into consideration possible interaction between the droplets formed from the distribution jets. The practical implications of multiple jet injection includes the superimposition of the clouds of droplets generated by each jet, resulting in the increase in coalescence and in the liquid film on the walls, phenomena that may reduce the equipment performance.

Therefore, the objective of the present experimental investigation was to measure the effect that multiple jet liquid injection has on the formation and distribution of droplets in a Venturi scrubber for the different liquid injection configurations, with gas velocity and liquid flow rates as parameters. The evolution of the droplet size along the axis of the Venturi scrubber was also studied.

2. Theory

2.1. Studies of jet atomization in airstreams

The liquid for cleaning gas in a scrubber is generally introduced through small orifices located in the throat. When the liquid passes through the small orifices, it first assumes the form of a jet that is transversal to the air stream. This jet becomes curved due to the drag force as can be observed in Fig. 2.

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Nomenclature

D_{or}	diameter of orifice (m)
D_{32}	Sauter mean diameter (m)
G	volumetric gas flow rate (m^3/s)
ℓ^*	liquid jet penetration (m)
ℓ^{**}	liquid jet central penetration (m)
L	volumetric liquid flow rate (m^3/s)
L/G	ratio between liquid and gas flow rate ($m^3/1000\,m^3$)
N_{or}	number of orifices for liquid injection
$V_{d,inj}$	droplet velocity at injection point (m/s)
V_g	gas velocity (m/s)
$V_{g,inj}$	gas velocity at injection point (m/s)
V_j	jet velocity (m/s)
x	distance between injection point of liquid and measurement point of droplet

Greek symbols

μ_l	liquid viscosity (kg/(m s))
ρ_l	liquid density (kg/m^3)
ρ_g	gas density (kg/m^3)
σ	surface tension (N/m)

Initially, the jet is a continuous body of liquid. However, atomization occurs rapidly and forms a great number of small droplets. The formed droplets are originally located in the proximity of the jet trajectory and then are dragged and dispersed by turbulent diffusion [12].

The droplets formed by jet atomization are responsible for the collection of existing contaminants in the gas stream. The jet contributes minimally to collection of particles in Venturi scrubbers because its surface area is small compared to the surface area of an equal volume of liquid in the form of droplets. The efficiency of a scrubber is affected by the characteristics of the droplets formed, such as size, quantity, relative velocity and spatial distribution. On the other hand, these characteristics are determined in part by jet characteristics such as velocity, diameter, trajectory, penetration of the air stream and atomization mechanisms. Particularly, jet penetration is one of the most important factors in the determination of the spatial distribution of the droplets. Jets with insufficient or excessive penetration can cover a throat inadequately and diminish the efficiency of collection [13].

Jet penetration is defined as the minimum transversal distance that the liquid jet penetrates into a gas stream before its complete atomization [1]. In 1983, Viswanathan et al. [14] proposed a very simple semi-empirical model to calculate the atomization point of each individual jet. In accordance with this model, the jet can be characterized by two important distances: jet penetration (ℓ^*) and maximum penetration of the central line of the jet (ℓ^{**}), as can be seen in Fig. 2. The authors arrived at the following expressions for jets:

$$\frac{\ell*}{D_{or}} = 0.075\frac{\rho_l V_j}{\rho_g V_g} \tag{1}$$

$$\frac{\ell**}{D_{or}} = 0.1145\frac{\rho_l V_j}{\rho_g V_g} \tag{2}$$

where the jet velocity is given by:

$$V_j = \frac{4L}{\pi D_{or}^2 N_{or}} \tag{3}$$

Gonçalves et al. [13] developed a numeric resolution model that differs from the model by Viswanathan et al. [14] principally because it does not consider the hypothesis of a single point of atomization.

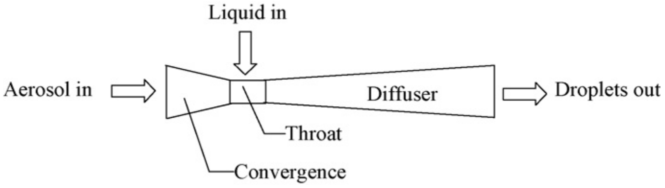

Fig. 1. Scheme of a typical Venturi scrubber.

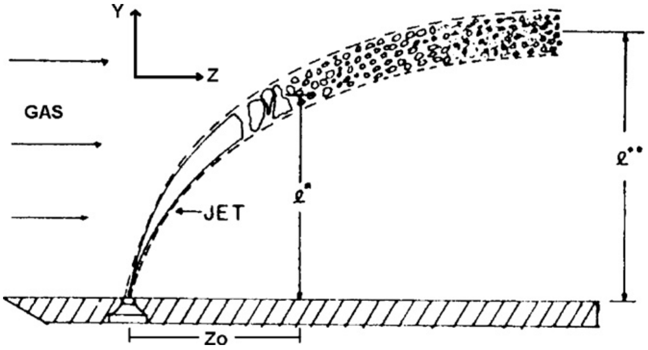

Fig. 2. Trajectory and penetration of a transversal jet according to Viswanathan et al. [14].

The process of atomization is not only of interest in relation to scrubbers. Some research studies about the process of atomization also take into account its application in combustion devices. Wu et al. [15] carried out a study of the rupture of a liquid jet transversal to air stream with injection from a flat orifice. The authors divided the region of rupture into: a column region with large droplets and a spray region. This rupture process of a liquid jet is presented in Fig. 3. The larger droplets are formed in the fracture region at the point of the jet column depicted in Fig. 3. Subsequently these droplets break into small droplets. Simultaneously, small droplets may be formed directly on the surface of the jet. Thus, the rupture of the liquid jet could occur due to the surface jet rupture mechanism and the mechanism for the column rupture.

Research studies by Fuller et al. [16] and Costa et al. [17] took into account the effect of the injection angle of the liquid and the effect of jet turbulence in the atomization process. Fuller et al. [16] observed that decrease of the injection angle resulted in a reduction of the aerodynamic forces acting on the liquid column.

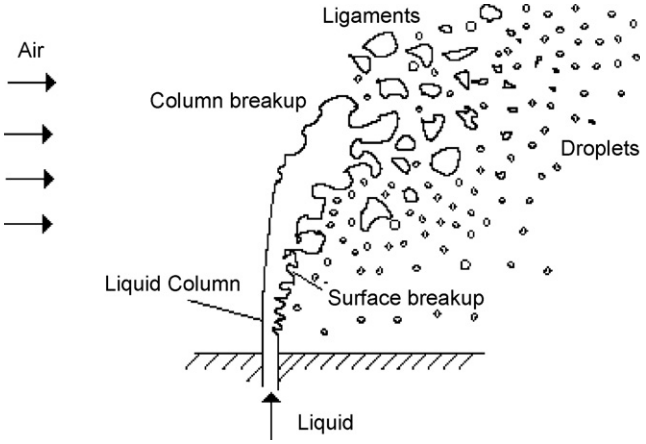

Fig. 3. Rupture process of a liquid jet by air in crossflow according to Wu et al. [15].

2.2. Studies on droplet size in the process of atomization

The size of droplets is one of the most important parameters that affect performance and is therefore essential for reliable modeling of a Venturi scrubber [7,18]. Among the studies on droplet size, two are notable due to the fact that the proposed empirical correlations for droplet size are widely utilized in project equations and efficiency estimation of Venturi scrubbers. These classical studies were now conducted by Nukiyama and Tanasawa [19] in pneumatic atomizers and Boll et al. [5] in a Venturi scrubber.

The study on the distribution of droplet size carried out by Nukiyama and Tanasawa [19] in pneumatic atomizers is most frequently applied to Venturi scrubbers. The authors investigated droplets formed from a liquid jet injected parallel to a high velocity air stream. The air velocity and L/G ratio were varied. The correlation proposed by Nukiyama and Tanasawa [19] to estimate Sauter droplet diameter is:

$$D_{32} = \frac{0.585}{V_{\mathrm{g,inj}} - V_{\mathrm{d,inj}}}\sqrt{\frac{\sigma}{\rho_{\mathrm{l}}}} + 1.683 \times 10^{-3}\left(\frac{\mu_{\mathrm{l}}}{\sqrt{\sigma\rho_{\mathrm{l}}}}\right)^{0.5}\left(\frac{\mathrm{L}}{\mathrm{G}}\right)^{1.5} \qquad (4)$$

In 1974, Boll et al. [5] measured the size of droplets in Venturi scrubbers on a large scale Venturi in order to compare results with the values obtained by the correlation by Nukiyama and Tanasawa [19], which were developed under atypical operating conditions for scrubbers. The authors proposed an empirical correlation for the Sauter mean diameter measured under the experimental conditions employed in their study:

$$D_{32} = \frac{4.22 \times 10^{-2} + 5.77 \times 10^{-3}(\mathrm{L/G})^{1.922}}{V_{\mathrm{g,inj}}^{1.602}} \qquad (5)$$

In 1995, Kihm et al. [20] measured the size of droplets that originated from the atomization of a jet in an air stream. The authors proposed that the Sauter mean diameter is inversely proportional to the velocity of the liquid jet.

In 1998, Wu et al. [21] also studied the droplets formed by the atomization of a single liquid jet that was injected into a stream of air. The authors verified that the mean diameters diminished with the increase of air velocity and the increase in jet velocity.

3. Materials and methods

3.1. Experimental apparatus

The Venturi scrubber utilized in this work was mounted horizontally, had a rectangular geometry with the transversal throat dimensions of 0.040 m × 0.027 m. Water was injected through 0.001 m diameter orifices, located at the beginning of the throat. The injection of the liquid was made by an MS Type Helicoid Pump and the water flow rate was measured by a rotameter. The air stream was generated by a CR-8 model radial blower.

To make visualization of the flow in throat possible, a 0.14-m glass front was used on the throat. The lateral wall was given a black background to improve the contrast of the jet of water. The images were made utilizing a Sony DCR-DVD 403 video camera with a resolution of three mega pixels. To capture the images, the video camera was positioned very close to the glass wall of the throat. The throat was well illuminated by a 1000 W reflector located about 40 cm from the glass wall.

A Malvern Spraytech® equipment was used to study the size of the droplets. When a laser ray hits a droplet, part of the luminous energy is reflected, part is diffracted and part is absorbed. The diffraction angle is inversely proportional to the size of the droplet, thus making it possible to obtain the size distribution of droplets in a spray by measuring the diffraction angle.

To create and analyze the diffraction, the Malvern Spraytech® utilizes a system originally developed by Swithenbank et al. [22]. In this equipment, a 3 mW Helio-Neon laser generator produces laser light at a wavelength of 632.8 nm. The beam of light is expanded by a lens and passes through the spray where a part of the light energy is diffracted at various angles that depend on the size distribution of the droplets in the spray. Several characteristic diameters can be measured by the equipment, including the Sauter diameter, represented by D_{32}.

One of the problems associated with optical methods is gaining access to the interior flow when its characteristics cannot be altered. Fig. 4 shows the section of tests used to get around this difficulty.

3.2. Experimental conditions

In the tests performed, the velocity of gas in the throat was kept at 59, 64, 69 and 74 m/s, the liquid jets were introduced into the equipment at flow rates ranging from 0.5×10^{-5} to 2×10^{-5} m^3/s, with the liquid to gas ratio, L/G, kept between 0.07 and 0.3 m^3/1000 m^3. The size of the droplets was measured at three axial positions, x, after the injection of the liquid: 0.12, 0.18 and 0.24 m. Fig. 5 shows a diagram of the scrubber set-up utilized for varying the axial distance x for droplet size measurement. The axial positions were varied by adding different lengths of throat between the injection of the liquid and the test section. As can be seen in Fig. 5, test section 1 represents the shortest throat length (x = 0.06 m), and test section 2 represents the longest throat length (x = 0.12 m). Test section 3 permits optical access to the inside of the equipment. The laser beam that measured the size of the droplet passed through the center of the optical access piece.

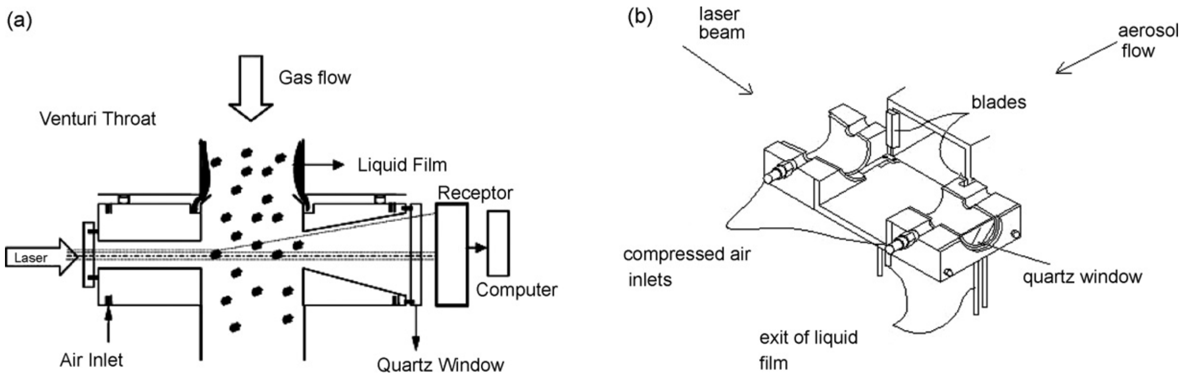

Fig. 4. Test section used to access the Venturi throat optically: (a) schematic view and (b) details of the section.

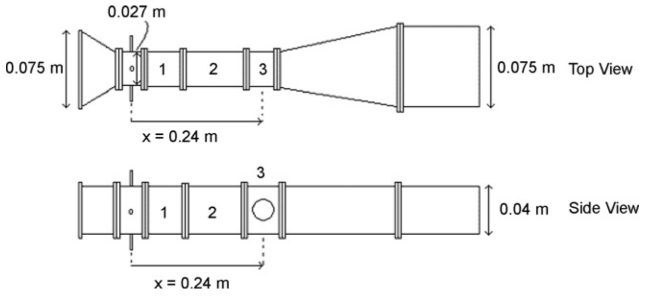

Fig. 5. Scheme of the scrubber with the extended throat ($x = 0.24$ m). The removal of sections 1 and 2 allows for $x = 0.18$ and 0.12 m, respectively.

The number of orifices for liquid injection varied from 1 to 4. The liquid injection points can be seen in Fig. 6 and Table 1 lists the combination of injection points tested.

The total liquid flow rate injected into the equipment varied from 0.5×10^{-5} to 2×10^{-5} m^3/s, depending on the configuration of the liquid injection. The feeding of liquid to the orifices was individually controlled so that the flow rate in *each* orifice could be measured.

The jet images were made by varying the liquid flow rate, the velocity of the gas in the throat and the number of orifices for liquid injection. The 4-orifice configuration was not filmed since one wall needed to be orifice-free to allow visualization of the jets.

It must be noted that, due to the limitation of pumping power, a maximum liquid flow rate of 1×10^{-5} m^3/s for injection of liquid through 1 orifice, 1.8×10^{-5} m^3/s for injection through 2 orifices mode 1 and a 1.5×10^{-5} m^3/s flow rate through mode 2 configuration was achieved.

4. Results and discussion

4.1. Liquid jet images

In Figs. 7–9, the images obtained from the Venturi throat in different operational conditions are depicted.

Fig. 7 shows images of a single jet. Fig. 7a and b shows the jet penetration for a liquid injection through a single orifice that is transversal to the gas stream, maintaining a constant gas velocity and varying the liquid flow rate. They confirm that atomization does not occur at only a single point of the jet and demonstrates the continuous detachment of mass along the jet and detachment of droplets beginning at a short distance from the jet basis in the Venturi throat. These observations were also found by Gonçalves et al. [13]. In these figures, it can also be noted that the increase of liquid flow rate contributes to the increase in jet velocity and consequently greater jet penetration in the throat of the scrubber because the jet penetration is directly proportional to its velocity, as shown by Eqs. (2) and (3). The figures also show that the increase in liquid jet penetration occasioned a better and desirable covering of the throat as a better distribution of the liquid

Table 1
Configuration utilized for liquid injection

Number of active orifices	Orifices in operation (see Fig. 6)
1	1
2	1 and 3—mode 1 2 and 4—mode 2
3	1, 2 and 3
4	1–4

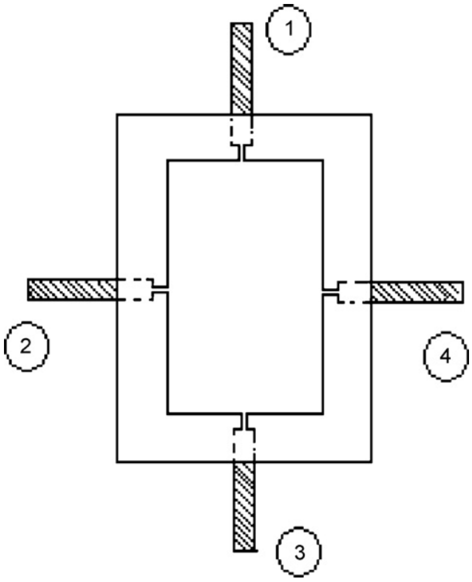

Fig. 6. Positioning of the liquid injection orifices in the scrubber throat.

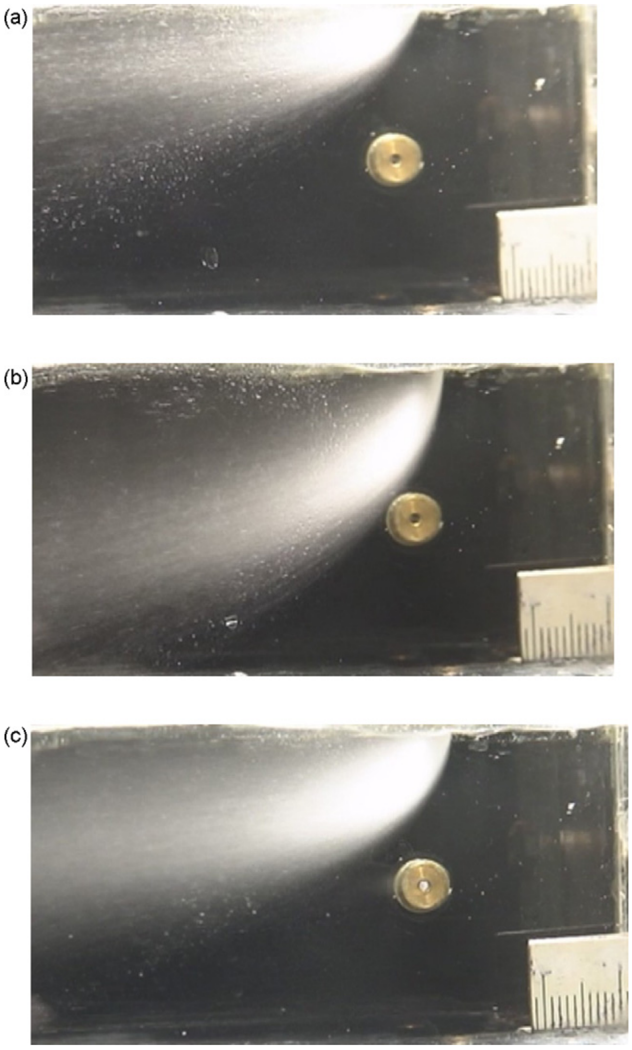

Fig. 7. Image of jet injection through 1 orifice: (a) $V_g = 59$ m/s; $V_j = 6.37$ m/s; $L = 0.5 \times 10^{-5}$ m^3/s; (b) $V_g = 59$ m/s; $V_j = 12.74$ m/s; $L = 1 \times 10^{-5}$ m^3/s; (c) $V_g = 74$ m/s; $V_j = 12.74$ m/s; $L = 1 \times 10^{-5}$ m^3/s.

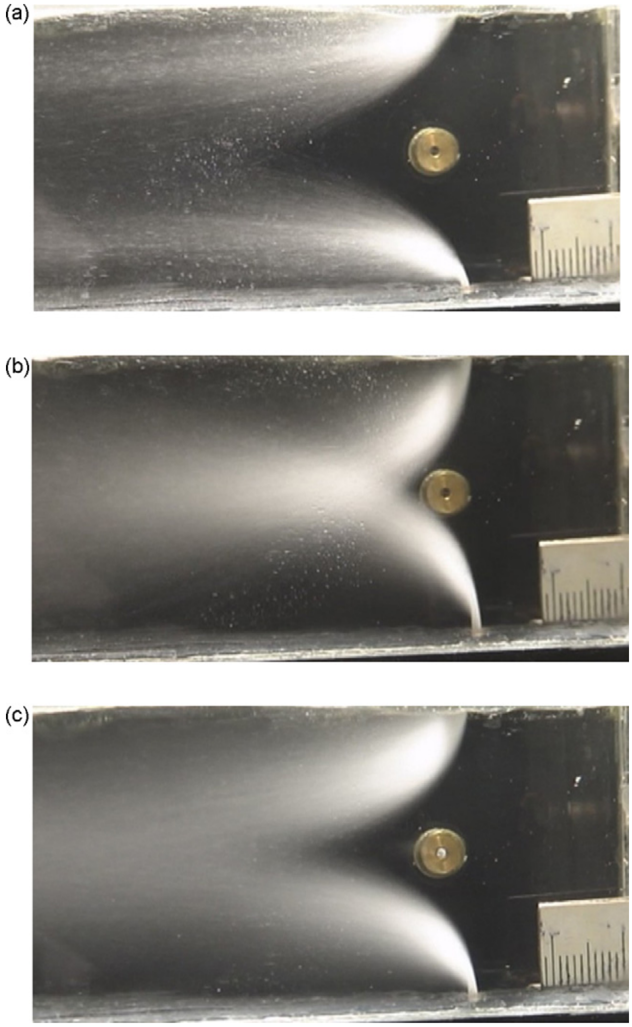

Fig. 8. Image of jet injection through 2 orifices: (a) $V_g = 59$ m/s; $V_j = 6.37$ m/s; $L = 1 \times 10^{-5}$ m^3/s; (b) $V_g = 59$ m/s; $V_j = 11.68$ m/s; $L = 1.8 \times 10^{-5}$ m^3/s; (c) $V_g = 74$ m/s; $V_j = 11.68$ m/s; $L = 1.8 \times 10^{-5}$ m^3/s.

inside the equipment providing a greater area for liquid–particle contact, for collection, thus increasing the efficiency of collection. A comparison of Fig. 7b and c shows that the increase in gas velocity provides a greater flattening of the liquid jet caused by the increase of the drag force in consequence of the increase in velocity when generating jets that are less penetrating for the same liquid flow rate.

Fig. 8 illustrates the injection through two orifices (mode 1). Fig. 8a and b clearly shows greater interaction between jets as the liquid flow rate is increased. Fig. 8a presents the image of a jet with a total flow rate of 1×10^{-5} m^3/s, which provides a flow rate of 0.5×10^{-5} m^3/s at each orifice. It can be noted that the jets behave in a practically individual manner as the low penetration has caused them to be almost parallel to the air stream. However, with the increase in liquid flow rate (Fig. 8b), frontal impact between jets can be seen and the interaction that occurs between them occasion a great quantity of liquid flowing through the center of the throat of the scrubber. Also, it can be inferred from the intense interaction of the two opposite droplet clouds, that droplet size is likely to be affected by agglomeration/coagulation processes. In Fig. 8c a further increase in gas velocity again provided a greater flattening of liquid jets causing less interaction between each other (when compared to a lower gas velocity in Fig. 8b).

Fig. 9 shows images of the jets originating from 3 orifices. Due to low liquid flow rate, in Fig. 9a a great fraction of liquid is seen flowing on the walls of the scrubber. This liquid loss to the wall is the result of the low penetration of the jet into the throat of the scrubber, which in turn causes a smaller formation of droplets due to less jet–air stream interaction due to the experimental conditions. This film affects the performance of collection in the scrubber as droplet surface area is reduced, lowering the efficiency of collection by the equipment and causing a greater waste of liquid load. With the increase in liquid flow rate (Fig. 9b and c) and the consequent increase in jet penetration, a greater jet–air interaction occurs, providing an improvement in atomization and a decrease of liquid loss to the equipment walls.

4.2. *Variation of the droplet diameter with L/G*

There are various factors that can cause a variation in the diameter of the droplet inside a Venturi scrubber such as different atomization processes (depending on the experimental condition adopted), droplet coalescence, secondary atomization and higher incidence of droplet deposit on the walls of the equipment.

Figs. 10 and 11 present the experimental data for Sauter mean diameter, D_{32}, as a function of L/G for different operational conditions. It can be noticed that, in all cases, the droplet size tended

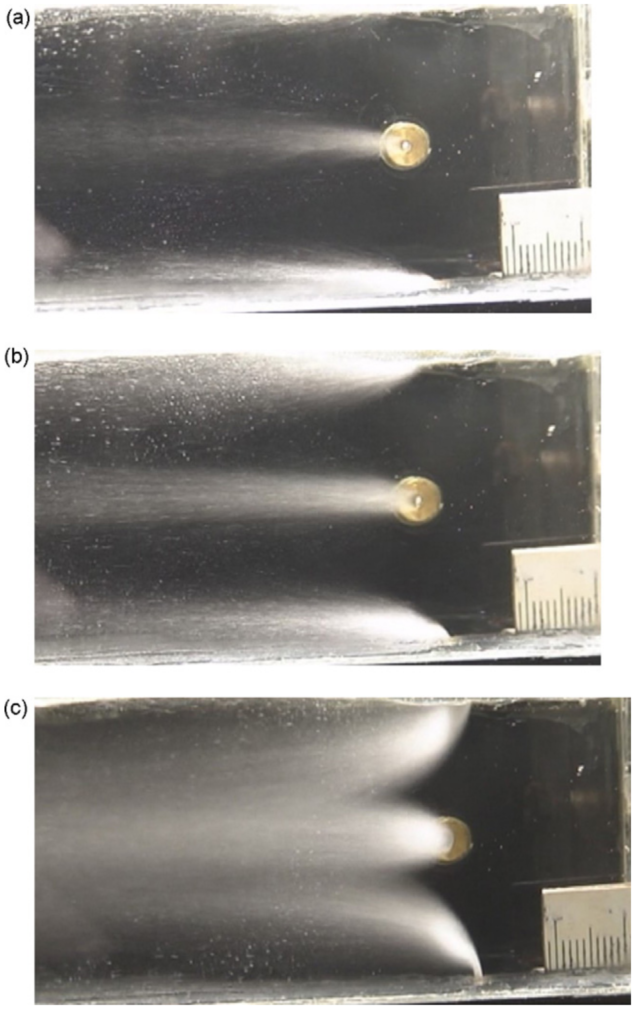

Fig. 9. Image of jet injection through 3 orifices: (a) $V_g = 59$ m/s; $V_j = 2.12$ m/s; $L = 0.5 \times 10^{-5}$ m^3/s; (b) $V_g = 59$ m/s; $V_j = 4.25$ m/s; $L = 1 \times 10^{-5}$ m^3/s; (c) $V_g = 59$ m/s; $V_j = 8.49$ m/s; $L = 2 \times 10^{-5}$ m^3/s.

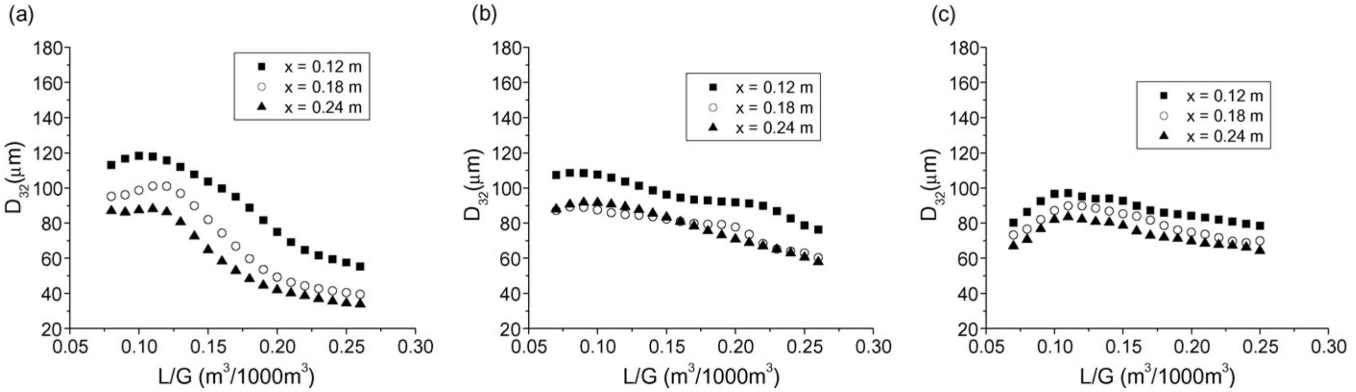

Fig. 10. Variation of the Sauter mean diameter with the distance along the throat, x: (a) 2 orifices mode 1, $V_g = 64$ m/s; (b) 3 orifices, $V_g = 69$ m/s; (c) 4 orifices, $V_g = 74$ m/s.

to be smaller at high values of L/G. Kihm et al. [20] and Wu et al. [21] observed similar behavior when studying the size of droplets originating from a jet of water injected transversally to an air stream. Here, however, in some cases (e.g. Figs. 10c and 11b), the dependence between D_{32} and L/G passes through a maximum in the region of L/G between 0.10 and 0.15 m^3/1000 m^3. It is worth noting that these tendencies occur for 4-orifice injection, where the liquid flow L is divided in four jets. This, together with the fact that the maximum droplet size occurs at low values of L/G, means that each jet penetrates little in the gas stream. Therefore the jet–wall interaction may be the reason for the observed behavior.

Fig. 10 shows the droplet size vs. L/G at the different positions x along the throat of the scrubber, for three different orifice configurations. It can be verified that, independent of the injection configuration, of the liquid flow rate and of the gas velocity, the size of the droplets measured experimentally were greater in the shorter axial distance ($x = 0.12$ m). The decrease in size with the axial distance x was also reported by Kihm et al. [20]. Measurements taken downstream from the point of liquid injection, at $x = 0.18$ and

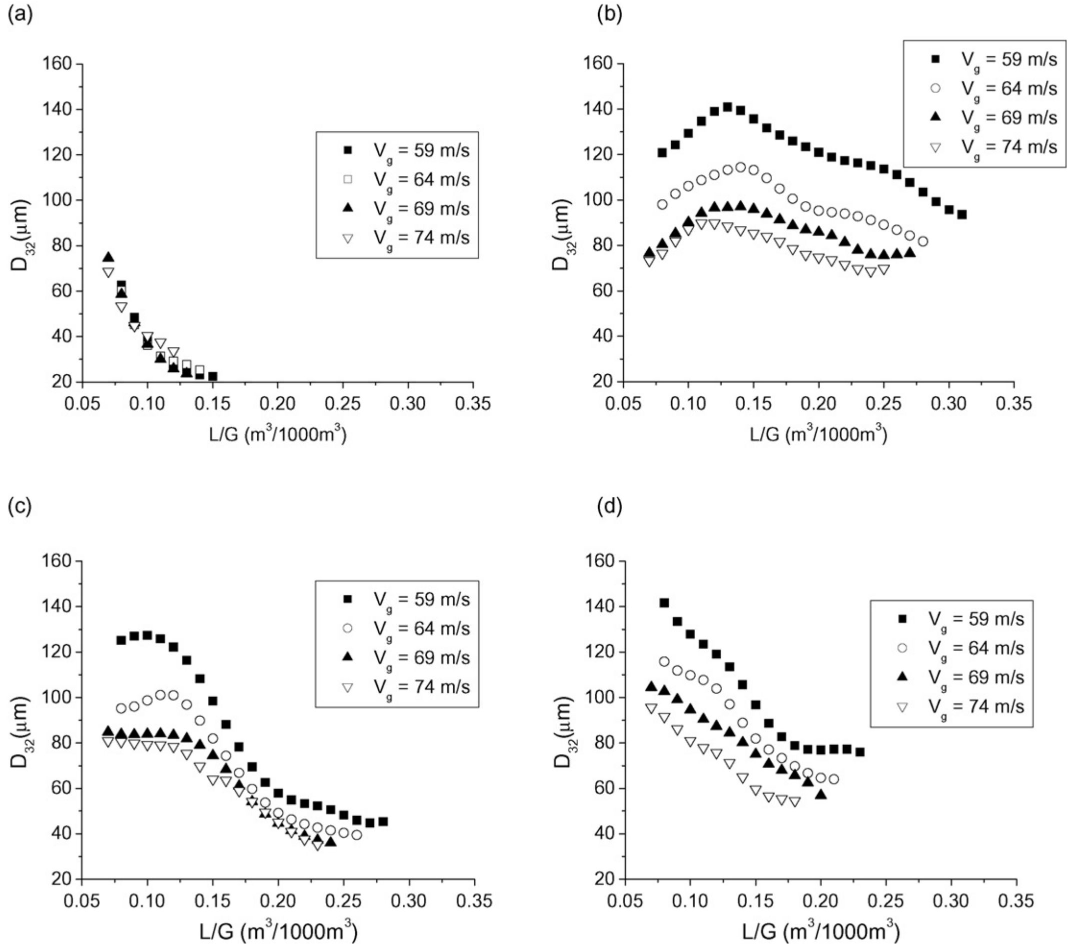

Fig. 11. Variation of the Sauter mean diameter with L/G ratio for different configurations of liquid injection for $x = 0.18$ m: (a) 1 orifice, (b) 4 orifices, (c) 2 orifices mode 1 and (d) 2 orifices mode 2.

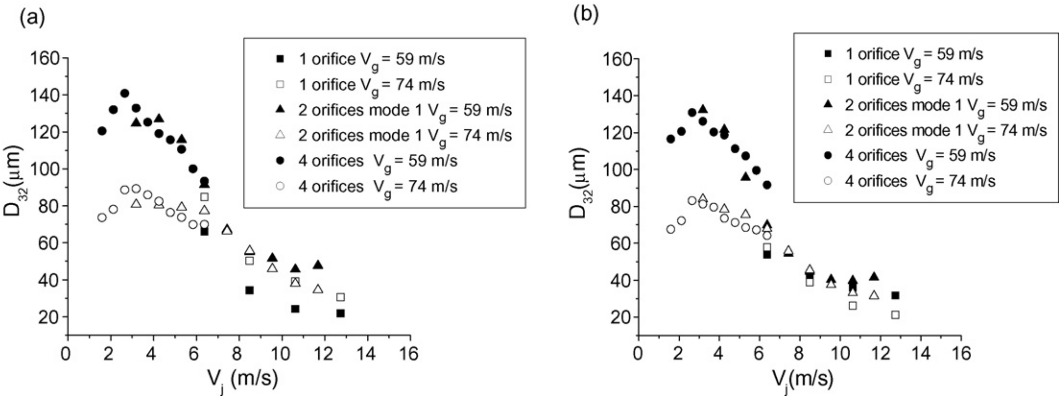

Fig. 12. Variation of the Sauter mean diameter as a function of jet velocity: (a) $x = 0.18$ m and (b) $x = 0.24$ m.

0.24 m, show D_{32} to be close in size, suggesting that, once generated, the droplet size tends to stabilize quickly as it flows. It can also be inferred from the decrease in droplet size with x that the phenomenon of coalescence did not occur significantly downstream from the injection point.

In virtue of the greater stabilization of the atomization process when the measurements were taken at 0.18 and 0.24 m from the point of liquid injection, the majority of the following results are taken at these distances.

The influence of the L/G ratio on the droplet size is also shown in Fig. 11, for 4-orifice configurations, taken at $x = 0.18$ m, for four different gas velocities, V_g. It can be observed that, in general, an increase in gas velocity results in a decrease in the mean size of the droplets. This behavior was expected because the increase in gas velocity resulted in an increase in the aerodynamic forces acting on the liquid jet, favoring the process of atomization. Yet, Fig. 11a shows that the gas velocity had little influence on droplet size for the 1-orifice configuration. For the rest of the configurations (Fig. 11b–d) the larger droplets were obtained at a lower gas velocity, and with the continuous increase in gas velocity, the droplet sizes tended to uniformize, as can be seen in Fig. 11c for the 69 and 74 m/s velocities. It is noticeable, however, that the distance between walls can affect this tendency. Fig. 11d and c, both with two orifices but with different distance between walls, shows distinct trends in the droplet size. This evidence, plus the fact that the droplet sizes tend to be larger at higher L/G in Fig. 11d is indicating that cloud interaction may occur more strongly in these conditions (namely, of Fig. 11d).

4.3. Variation of the droplet diameter with the liquid jet velocity V_j

The decrease in the droplet size with the increase in the liquid jet velocity (calculated from Eq. (3)) can be observed in Fig. 12. The increase in V_j may be seen as favoring the rupture mechanism of the liquid jet since the increase in jet velocity increases its interaction with air stream at high velocity. Also, it is apparent that, at low V_j, the influence of the gas velocity is paramount in the size of the formed droplet. At greater jet velocities though (above 7 m/s), the droplets are similar in size probably due to the complete disintegration of the liquid jet with the generation of a great number of smaller droplets.

The initial increase observed at lower jet velocities with injection through 4 orifices could be justified by the fact that in this configuration there is less penetration by the liquid jets. In this case, the jets are almost parallel to the air stream (as depicted in Fig. 9a) and the liquid interaction with the scrubber wall is intense. This situation can occur up to a jet velocity of about 3 m/s in this configuration. However, with the continuous increase of liquid flow rate and the consequent increase in jet velocity, better atomization occurs due to the generation of smaller droplets.

The increase in jet velocity not only favors the rupture mechanism for the jet surface that produces smaller droplets, but may also cause a preferential deposition of larger droplets on the opposite walls of the scrubber, once the increase in jet velocity also increases the jet penetration. For this reason, jets with excessive penetration in the throat can cause deposition of the larger droplets on the walls opposite the liquid injection due to the greater inertia of

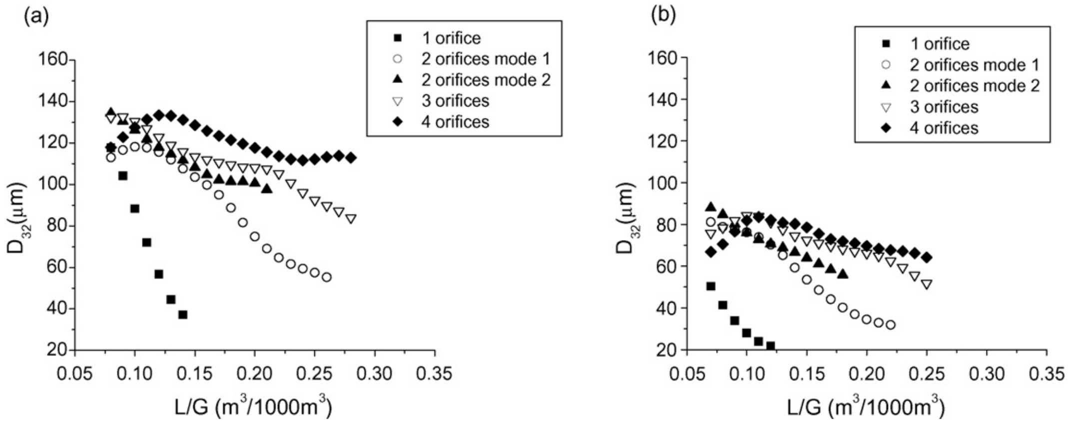

Fig. 13. Comparison of the Sauter mean diameter between configurations: (a) $x = 0.12$ m, $V_g = 64$ m/s; (b) $x = 0.24$ m, $V_g = 74$ m/s.

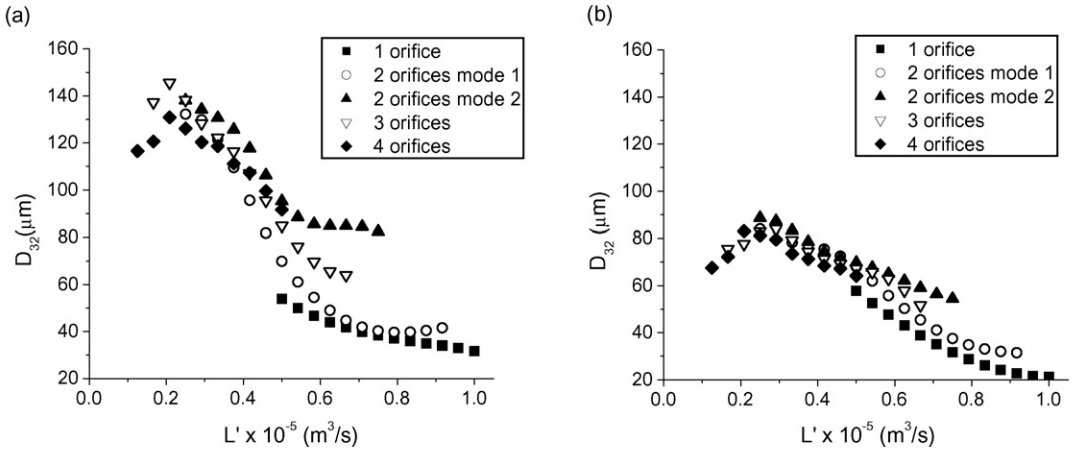

Fig. 14. Variation of the Sauter mean diameter with liquid flow rate at each orifice, $x = 0.24$ m: (a) $V_g = 59$ m/s and (b) $V_g = 74$ m/s.

these droplets and their proximity to the wall while the majority of smaller droplets do not have enough inertia to cross the entire throat section because they rapidly lose initial inertia, and rapidly spread throughout the throat area due to gas turbulence. In the case of less penetrating jets, the opposite occurs. According to the atomization process described by Wu et al. [15], the larger droplets are formed at the top of the jet, and in case of low penetration as illustrated in Fig. 7a, the larger droplets can flow freely through the air stream without hitting the opposite wall. Preferential deposition therefore depends on the operating conditions employed, the dimensions of the equipment and the position in which the analysis of the droplet size is being made, as pointed out by Gonçalves et al. [12].

4.4. Variation of the droplet diameter with the injection configuration

The liquid injection configuration also showed a significant influence on the size of the droplet, as already shown in Fig. 13, which compares the different configurations for liquid injection at different gas velocities and axial positions. The smaller droplet sizes were obtained by injection through a single orifice and, as the number of operating orifices increases, also increased the size of the droplets. It is worth noticing that the liquid flow rate L, plotted in Fig. 13, is the total liquid input, i.e. the sum of the liquid flow through all the orifices in each test. The significant variation in the size of the droplets with the number of orifices for liquid injection can be associated to the different jet velocities obtained by the number of orifices operating, because the liquid flow rate introduced into the scrubber is divided by the number of orifices for liquid injection. This fact justifies the smaller size of droplets measured for the configuration of the single orifice once this configuration generated jet with higher velocities, as already seen in Fig. 12. For this reason, the generation of smaller droplets is favored by configurations with less numbers of orifices for the conditions tested here. Besides, in injection through a single orifice there is no type of interaction between jets or between droplets coming from other jets. For the other configurations, the interaction between jets may be interfering in the size of the droplets, once the increase in liquid flow rate increases the jet penetration and causes them to hit each other as illustrated in Fig. 8b.

4.5. Evidence of jet and cloud interaction

The possible interference in the size of droplets can be better seen in Fig. 14, where the size of the droplet as a function of the liquid flow rate *at each orifice*, L', for liquid injection is shown. It can be noticed that, independent of injection configuration, the diameter of the droplets are similar for small liquid flow rate (up to 0.4×10^{-5} m^3/s). Low liquid flow mean smaller jet penetration and results in less interaction between the jets, as evidenced in Figs. 8a and 9a and b. However, with the increase of liquid flow rate, the jet clouds reach each other, allowing their interaction. In Fig. 14a it can be verified that, for liquid flow rates above 0.5×10^{-5} m^3/s, the droplets size increases with the increase in the number of orifices. Bearing in mind that, in this case L' accounting for the flow *at each orifice*, increasing the number of orifices means increasing the possibility of jet/cloud interaction (as illustrated in Fig. 9c). Fig. 14b

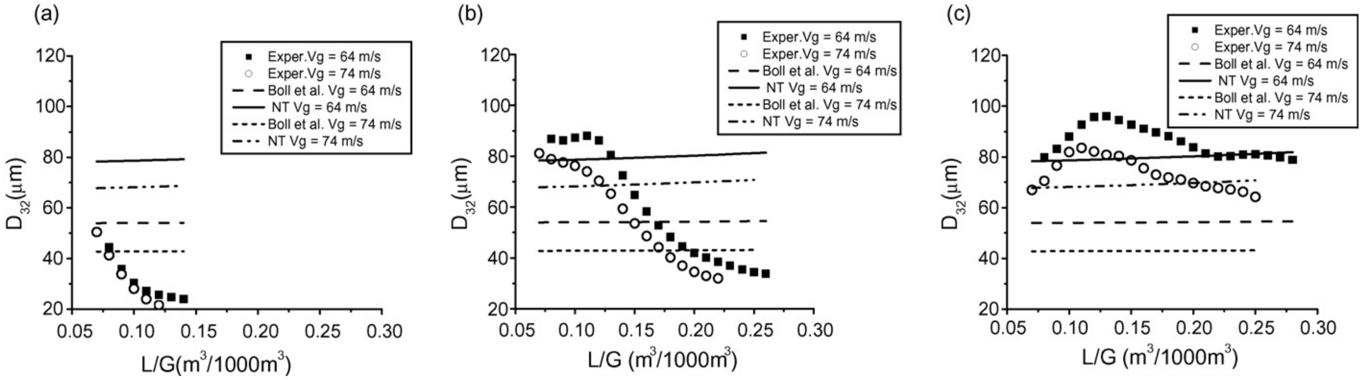

Fig. 15. Comparison between experimental and theoretical diameters for $x = 0.24$ m for $V_g = 64$ m/s and $V_g = 74$ m/s: (a) 1 orifice, (b) 2 orifices mode 1 and (c) 4 orifices.

shows a decrease in jet interaction as the gas velocity increases from 59 to 74 m/s. At greater velocity, the droplet size become closer to the values obtained for injection through a single orifice. This behavior is possibly due to the fact that the increase in gas velocity causes greater flattening of the jets as shown in Figs. 7c and 8c. This greater flattening lessens the jet/cloud interaction and results in droplet sizes closer to those from the injection through a single orifice.

Fig. 14 also shows a significant difference in the size of the droplets formed by injection through 2 orifices, when comparing mode 1 to mode 2. Despite the fact that the liquid injections occurred through the same number of orifices, they are positioned at different locations in the throat. The size of the droplets was larger for mode 2, where the distance between inlet orifices was shorter (0.027 m) than the distance between orifices in mode 1 (0.040 m). The shorter distance traveled may have caused the jets to hit each at greater intensity, resulting in the larger size of droplets in this configuration. This difference suggests that the positioning of each orifice in the throat of the Venturi scrubber will also influence the droplet size inside the equipment.

4.6. Comparison of the experimental droplet size with the theoretical predictions

A comparison of the experimental Sauter mean diameter was compared to those predicted by the correlations of Boll et al. [5] and Nukiyama and Tanasawa [19], and the results are shown in Fig. 15. It can be verified that the behavior described by the correlations proposed by Boll et al. [5] and Nukiyama and Tanasawa [19] are very different from those obtained in this work. The increase in the liquid flow rate significantly decreased the size of the droplet formed experimentally whilst the correlations predicted a slight increase. It is necessary to note that in the study by Boll et al. [5] the values utilized for L/G (between 0.6 and 2.4 $m^3/1000\,m^3$) were greater than those employed in this study (0.07–0.3 $m^3/1000\,m^3$) and that the liquid was introduced through a different system of atomizers.

The research study conducted by Nukiyama and Tanasawa [19] was performed with pneumatic atomizers. It is worth noting that it is a characteristic of this type of atomizers that the increase in the liquid flow rate results in an increase in the droplet size.

These figures also show that, with the increase in the number of orifices for liquid injection and the increase in L/G (see, for example Fig. 15c, for L/G above 0.25 $m^3/1000\,m^3$), the values for the experimental diameters were close to those calculated by the correlation of Nukiyama and Tanasawa [19]. This suggests that the correlation by Boll et al. [5] and the proposal by Nukiyama and Tanasawa [19], both have a limited range of application and the number of orifices for liquid injection is significant for the droplet size generated inside the equipment and was not predicted by these correlations.

5. Conclusions

The results obtained confirm that atomization does not occur at only one point of the jet, but occurs as a continuous detachment of mass along the length of the jet. Greater velocities of gas occasion a greater flattening of the jet due to the greater drag force intensity. The increase in liquid flow rate could generate jets with excessive jet penetration, so that they hit each other, and this interaction was responsible for a greater dispersion of the liquid in the center of the throat of the scrubber.

In relation to the size of the droplet generated, it is possible to verify that the liquid flow rate significantly influenced the size of the droplets, in that jets with faster velocities and consequently greater penetration generated smaller droplets independent of the injection configuration adopted. The number of orifices for liquid injection was shown to be a relevant factor for droplet size because an increase in droplet size was observed when the number of orifices operating increased. Evidence of interaction between jets was shown.

The proposed correlations for droplet size inside Venturi scrubbers are not satisfactory when compared to the experimental results, suggesting that these correlations may have a limited range of application, and also do not take into account the number of orifices for liquid injection, which was shown to have a significant influence on the size of the droplet inside the equipment.

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