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Atomization of liquids in a Pease-Anthony Venturi scrubber Part I. Jet dynamics

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Abstract

Jet dynamics, in particular jet penetration, is an important design parameter affecting the collection efficiency of Venturi scrubbers. A mathematical description of the trajectory, break-up and penetration of liquid jets initially transversal to a subsonic gas stream is presented. Experimental data obtained from a laboratory scale Venturi scrubber, operated with liquid injected into the throat through a single orifice, jet velocities between 6.07 and 15.9 m/s, and throat gas velocities between 58.3 and 74.9 m/s, is presented and used to validate the model.

Keywords: Jet trajectory; Jet penetration; Jet atomization; Transversal injection; Venturi scrubber

1. Introduction

Venturi scrubbers are very efficient devices for removing particulate pollutants from industrial gases before their release to the atmosphere. The increasing public concern for environmental issues has led to a surge of industrial and academic interest in these equipments.

Scrubbers utilize liquid to collect the particulate pollutants. In Venturi scrubbers, the liquid is more commonly introduced as jets, which soon atomizes to form many small droplets. The penetration and break-up of the jets, which affect the initial droplet concentration distribution, are of fundamental importance to the equipment performance. A liquid injection design leading to an optimized jet penetration and good droplet throat coverage can increase performance while minimizing liquid usage, thus reducing operational costs.

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Nomenclature

A_{proj}	jet projected area in the direction of gas velocity (m^2)
C_D	drag coefficient
D	diameter (m)
e	constant in Eq. (3)
f_P	forcing parameter, Eq. (4)
F_D	drag force ($kg\,m/s^2$)
F_N	normal component of drag force ($kg\,m/s^2$)
F_T	tangential component of drag force ($kg\,m/s^2$)
K_A	constant in Eq. (3)
K_P	constant in Eq. (8)
l^*	jet penetration, Eq. (1) (m)
l^{**}	jet centerline maximum penetration, Eq. (2) (m)
$\dot{\bar{m}}$	mass loss rate (kg/(s m))
s	jet arc length (m)
s_0	distance traveled by jet without mass loss (m)
t	time (s)
V	velocity (m/s)

Greek symbols

β	constant in Eq. (4)
θ	angle between jet velocity and gas velocity
λ	wavelength (m)
μ	viscosity (kg/(m s))
ν	viscous damping parameter, Eq. (5) (m^2/s)
ρ	density (kg/m^3)
σ	surface tension (kg/s^2)

Subscripts

g	gas
j	jet
l	liquid
m	minimum
or	orifice
r	relative between gas and liquid
σ	related to capillary waves as opposed to acceleration waves

The purpose of this paper is to present a mathematical description of the trajectory, penetration and break-up of a jet in a Venturi scrubber. Such description will be used in a subsequent paper to model droplet concentration distribution. The model presented here is based on the superficial wave formation and growth mechanism described by Adelberg [1]. The model was tested, parameterized, and validated by the use of data obtained by imaging techniques in a rectangular laboratory scale Venturi scrubber.

The atomization of transversal jets in subsonic gas streams is a process common to many industrial operations, such as combustion and evaporative cooling, as well as agricultural and medical equipments. Thus, the model presented here can be of interest to engineers working in applications other than gas cleaning.

2. Theory

A Venturi scrubber is shown schematically in Fig. 1. The gas carrying particles is accelerated in the convergence to reach a velocity in the order of 50–120 m/s at the throat. The increase in kinetic energy is obtained at the expense of pressure. In the divergence, the velocity is reduced allowing some pressure recovery. The liquid is more commonly introduced through small plain orifices located at the beginning of the throat, although other forms of liquid injection can be used. As the liquid pass through the orifices, it assumes the shape of jets, initially transversal to the gas stream. Due to gas drag, the jets follow curved trajectories before being completely atomized into many small droplets. Ultimately, the droplets are responsible for collecting the contaminants. The efficiency of the scrubber is affected by droplet characteristics such as size, quantity, relative velocity and spatial distribution. On the other hand, these are determined in part by jet characteristics, such as jet velocity, diameter, trajectory, penetration into the gas stream, and atomization mechanisms. In particular, jet penetration, defined here as the transversal distance traveled by the jet before its complete atomization (Fig. 2), is one of the most important factors determining the initial droplet spatial distribution. Jets with insufficient or excessive penetration can lead to bad throat coverage, thus decreasing the collection efficiency.

Although the importance of jet penetration and droplet throat coverage in the efficiency of Venturi scrubbers has been recognized long ago [2], such aspects are not easily incorporated into models. In fact, many mathematical models for Venturi scrubbers [3–6] are one-dimensional, that is, they consider that the properties vary only along the axis of the equipment. In this case, jet dynamics and droplet spatial distribution, which are essentially multi-dimensional phenomena, cannot be accounted for. According to Boll [4], this intrinsic drawback of one-dimensional models for collection efficiency explains why such models cannot yield good results.

Taheri and Sheih [7] were the first authors to propose a three-dimensional model for the collection efficiency of Venturi scrubbers, which took into account the droplet concentration distribution. However, the model had no real description of jet dynamics, assuming simply

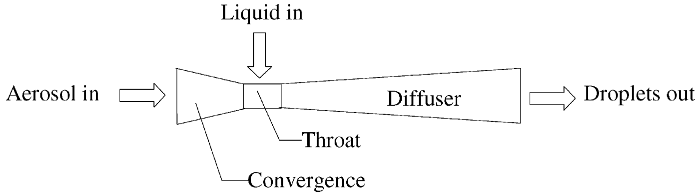


Fig. 1. Schematic representation of a Venturi scrubber.

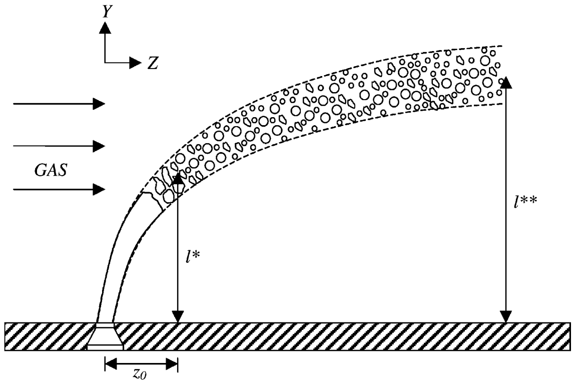


Fig. 2. Jet trajectory, jet penetration (l^*) and jet centerline maximum penetration (l^{**}) according to Viswanathan et al. [8].

that all jets atomized at a single point located on the scrubber axis. According to this hypothesis, the jets had always the same penetration regardless of the fluid velocities and jet diameter, leading consequently to the same initial throat coverage, which then ceased to be a variable influencing the collection efficiency. Thus, one of the main justifications for a three-dimensional model was neutralized by the use of a too simplistic description of the jet dynamics.

Viswanathan et al. [8] addressed this problem by proposing a simple semi-empirical model for the jet dynamics. According to that model, the jet can be characterized by two important distances (Fig. 2): (a) the jet penetration (l^*) and (b) the maximum penetration of the jet's centerline (l^{**}), calculated, respectively by:

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

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

where D_{or} is the orifice diameter, ρ_l and ρ_g are the liquid and gas densities, respectively, and V_j and V_g are the jet and gas velocities, respectively.

In a subsequent publication, Viswanathan [9] proposed the value of 0.06 to the constant in Eq. (1), instead of 0.075. Viswanathan et al. [8] and Viswanathan [9], also considered by way of simplification, the distance identified in Fig. 2 as z_0 as equal to zero and the velocity of the jet at the point (z_0, l^*) as being equal to its velocity as it leaves the orifice. Such jet dynamics description has been utilized by all subsequent two- or three-dimensional models for Venturi scrubbers [9–15].

Although the model of Viswanathan et al. [8] has been helpful and useful, it is based on some simplification hypotheses that are in disagreement with available photographic evidence [16,17]. In particular, the photographs show that it is too simplistic to assume a single atomization point for each jet. Rather, a short distance after leaving the orifice the jet starts losing mass at a certain rate, a process that continues along its trajectory until all the mass has been transformed into droplets. Moreover, as the droplets newly formed at each point along the jet's trajectory seem to inherit the jet momentum at that point, it is important to know how the jet velocity varies with distance both in absolute value and direction.

In order to develop a more realistic model for the jet dynamics, it is necessary to understand the mechanisms controlling its atomization. The atomization of both parallel and transversal liquid jets in gaseous streams has been subject of study by many researchers since the XIX century (for a summary of the research in this area see [18,19]). In the range of operational conditions usually found in Venturi scrubbers, that is, gas velocity between 50 and 120 m/s, jet velocity from 1 to 25 m/s, and injection through plain orifices of the order of a few millimeters, three different atomization mechanisms have been proposed: (a) wave formation and growth; (b) jet distortion with steady liquid shear from the edges; (c) cloud atomization.

The mechanism of wave formation and growth for transversal jets was identified and described by Adelberg [1] and Roberts and Hill [17]. Other authors (see [18]) described similar mechanisms for parallel jets in similar operational conditions. According to this mechanism, the wind (or gas flow around the jet) induces a relative movement between the jet surface and its internal layers, which in turn, provokes the formation of waves of short length and high frequency. The waves grow in amplitude as they move along the jet. The impact of the gas on the waves of greater amplitude causes the separation of liquid filaments from the waves. The filaments suffer further atomization to produce very small droplets. In this way, the liquid jet loses mass gradually until it eventually ceases to exist as a jet.

In addition to wave formation and growth, Roberts and Hill [17] observed in some cases a second mechanism happening in conjunction with the former, namely, jet distortion with steady liquid shear from the edges. This mechanism, also described by Schetz [19], involves the distortion and flattening of the cross-section of the jet, and the release of liquid mass from the edges of the distorted jet.

Hesketh [20] described an atomization mechanism in Venturi scrubbers that formed not independent droplets, but "clouds" of at least 170 μm, which moved as single entities, and were formed by a large number of droplets of less than 10 μm. Roberts and Hill [17] could not observe this mechanism, although they designed experiments specifically to observe it.

3. Model development

The present model assumes that the mechanism of wave formation and growth is the only one acting. This assumption is admittedly a limitation of the present model. There is enough evidence that in some cases the jet flattening mechanism occurs in conjunction with the mechanism of wave formation [17]. The reasons for limiting the present analysis to the wave growth mechanism include: (a) the evidence presented by Roberts and Hill [17] suggest that the wave growth mechanism is predominant and always present in the range of conditions encountered in Venturi scrubbers; (b) the wave growth mechanism has been better established and better described in the literature in comparison with the jet distortion mechanism; (c) it is more prone to mathematical description.

The model developed here is based on the work of Adelberg [1]. Adelberg made a distinction between capillary waves and acceleration waves. According to the criteria given by him, the waves present in Venturi scrubber jets would grow typically as capillary waves, a conclusion which is in agreement with Roberts and Hill [17].

Utilizing Lamb's capillary wave growth theory, Adelberg [1] derived an expression for the mass loss rate ($\bar{\dot{m}}$) of a jet:

$$\bar{\dot{m}} = \frac{K_A \rho_l}{eD_j - \lambda_{m\sigma}} \left\{ \frac{2}{5} f_P [(eD_j)^{5/2} - \lambda_{m\sigma}^{5/2}] - \nu [eD_j - \lambda_{m\sigma}] \right\} \tag{3}$$

where D_j is the jet diameter, K_A is a constant normally taken to be 1, e is a constant so that eD_j represents the maximum wavelength, and the force parameter f_P, the viscous damping parameter ν, and the minimum wavelength $\lambda_{m\sigma}$ are given, respectively, by:

$$f_P = \frac{\beta (\pi/2)^{1/2} \rho_g V_g^2}{(\rho_l \sigma)^{1/2}} \tag{4}$$

$$\nu = \frac{8\pi^2 \mu_l}{\rho_l} \tag{5}$$

$$\lambda_{m\sigma} = 15.8326 \left[\frac{\mu_l (\sigma/\rho_l)^{1/2}}{\beta \rho_g V_g^2} \right]^{2/3} \tag{6}$$

where β is an experimentally determined constant, μ_l is the liquid viscosity and σ is the surface tension.

Eq. (3) quantifies the jet's liquid mass loss rate assuming only the wave growth mechanism. When liquid evaporation is a significant source of mass loss for the jet, as for instance when hot gases are being scrubbed, Eq. (3) should include an evaporation term.

Considering that the jet diameter variation is due only to its mass loss, it is possible to write:

$$\bar{\dot{m}} = -\frac{\pi}{4} \rho_l V_j D_j \frac{dD_j}{ds} \tag{7}$$

where s is the distance traveled by the jet along its trajectory.

There is no mass loss until a certain distance (s_0) after the jet leaves the orifice because the waves need a certain time to grow to an amplitude capable of shredding ligaments. This distance is proportional to the jet velocity (V_j) and the wave time modulus ($\rho_l \lambda_{m\sigma}^2 / 8\pi \mu_l$), and can be estimated by:

$$s_0 = K_P \frac{\rho_l V_j \lambda_{m\sigma}^2}{\mu_l} \tag{8}$$

where K_P is an experimental proportionality constant.

The jet trajectory can be calculated from a force balance on a jet element of infinitesimal length (Fig. 3), considering that the drag force is the only one acting on the jet. This force can be given by:

$$d\vec{F}_D = \tfrac{1}{2} C_D \rho_g A_{proj} V_r \vec{V}_r \approx \tfrac{1}{2} C_D \rho_g D_j \, ds \sin\theta \, V_r \vec{V}_r \tag{9}$$

where $\vec{F}_D$ and C_D are the drag force and the drag coefficient for a cylinder in a gaseous stream (for the typical operational conditions of Venturi scrubbers this can be approximated

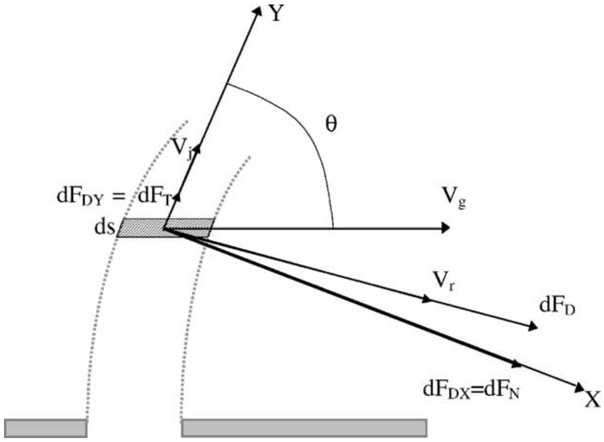


Fig. 3. Force balance on a jet element of infinitesimal length d*s*.

by a constant value of 1.1), θ is the angle between the jet and the gas velocities, A_{proj} is the projected area of the jet element under consideration and V_r is the relative velocity between jet and gas. The drag force can be decomposed into its tangential (F_T) and normal (F_N) components in relation to the jet velocity:

$$dF_T = \tfrac{1}{2} C_D \sin\theta\, \rho_g (V_g \cos\theta - V_j) V_r D_j\, ds \quad (10)$$

$$dF_N = \tfrac{1}{2} C_D \sin^2\theta\, \rho_g V_g V_r D_j\, ds \quad (11)$$

The tangential force can be related to the jet velocity as:

$$dF_T = \rho_l \frac{\pi D_j^2}{4}\, ds\, \frac{dV_j}{dt} = \rho_l \frac{\pi D_j^2}{4} V_j\, dV_j \quad (12)$$

The relation between $d\theta$ and the drag force components can be expressed as:

$$d\theta = -\frac{dF_N}{(\pi D_j^2/4)\rho_l V_j^2} \quad (13)$$

Eqs. (7), (10)–(13) can be combined to produce three differential equations that, together with Eq. (3), represent the jet dynamics:

$$\frac{ds}{d\theta} = -\frac{\pi D_j \rho_l V_j^2}{2 C_D \sin^2\theta\, \rho_g V_g V_r} \quad (14)$$

$$\frac{dV_j}{d\theta} = \frac{V_j (V_j - V_g \cos\theta)}{V_g \sin\theta} \quad (15)$$

$$\frac{dD_j}{d\theta} = \frac{4\bar{\dot{m}} V_j}{2 C_D \sin^2\theta\, \rho_g V_g V_r} \quad (16)$$

The model is solved through the simultaneous numerical integration of Eqs. (14)–(16). As Eq. (3) only makes sense when $eD_j > \lambda_{m\sigma}$, the integration must stop when the jet diameter becomes close to the minimum wavelength. The termination criteria can be written as:

$$D_j \le 1.05\frac{\lambda_{m\sigma}}{e} \tag{17}$$

where the constant 1.05, admittedly rather arbitrary, proved to save many integration steps without dislodging significantly the termination point coordinates in comparison to the ones obtained if a value closer to 1.0 would be used.

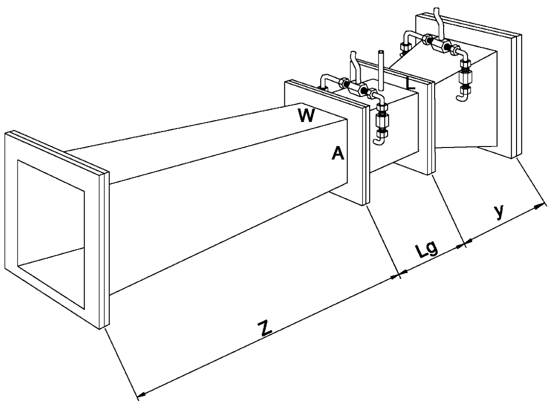
4. Experimental

The experimental facility utilized in this work, illustrated in Fig. 4, consisted of a rectangular Venturi scrubber with a throat cross-section of 35 mm × 24 mm. The Venturi was located horizontally in relation to the ground. Water was injected transversally into the air stream though a single orifice, with a 1 mm diameter, located approximately 40 mm after the beginning of the throat on its topside. The total throat length was 140 mm. The Venturi was built in acrylic and glass to allow optical access to its interior.

Tests were performed at jet velocities between 6.07 and 15.9 m/s and gas velocities between 58.3 and 74.9 m/s. The pressure in the throat was slightly higher than the atmospheric pressure, and the inlet air temperature averaged 30 °C.

A Panasonic M3000 video camera was used to take motion pictures of the jet. The shutter opening time could be adjusted up to 1/8000 s. This speed proved to be adequate for the resolution of the jet trajectory, as Fig. 5 shows. The throat of the Venturi was illuminated with a halogen 1000 W light, positioned about 40 cm above the throat. A black paper was placed on the wall opposing the wall from which the pictures were taken, in order to improve the contrast.

The images obtained were analyzed in a PC, with the aid of the “Image Pro” technical image analyzer. For each operational condition, several still pictures were captured, representing different shutter opening speeds.



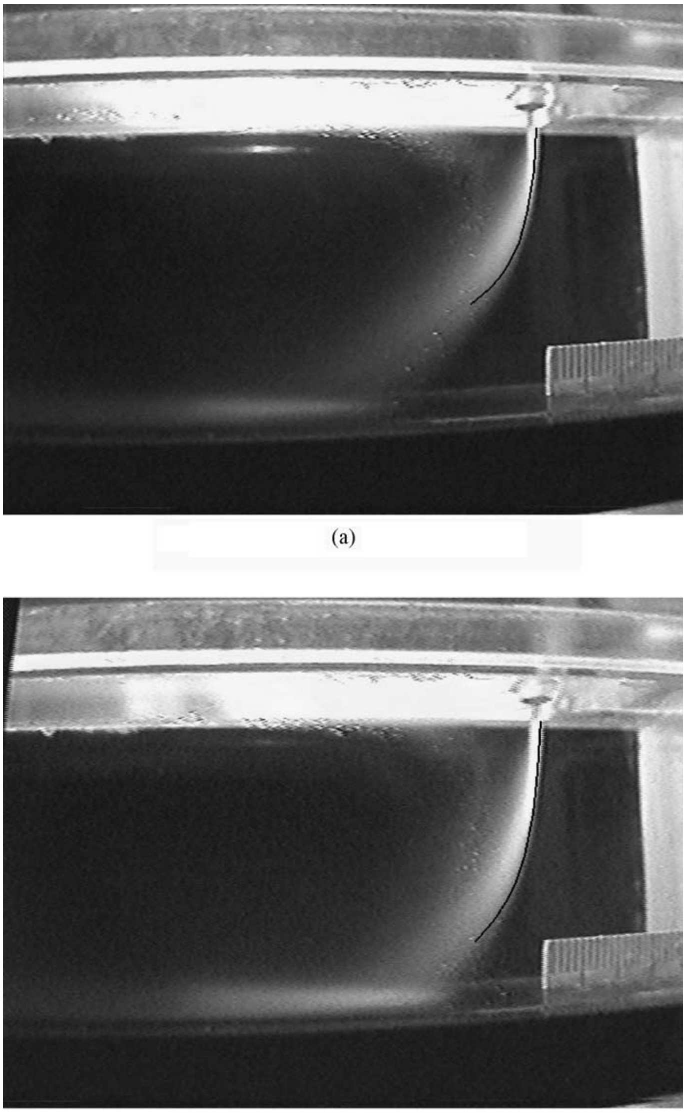
Dimensions	(m)
Z	0.28
Lg	0.140
Y	0.099
W	0.024
A	0.035

Fig. 4. Schematic representation of the Venturi scrubber used in the present experiments.

5. Results and discussion

Jet images are shown in Fig. 5, with superimposed lines representing the model solution. In the images, the whiter areas represent a higher concentration of liquid.

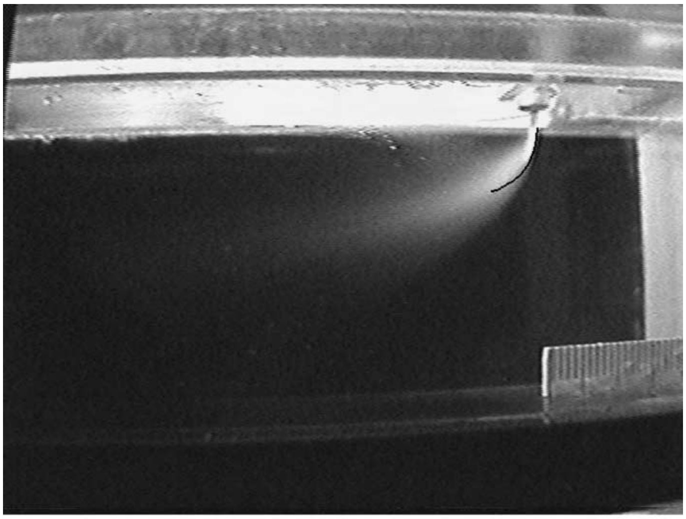
It can be observed that the jet atomizes gradually, that is, it loses mass continually during its trajectory, and does not have a single atomization point. The images also confirm that



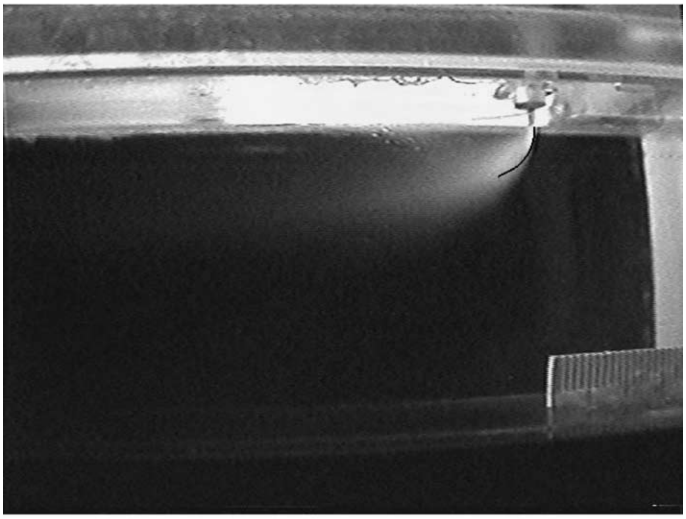
(a)

(b)

Fig. 5. Images of transversal jets, with the curves calculated by the model: (a) $V_g = 58.3$ m/s and $V_j = 12.2$ m/s; (b) $V_g = 58.3$ m/s and $V_j = 15.9$ m/s; (c) $V_g = 66.6$ m/s and $V_j = 6.01$ m/s; (d) $V_g = 74.9$ m/s and $V_j = 6.12$ m/s.



(c)



(d)

Fig. 5. (*Continued*).

the atomization does not begin at the jet base, that is, at the point the jet leaves the orifice, but only after a certain distance from the orifice. With the aid of the "Image Pro" technical image analyzer, this distance (s_0) was measured for each operational condition utilized and correlated with $\rho_l V_j \lambda_{m\sigma}^2 / \mu_l$, after both these quantities have been made dimensionless with the help of the orifice diameter. The results are shown in Fig. 6, where it can be seen that the correlation can be approximated by a line, as in Eq. (8).

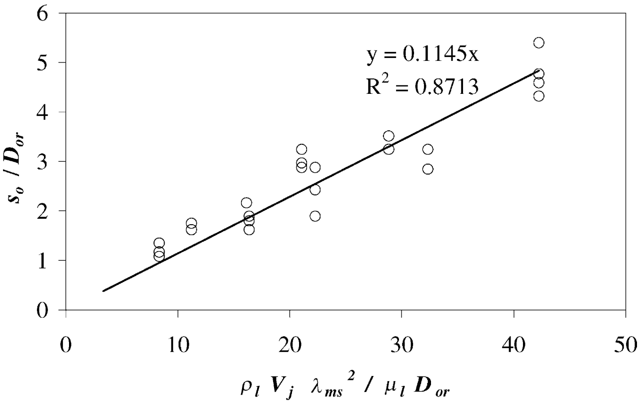


Fig. 6. Distance traveled by the jet without losing mass (Eq. (8)).

The beginning of the formation of a liquid film on the equipment lateral walls is visible in Fig. 5, and it shows that the droplets spread quickly in the radial direction (transverse to the direction of jet motion). Droplet dispersion is caused mainly by turbulent diffusion, and is very important to the performance of Venturi scrubbers. This phenomenon will be further investigated by the present authors in a follow up of this paper. However, although the droplets spread in all directions, the images show that the majority tend to continue moving in such a way as to form an extension of the jet's trajectory. It seems reasonable to adopt the hypothesis that the droplets initial momentum is inherited from the jet.

The model constants used in the calculation of the theoretical trajectories shown in Fig. 5 were:

(a) $\beta = 0.348$ (same value proposed by Adelberg [1]);
(b) $K_A = 1$ (same value proposed by Adelberg [1]);
(c) $e = 0.4$, which is seven times greater than that proposed by Adelberg [1]. The value used in the present study suggests that the maximum wavelength was about half the size of the orifice. The maximum wavelengths measured by Roberts and Hill [17] are of the order of magnitude of the orifice, suggesting a value for the constant e closer to unity, and also closer to the present value than to the one proposed by Adelberg [1];
(d) $K_P = 0.1145$, obtained through the linear regression shown in Fig. 6.

It can be observed that the model performs reasonably well for the different operational conditions utilized, predicting satisfactorily not only the trajectory, but also the jet penetration.

Figs. 7 and 8 show, respectively, the calculated evolution of the velocity and diameter of the jet with distance, when $V_g = 58.3$ m/s and $V_j = 6.07$ m/s.

The main advantage of the present model is that it can calculate the whole jet trajectory and its continuous loss of mass, instead of assuming a bursting off in a single point, the alleged "atomization point". These calculations will cause an appreciable improvement in the modeling of the droplet dispersion [21].

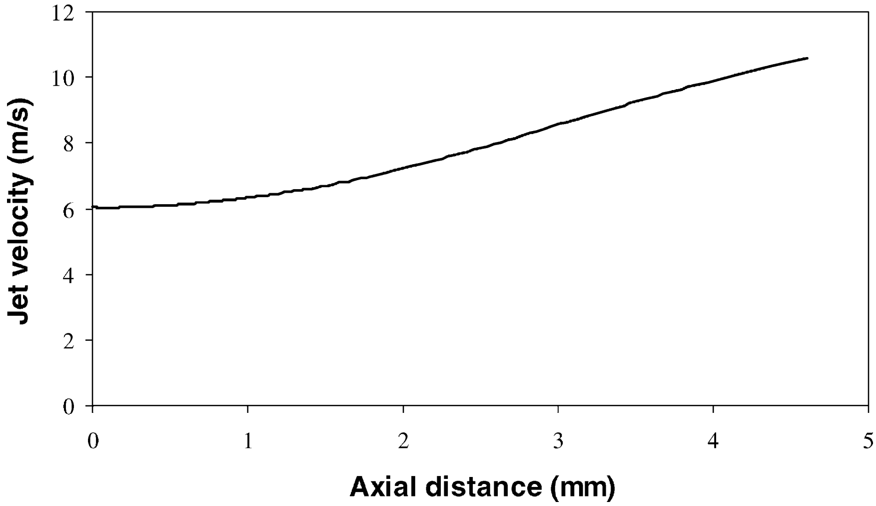


Fig. 7. Evolution of the jet velocity with axial distance: $V_g = 58.3$ m/s and $V_j = 6.07$ m/s.

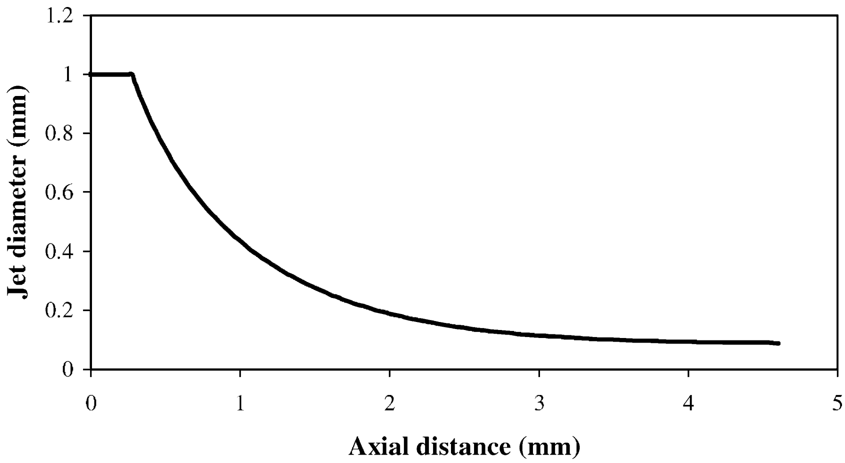


Fig. 8. Evolution of jet diameter with axial distance: $V_g = 58.3$ m/s and $V_j = 6.07$ m/s.

6. Conclusions

From the above, it may be concluded that in the operational range of gas and jet velocities studied:

(a) the jet atomizes gradually, that is, it loses mass continually during its trajectory, and does not have a single atomization point;

(b) the atomization does not begin at the jet base, but only after a certain distance from the orifice. This distance can be estimated by Eq. (8) with a value of 0.1145 for the proportionality constant;
(c) the proposed model for the jet dynamics is consistent with the data presented.

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