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Atomization of liquids in a Pease–Anthony Venturi scrubber Part II. Droplet dispersion

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Abstract

Droplet distribution is of fundamental importance to the performance of a Venturi scrubber. Ensuring good liquid distribution can increase performance at minimal liquid usage. In this study, droplet dispersion in a rectangular Pease–Anthony Venturi scrubber, operating horizontally, was examined both theoretically and experimentally. The Venturi throat cross-section was 24 mm × 35 mm, and the throat length varied from 63 to 140 mm. Liquid was injected through a single orifice (1.0 mm diameter) on the throat wall. This arrangement allowed the study of the influence of jet penetration on droplet distribution. Gas velocity at the throat was 58.3 and 74.6 m/s, and the liquid flow rate was 286, 559 and 853 ml/min. A probe with a 2.7 mm internal diameter was used to isokinetically remove liquid from several positions inside the equipment. It was possible to study liquid distribution close to the injection point. A new model for droplet dispersion, which incorporates the new description of the jet atomization process developed by the present authors in the first article of this series, is proposed and evaluated. The model predicted well the experimental data.

Keywords: Venturi scrubbers; Droplet dispersion; Gas cleaning

1. Introduction

The Venturi scrubber is a relatively compact and highly efficient gas-cleaning device. It uses a liquid in the form of droplets to collect and remove micron size particles from gaseous streams. In a Pease–Anthony Venturi scrubber, the washing liquid is introduced as jets, usually at the throat of the Venturi. The high speed gas causes the atomization of the jets, forming droplets of varying sizes. The droplets, initially concentrated near the trajectories of the jets, disperse due to the gas drag and turbulence.

The importance of droplet distribution in the performance of Venturi scrubbers has been recognized since the first theoretical studies [1] on these gas-cleaning devices. Scrubbers with bad droplet distribution, that is, with regions of high and low concentration of liquid, will present a poorer performance in comparison with scrubbers with good droplet distribution, in which the droplet throat coverage is approximately uniform.

Droplet distribution is a function of design parameters such as the injection system and the fluid velocities. The use of an adequate droplet dispersion model can help the designer to optimize droplet throat coverage without increasing liquid usage unnecessarily, thus reducing operational costs.

This paper aims at studying droplet dispersion both experimentally and theoretically. It presents a new mathematical model, based on the earlier models of Fathikalajahi et al. [2], Viswanathan et al. [3], and Viswanathan [4], which, in addition, utilizes the new jet dynamics description proposed by the present authors in the previous article of this series [5] to locate droplet source points. The model was tested and parameterized by the use of data obtained in a rectangular laboratory scale Venturi scrubber.

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Nomenclature

c_d	droplet mass concentration (kg/m^3)
$\bar{c}_d$	time averaged droplet mass concentration (kg/m^3)
c'_d	droplet fluctuation mass concentration (kg/m^3)
C_D	drag coefficient (dimensionless)
D_d	droplet diameter (m)
D_1, D_2, D_3	distances (in the x-direction) from the injection point (mm)
D_{32}	Sauter mean diameter (m)
E_d	droplet eddy diffusivity coefficient (m^2/s)
E_g	gas eddy diffusivity coefficient (m^2/s)
l_d	droplet Prandtl mixing length (m)
l_g	gas Prandtl mixing length (m)
n	characteristic parameter in the Rosin–Rammler function (dimensionless)
$\mathbf{n}_d$	droplet mass flux (kg/m^2 s)
$n_{d,average}$	average droplet mass flux through the Venturi throat (kg/m^2 s)
$n_{d,local}$	droplet mass flux through the probe (kg/m^2 s)
$n_{d,local,norm}$	normalized droplet mass flux (dimensionless)
Pe	Peclet number (dimensionless)
r_d	rate of production of droplets (kg/m^3 s)
Re_d	Reynolds number based on droplet diameter (dimensionless)
t	time (s)
$\bar{\mathbf{u}}_d$	time averaged droplet velocity (m/s)
$\mathbf{u}'_d$	droplet fluctuation velocity (m/s)
$\mathbf{u}_g$	mean gas velocity through the Venturi throat (m/s)
$\bar{\mathbf{u}}_g$	time averaged gas velocity (m/s)
u_j	mean jet velocity as it leaves the injection orifice (m/s)
X	characteristic parameter in the Rosin–Rammler function (m)

Greek symbols

ρ_d	droplet density (kg/m^3)
ρ_g	gas density (kg/m^3)
ϕ	fraction of total mass contained in droplets of diameter less than D_d (dimensionless)

2. Literature review

Most Venturi scrubber models assume that the droplets are uniformly distributed in the Venturi throat, including the well-known works of Calvert [6] and Boll [7].

Taheri and Haines stressed the importance of the non-uniformity in the droplet dispersion [8] and are responsible for the first mathematical model that takes this into account [9]. That model, tri-dimensional, considers an incompressible gas flowing in a rectangular Venturi and a single droplet source point located in the center of a throat cross-section in the beginning of the throat. A partial differential equation for droplet concentration was obtained through a mass balance following an Eulerian approach and further simplified by assuming the flowing hypothesis:

- In comparison with convective and turbulent diffusion terms, molecular diffusion can be neglected.
- Convection acts only in the direction of flow, that is, the axial direction.
- The turbulent diffusion is significant in the transversal directions only, being neglected in the axial direction on account of being much smaller than the convection in that direction.
- The gradient diffusion hypothesis was assumed in modeling the turbulence, and, accordingly, a droplet eddy diffusivity coefficient was used.

The model equation was solved numerically for droplet concentration by using a particle in cell technique. The drag coefficient was estimated according to Calvert [10]. Droplets were assumed to be all of the same size, estimated according to Nukiyama and Tanasawa [11]. The eddy diffusivity for the droplets was modeled according to Longwell and Weiss [12], assuming the Peclet number to be constant (Baldwin and Walsh [13]) and equal to 10.

Viswanathan et al. [3] improved the above described model by incorporating the possibility of multiple source points, one for each jet injected into the throat. The coordinates of such points could be determined by Viswanathan's jet penetration theory [3] which was critically review by the present authors in the first article of this series [5].

Fathikalajahi et al. [2] advanced the droplet dispersion modeling mainly by proposing to estimate the eddy diffusivity coefficient for the droplets as a function of the distance traveled by a droplet during the average time that an eddy persisted as a single entity. This average time was obtained by applying Prandtl's mixing length theory to the gas phase flow.

Boll [14], based on photographic evidence, and Viswanathan [4] considered that the initial transversal moment of the droplets was very important for determining droplet concentration distribution and could not be neglected as it was done in all the models reviewed above. Accordingly, the model of Viswanathan [4] included a term for droplet velocity in the direction of the transversal jet penetrating the Venturi. The initial droplet velocity was made equal to the jet velocity, not at the breakup point, but rather at the point the jet passes the orifice and enters into the Venturi scrubber. Viswanathan [4] also included a droplet size distribution function into his model. Despite these advances, Viswanathan's model still calculates the droplet eddy diffusivity according to the scheme proposed originally by Taheri and Sheih [9]. Ananthanarayanan and Viswanathan [15] extended Viswanathan's model [4] to cylindrical geometries.

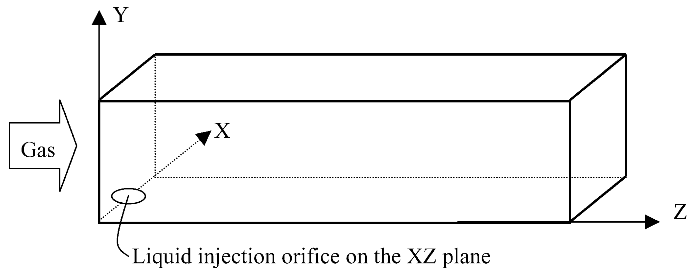


Fig. 1. Cartesian coordinate system used in this study.

3. Proposed model

A mass balance for the droplets over an element of infinitesimal volume yields:

$$\frac{\partial c_\mathrm{d}}{\partial t} = -(\nabla \cdot \mathbf{n}_\mathrm{d}) + r_\mathrm{d} \tag{1}$$

where c_d is the droplet concentration inside the element, $\mathbf{n}_\mathrm{d}$ the droplet mass flux through the element frontiers, and r_d the rate of production of droplets inside the element.

As the Venturi throat is characterized by high gas velocities and turbulence, it is possible to neglect diffusion by natural convection and express the droplet flux as:

$$\mathbf{n}_\mathrm{d} = (\bar{\mathbf{u}}_\mathrm{d} + \mathbf{u}'_\mathrm{d}) \cdot (\bar{c}_\mathrm{d} + c'_\mathrm{d}) \tag{2}$$

where $\bar{\mathbf{u}}_\mathrm{d}$ and $\bar{c}_\mathrm{d}$ are the droplet mean velocity and mean concentration, respectively, and $\mathbf{u}'_\mathrm{d}$ and c'_d the droplet fluctuation velocity and fluctuation concentration, respectively. Substituting Eq. (2) into Eq. (1), and considering steady-state regime, we obtain, after a time averaging operation:

$$-\nabla \cdot (\bar{\mathbf{u}}_\mathrm{d}\bar{c}_\mathrm{d}) - \nabla \cdot (\overline{\mathbf{u}'_\mathrm{d}c'_\mathrm{d}}) + r_\mathrm{d} = 0 \tag{3}$$

where the quantity $\overline{\mathbf{u}'_\mathrm{d}c'_\mathrm{d}}$ is the turbulent mass flux. There are several ways of estimating this flux. Since Taheri and Sheih [9], it has been customary for Venturi scrubber models to assume a gradient diffusion hypothesis in order to estimate this turbulent mass flux. We adapt this suggestion and estimate the components of the flux vector as:

$$(\overline{\mathbf{u}'_\mathrm{d}c'_\mathrm{d}})_i = -E_{\mathrm{d}i}\frac{\mathrm{d}\bar{c}_\mathrm{d}}{\mathrm{d}i} \tag{4}$$

where $E_{\mathrm{d}i}$ ($i = x$ or y) is the eddy diffusivity coefficient for the droplets, which, in the present model, assumes non-isotropic turbulence. Substituting Eq. (4) into Eq. (3), considering a Cartesian coordinate system (Fig. 1) in which the z-axis coincides with the Venturi axis and the y-axis is parallel to the initial jet velocity, and also considering that the transport of droplets in the z-direction due to the turbulent flux vector is small compared to the transport due to the time averaged velocity in that direction, we obtain:

$$-\frac{\partial(\bar{c}_\mathrm{d}\bar{u}_{\mathrm{d}z})}{\partial z} - \frac{\partial(\bar{c}_\mathrm{d}\bar{u}_{\mathrm{d}y})}{\partial y} + E_{\mathrm{d}x}\frac{\partial^2\bar{c}_\mathrm{d}}{\partial x^2} + E_{\mathrm{d}y}\frac{\partial^2\bar{c}_\mathrm{d}}{\partial y^2} + r_\mathrm{d} = 0 \tag{5}$$

Apart from the allowance for different eddy coefficients for each direction, the differences between Eq. (5) and the mass balances developed by Viswanathan [4] and Fathikalajahi et al. [2] are summarized in Table 1.

In order to solve Eq. (5) it is necessary to find expressions for the droplet time averaged velocity, for the droplet eddy diffusivity coefficient, and also to identify droplet source points inside the Venturi scrubber.

The velocities of the droplets are calculated after a force balance. The present model neglects the force of gravity and assumes that the drag force is the only one acting on a droplet. Under the conditions encountered in Venturi scrubbers, with small droplets, high relative velocities between gas and droplets, and small residence time, it is reasonable to consider the drag force much greater than the gravity force. Accordingly, the droplet acceleration can be expressed as:

$$\frac{\mathrm{d}\bar{\mathbf{u}}_\mathrm{d}}{\mathrm{d}t} = \frac{3}{4}\frac{C_\mathrm{D}\rho_\mathrm{g}}{D_\mathrm{d}\rho_\mathrm{d}}|\bar{\mathbf{u}}_\mathrm{g} - \bar{\mathbf{u}}_\mathrm{d}|(\bar{\mathbf{u}}_\mathrm{g} - \bar{\mathbf{u}}_\mathrm{d}) \tag{6}$$

where $\mathbf{u}_\mathrm{g}$ is the gas velocity vector, C_D the drag coefficient and D_d the droplet diameter. In this work, a simple model was assumed for the gas phase flow, allowing us to calculate the gas velocity simply by dividing the volumetric gas flow rate by the cross-section area. The following assumptions were made:

Table 1
Main differences in the mass balances adopted in the present paper and those of Viswanathan [4] and Fathikalajahi et al. [2]

Terms included in mass balance	Present model	Viswanathan [4]	Fathikalajahi et al. [2]
Convective mass flux in x-direction	No	No	No
Convective mass flux in y-direction	Yes	Yes	No
Convective mass flux in z-direction	Yes	Yes	Yes
Turbulent mass flux in x-direction	Yes	No	Yes
Turbulent mass flux in y-direction	Yes	Yes	Yes
Turbulent mass flux in z-direction	No	Yes	No

- The gas was considered incompressible.
- One-way phase coupling was assumed, that is, while the flow of the droplets was influenced by the flow of the carrier phase, the contrary was assumed not to occur, and the gas flow was considered not affected by the presence of the dispersed phase.
- A flat gas velocity profile was assumed.

C_D was estimated by the Dickinson and Marshall equation (*apud* Licht [16]), stated to be valid within ±7% for $Re_d < 3000$:

$$C_D = 0.22 + \frac{24(1 + 0.15 Re_d^{0.6})}{Re_d} \tag{7}$$

Fernández Alonso et al. [17] measured drop sizes in a Venturi scrubber and concluded that the distribution of droplet diameters can be approximated by a Rosin–Rammler function:

$$1 - \phi = \exp\left[-\left(\frac{D_d}{X}\right)^n\right] \tag{8}$$

where ϕ is the fraction of total mass contained in drops of diameter less than D_d, and X and n the characteristic parameters. For the droplet size distribution near to the injection point, Fernández Alonso et al. [17] suggest a value of n equal to 2.15. The parameter X is the drop diameter such that 63.2% of the total liquid mass is in drops of smaller diameter. It can be related to the D_{32} (Sauter mean diameter) by means of the gamma function:

$$\frac{X}{D_{32}} = \Gamma\left(1 - \frac{1}{n}\right) \tag{9}$$

The Sauter mean diameter was estimated by the equation of Boll et al. [18], which was found to be in good agreement with the experimental results of Fernández Alonso et al. [17].

The droplet eddy diffusivity coefficient in the y-direction (E_{dy}) was calculated as a function of the gas eddy diffusivity coefficient (E_g), according to the work of Fathikalajahi et al. [2]:

$$\frac{E_{dy}}{E_g} = \frac{l_d^2}{l_g^2} \tag{10}$$

where l_d and l_g are the Prandtl mixing length for the droplets and gas respectively. The procedures for calculating E_g, l_g and l_d are detailed in the work of Fathikalajahi et al. [2], and depend on the assumption (Baldwin and Walsh [13]) that for high Reynolds numbers, the number of Peclet (based on the gas velocity and the duct equivalent diameter) remains constant. The rectangular cross-section of the Venturi studied here introduced the necessity of non-isotropic turbulence. The horizontal cross-section, being smaller than the vertical one, creates different constraints for each direction. Therefore, in the present model, the droplet eddy diffusivity coefficient in the x-direction (E_{dx}) was simply assumed to be higher than E_{dy} by a constant factor (= 5) which served really as a numerical adjustment parameter.

The source term (r_d) in Eq. (5) represents the points of droplet formation inside the Venturi. Fathikalajahi et al. [2] used the jet atomization theory proposed by Viswanathan et al. [19] in order to locate these points. According to that theory, the atomization of a jet occurs at a single point. Gonçalves et al. [5] proposed an alternative theory which considers that, after a certain initial distance, there is a continuous shredding of liquid from the jet until its final disruption. Consequently, there are many droplet source points along each jet trajectory. The initial velocity (in both z- and y-directions) of each newly created droplet is considered equal to the velocity of the jet at the point in which the droplet was created. The calculation of the jet trajectory is presented in details in Gonçalves et al. [5]. The present model for droplet dispersion utilizes this new jet atomization theory.

The injected liquid is divided into several parcels of droplets, each with a certain amount of mass and initial droplet position, size and velocity. For each parcel, a droplet velocity field is obtained by integrating Eq. (6). Eq. (5) is then solved progressively for concentration (for each parcel) using forward finite differences. The final droplet concentration at each grid point is obtained by summing the concentrations of all parcels at that point. The boundary conditions used are: (a) for $z = z_0$ the droplet concentration for the parcel is known; (b) there is no flux of matter across the equipment walls:

$$\left(\frac{\partial \bar{c}_d}{\partial x}\right)_{\text{walls}} = \left(\frac{\partial \bar{c}_d}{\partial y}\right)_{\text{walls}} = 0 \tag{11}$$

4. Experimental procedure

The experimental facility utilized in this work, illustrated in Fig. 2, 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 31.5 mm after the beginning of the throat on its top side. The Venturi was built in acrylic and glass to allow optical access to its interior. Throat length was varied by the introduction of extra sections between sections (2) and (3). Three throat lengths were utilized, so that concentration was measured at 29.5, 83.5 and 137.5 mm downstream from the liquid injection point.

The droplet sampling technique utilized here is similar to that used by Viswanathan et al. [3] and Koehler et al. [20]. The droplets were sampled isokinetically in nine positions for each throat, utilizing the sampling probe, (3), with 2.7 mm in diameter, and sucked through an high efficiency cyclone, (5), followed by a pre weighed silica gel column, (6). The silica gel column was necessary to capture small entrained droplets eventually not caught by the cyclone. Although this column also catches water vapor from the Venturi gas stream, this was found to be small in comparison to the total amount of liquid withdrawn, so that the error was negligible. The sampling probe insertion, as well as the sampling positions are

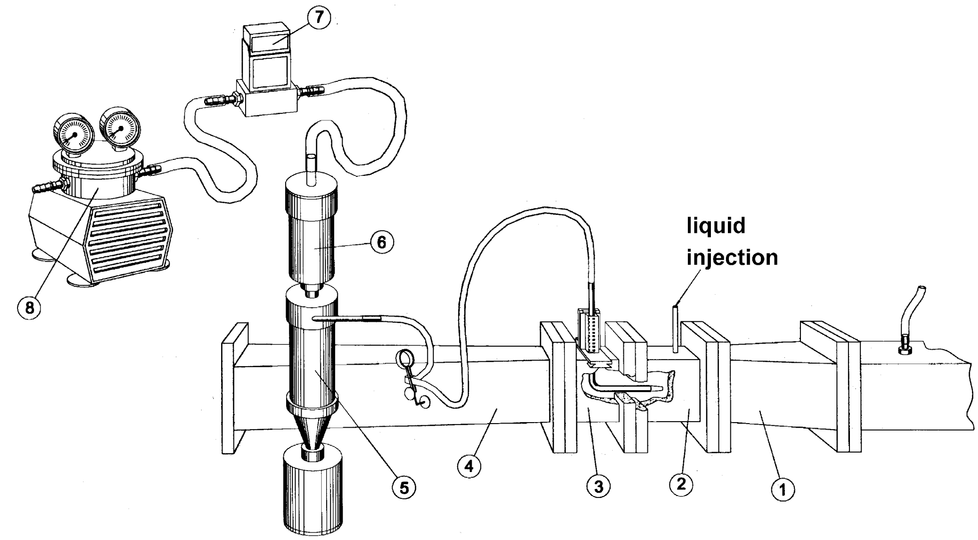


Fig. 2. General view of the equipment utilized, where: (1) converging section of the Venturi; (2) first section of the throat; (3) sampling probe insertion section; (4) diverging section of the Venturi; (5) cyclone for droplet collection; (6) silica-gel column; (7) flow controller; (8) suction pump.

shown in detail in Fig. 3. The droplet flux through the probe, $n_{d,local}$ was obtained from the mass of liquid in the cyclone reservoir plus the increase in mass in the silica gel column as follows:

$$n_{d,local} = \frac{\text{mass of liquid}}{\text{sampling time} \times \text{probe area}} \quad (12)$$

These values were normalized as $n_{d,local,norm}$, given by:

$$n_{d,local,norm} = \frac{n_{d,local}}{n_{d,average}} \quad (13)$$

$$n_{d,average} = \frac{\text{total flow of liquid injected in the throat (in kg/s)}}{\text{throat cross-sectional area}} \quad (14)$$

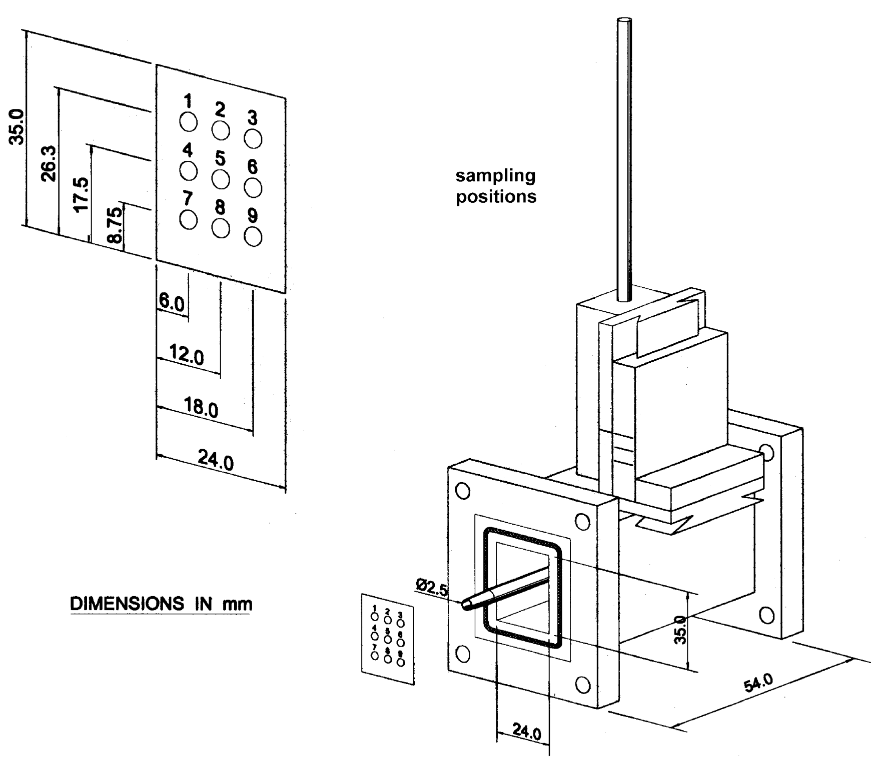
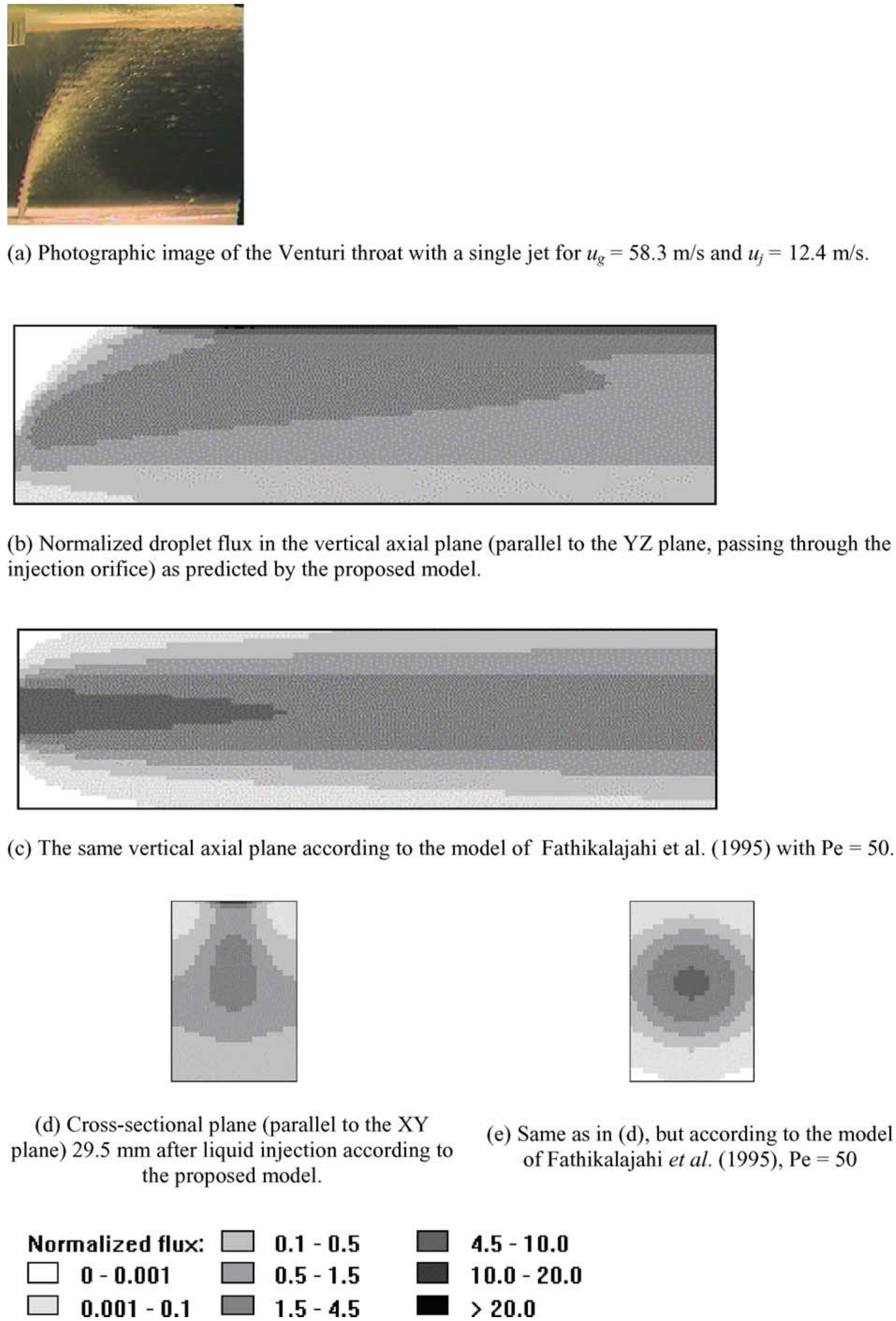


Fig. 3. Detail of the sampling probe insertion and sampling positions.



(a) Photographic image of the Venturi throat with a single jet for u_g = 58.3 m/s and u_j = 12.4 m/s.

(b) Normalized droplet flux in the vertical axial plane (parallel to the YZ plane, passing through the injection orifice) as predicted by the proposed model.

(c) The same vertical axial plane according to the model of Fathikalajahi et al. (1995) with Pe = 50.

(d) Cross-sectional plane (parallel to the XY plane) 29.5 mm after liquid injection according to the proposed model.

(e) Same as in (d), but according to the model of Fathikalajahi *et al.* (1995), Pe = 50

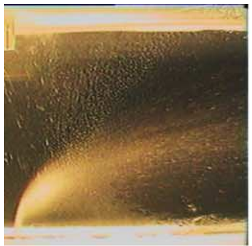
Fig. 4. Photographic image of the Venturi throat with a single jet and droplet dispersion as predicted by the model proposed here and the model of Fathikalajahi et al. [2] ($\mathbf{u}_g$ = 58.3 m/s and u_j = 12.4 m/s).

Tests were performed at three jet velocities (V_j = 6.07, 12.4 and 18.81 m/s) and three gas velocities (V_g = 58.3, 66.6 and 74.9 m/s). All tests were made in duplicate.

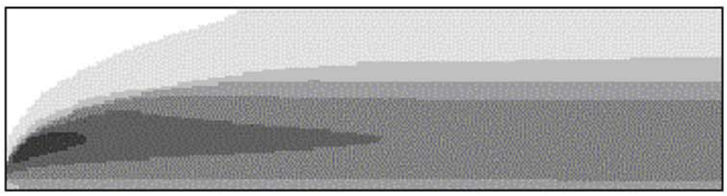
A Panasonic M3000 video camera was used to take motion pictures of the jet. The shutter opening time could be adjusted from normal speed to 1/8000 s. Pictures with varied shutter opening speeds were made. The throat of the Venturi was illuminated from above with a halogen 1000 W light. A black paper was placed on the wall opposing the wall from which the pictures were taken, in order to improve the contrast.

5. Results and discussion

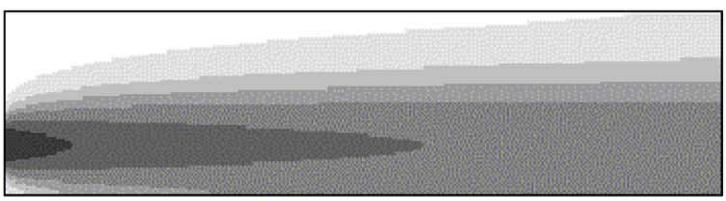
We first discuss the performance of the proposed model in a qualitative way. Figs. 4a and 5a represent photographs of part of the Venturi scrubber throat operating with a gas velocity of 58.3 m/s and a single jet with a velocity (at the orifice) of 12.4 m/s (Fig. 4a) and 6.07 m/s (Fig. 5a). One can see in the photos the wall which contains the orifice and its opposite wall. (Please note that although in these figures the injection orifice appears in the bottom wall, this orientation



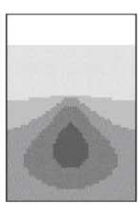
(a) Photographic image of the Venturi throat with a single jet for u_g = 58.3 m/s and u_j = 6.07 m/s.



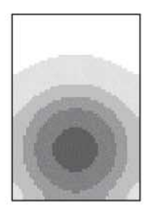
(b) Normalized droplet flux in the vertical axial plane (parallel to the YZ plane, passing through the injection orifice) as predicted by the proposed model.



(c) The same vertical axial plane according to the model of Fathikalajahi et al. (1995) with Pe = 50.



(d) Cross-sectional plane (parallel to the XY plane) 29.5 mm after liquid injection according to the proposed model.



(e) Same as in (d), but according to the model of Fathikalajahi *et al.* (1995), Pe = 50

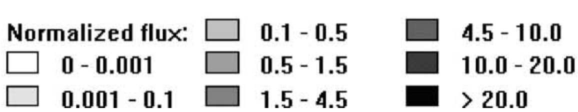


Fig. 5. Photographic image of the Venturi throat with a single jet and droplet dispersion as predicted by the model proposed here and the model of Fathikalajahi et al. [2] ($\mathbf{u}_g$ = 58.3 m/s and u_j = 6.07 m/s).

was adopted for comparison with the model results, which was solved with the axis oriented as in Fig. 1. As mentioned earlier in this paper, the orifice was physically located in the top wall, as in Fig. 2. As the model does not include gravity effects, the results are unchanged by rotation.) Horizontally, the picture covers about 35 mm, counting from the injection point. The jet shown in Fig. 4a has a high penetration, and the liquid soon reaches the opposite wall, whereas the jet seen in Fig. 5a has a smaller penetration. Droplets spread quickly, being possible to see the region were the lateral wall begins to be wetted. The liquid film that flows on this wall hinders, to some extent, optical access to the interior of the scrubber. Where this wall is not yet wetted, it is possible to distinguish regions of high and low concentration of liquid. The pictures also make clear that there is no single atomization point, but, after a short distance from the orifice, droplets are continuously shred from the jet. Fig. 4b–e and Fig. 5b–e show the predictions of the proposed model and the model of Fathikalajahi et

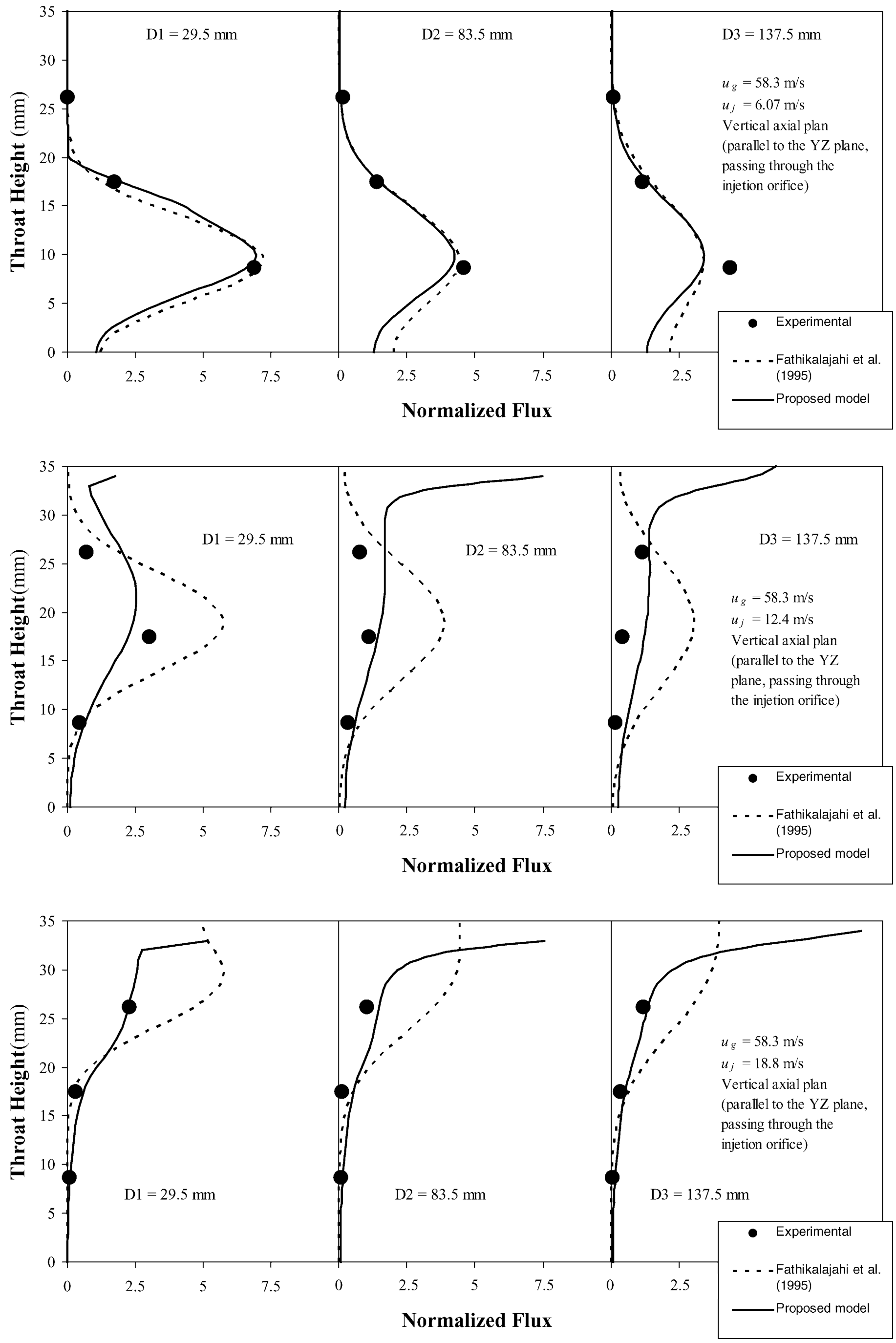


Fig. 6. Normalized droplet flow in the vertical plane that contains the jet (parallel to the *YZ* plane, passing through the injection orifice) at three distances from the injection (29.5, 83.5, 137.5 mm), for $\mathbf{u}_g$ = 58.3 m/s and u_j = 6.07, 12.4 and 18.8 m/s. Experimental points are compared to theoretical predictions.

al. [2] for droplet distribution in the throat (163 mm in length) of the Venturi scrubber operating with the same gas and jet velocities mentioned above. Fig. 4b and c and Fig. 5b and c show a vertical plane passing through the injection orifice, while Fig. 4d and e and Fig. 5d and e represent a cross-sectional cut 29.5 mm after the injection point.

The main difference between the proposed model and that of Fathikalajahi et al. [2] is clearly visible in Fig. 4b–e and Fig. 5b–e. The simpler jet dynamics adopted by Fathikalajahi et al. [2], which represents the jet by a single atomization point and does not attribute an initial transversal moment for the droplets, results in a droplet dispersion pattern that is symmetrical around the axis passing through the "atomization point". Such symmetry is not seen in the photographic evidence. On the other hand, the proposed model, by using a jet atomization theory which allows for multiple source points along the jet trajectory and also provides information on the jet velocity vector at each of these points,

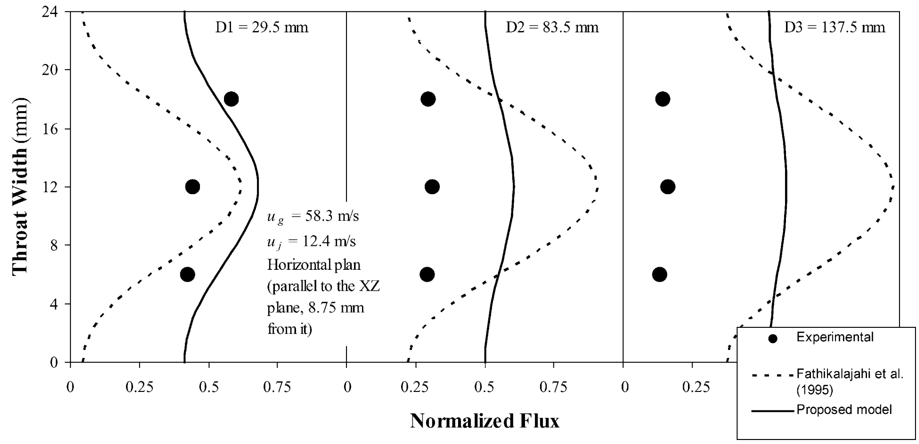


Fig. 7. Normalized droplet flow in the horizontal plane parallel to the wall which contains the liquid injection orifice (this wall coincides with the *XZ* plane) and distant 8.75 mm from such wall, at three distances from the injection (29.5, 83.5, 137.5 mm), for $\mathbf{u}_g$ = 58.3 m/s and u_j = 12.4 m/s. Experimental points are compared to theoretical predictions.

which can be used to describe the initial droplet moment in both the *y*- and *z*-directions, displays a better qualitative agreement with the photographic evidence. Although all of these factors contribute significantly to the better agreement, it seems that the consideration of the convective mass flux in the y direction is the most significant.

In order to evaluate the proposed model in a quantitative way, we present in Figs. 6–8 typical theoretical normalized droplet flux profiles and compare them with the experimental data. Fig. 6 illustrates the nine profiles in the vertical plane that contains the jet (parallel to the *YZ* plane, passing through the middle of the injection orifice), for a fixed gas velocity

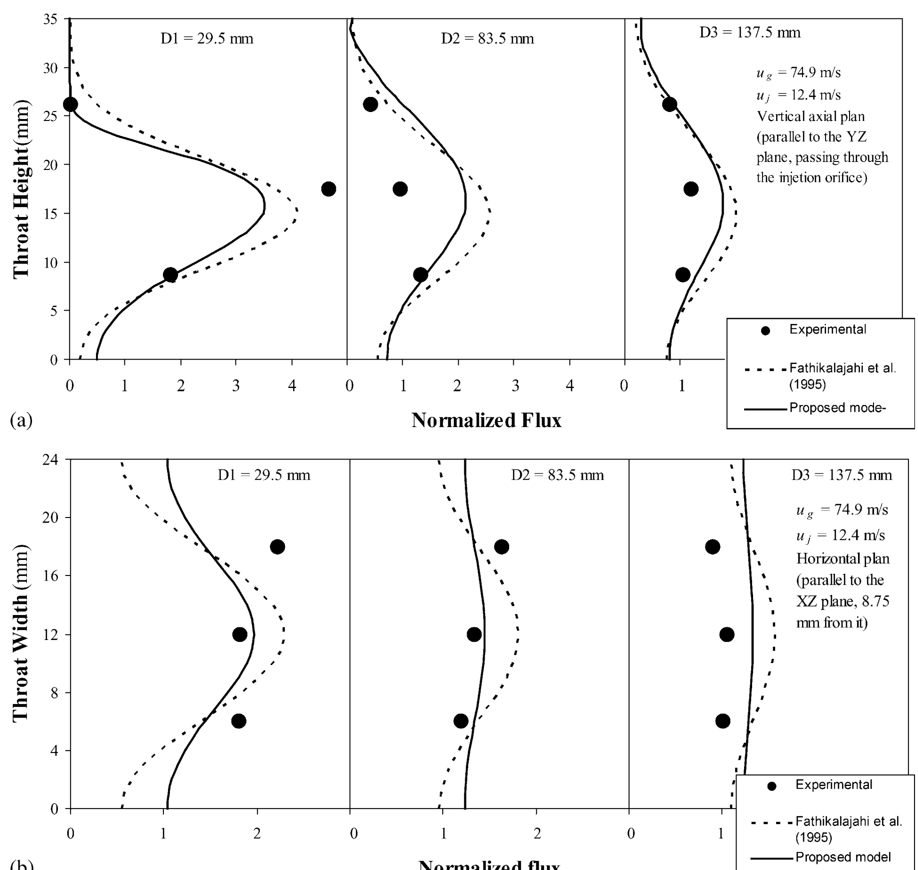


Fig. 8. Normalized droplet flow in (a) the vertical plane that contains the jet (parallel to the *YZ* plane, passing through the injection orifice) and in (b) the horizontal plane parallel to the wall which contains the liquid injection orifice (this wall coincides with the *XZ* plane) and distant 8.75 mm from such wall, at three distances from the injection (29.5, 83.5, 137.5 mm), for $\mathbf{u}_g$ = 74.9 m/s and u_j = 12.4 m/s. Experimental points are compared to theoretical predictions.

of 58.3 m/s, and combinations of the three liquid jet velocities (6.07, 12.4 and 18.8 m/s), representing both high and low penetrating jets, and the three measurement distances along the throat (29.5, 83.5 and 137.5 mm). Fig. 7 illustrates the profile in the horizontal plane parallel to the wall which contains the liquid injection orifice (the *XZ* plane), and distant 8.75 mm from it, for gas and jet velocities of 58.3 and 12.4 m/s, respectively (same condition as in Fig. 4), and three measurement distances along the throat. Fig. 8 illustrates the same vertical and horizontal planes for another gas velocity, namely, 74.9 m/s, and jet velocity of 12.4 m/s.

It can be seen that most of the experimental points are qualitatively correct: the maximum concentration point decreases as the droplet cloud travels down the throat (leading to a more uniform distribution) and are located in higher positions as jet velocity increases or gas velocity decreases (corresponding to jets with higher penetration). The proposed model predicts satisfactorily these tendencies in most cases.

Fig. 7 presents an experimental result which both models failed to predict. The droplet normalized flux in the plane represented in the figure (parallel to the *XZ* plane) decreased from an average of approximately 0.50 at distance D_1 to 0.15 at distance D_3. In any diffusion model, the tendency is towards a uniform distribution. This means that at a great distance from the injection point, the droplet normalized flux was expected to be close to one (only discounting loss to the wall) at any point. As at distance D_1 this flux is smaller than unity, both models predicted an increase with distance. Since the plane shown is located in the top half of a horizontal throat, gravitational settling, not considered in the models, may be more important than initially thought.

One of the difficulties with the proposed modeling procedure was in estimating the droplet diffusivity, hence the Peclet number. Fathikalajahi et al. [2] suggest $Pe = 130$, which underestimated the diffusion observed here. In the case of this work, the best results for the model of Fathikalajahi et al. [2] were obtained with $Pe = 50$ and, for the model proposed here, $Pe = 40$. Reported [13] values of *Pe* for clean air flowing in smooth tubing in fully developed flow are around 1000. A 10-fold decrease would be expected if wall roughness due to liquid film and convergent flow instabilities are taken into account [21]. Besides, Azzopardi and Teixeira [22] suggest that the presence of the droplets induces the increase in the intensity of the turbulence, resulting in higher diffusivities and decreasing *Pe* further. In Venturi scrubbers flows, the reported values for *Pe* are 130 [2], 100 [3] and 10 [9]. The value adopted in the proposed model ($Pe = 40$) is within this range.

The experimental data also indicate a quick dispersion of the droplets in the lateral (x) direction (see Figs. 4a, 5a, 7 and 8b), which was accounted for in present model by its assumption of non-isotropic turbulence.

6. Conclusions

The main conclusions can be summarized as:

- There are regions of high and low concentration of liquid in the throat of a Pease–Anthony Venturi scrubber. Liquid coverage in the throat is sensitive to operational conditions such as gas velocity and jet velocity.
- The proposed model, that incorporates momentum to the liquid jet and its partial atomization before bursting, produces simulations that are visually very similar to the actual jet.
- The droplet dispersion predicted by the proposed model represented well the experimental data.

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