Estimating Maximum Removal Efficiency in Venturi Scrubbers

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A simplified 2-D model to predict liquid flux distribution and collection efficiency in a Venturi scrubber was tested successfully with experimental data from pilot- and industrial-scale units. Establishing nonuniformity of flux distribution is the key to estimating collection efficiencies accurately. Liquid jet penetration and liquid injection velocity are critical in defining flux distribution for the entire range of conditions simulated. Increase in gas velocity makes flux distribution more uniform and enhances collection efficiencies. This effect becomes insignificant beyond a gas velocity as finer droplets get accelerated quickly to the throat gas velocity giving the collector very little interaction time. Increase or decrease in the liquid to gas (L/G) ratio beyond an optimum value made flux distribution more nonuniform and decreases collection efficiencies. Design parameters of the Venturi scrubber (aspect ratio and nozzle diameter) have an optimum that offers the most uniform flux distribution and the maximum collection efficiency. A new dimensionless group, the Venturi number, derived from the jet penetration correlation, could define both nonuniformity in flux distribution and collection efficiency for changes in the L/G ratio, aspect ratio, nozzle diameter, and number of nozzles. Simulation results indicate that a maximum efficiency exists for the Venturi number between 1.0 and 1.5×10^{-3}. The useful length of the scrubber throat could be determined from the L/G ratio defined by the Venturi number concept and appropriate throat gas velocity.

Introduction

The Venturi scrubber is a high energy impaction, atomizing system that is useful for controlling emissions of both particulate and gaseous pollutants (Figure 1). The particulate collection efficiency of a Venturi scrubber is a complex function of many variables including aerodynamic particle size, liquid-to-gas (L/G) ratio, liquid jet penetration, liquid drop-size distribution, throat coverage by liquid drops, film flow rates, and geometrical configuration of the scrubber. Several attempts have been made to theoretically optimize Venturi scrubbers (Goel and Hollands, 1977; Leith and Cooper, 1980; Cooper and Leith, 1984; Haller et al., 1989). The principal limitations of all of these design approaches were the assumption of the existence of only a homogeneous core with uniform flux across the scrubber and the absence of film flow on the wall. Visual observations and experimentation have indicated the existence of an annular two-phase, two component flow with a thin liquid layer on the walls and a high velocity gas stream carrying the droplets in the core (Azzopardi and Govan, 1984; Haller et al., 1989; Koehler et al., 1987; Viswanathan et al., 1984; Boll, 1973; Guntheroth, 1966). As a result, the earlier design approaches include efficiency models that generally overpredicted efficiencies at all L/G ratios. To accurately describe the physical phenomena occurring in a Venturi scrubber, a true representation of the flux distribution throughout the scrubber must be available as a function of both operating and design variables. This article presents a new design procedure that has been developed to estimate maximum particle collection efficiency as a function of operating and design variables.

Literature Review

Since the first pilot-plant application of a Venturi scrubber to a Kraft recovery furnace in the mid 1940s, many attempts to predict Venturi scrubber performance have been made. These Venturi scrubber particulate collection theories involved many approaches such as correlation of experimental data to primary operating variables, simple analytical models, and detailed analyses requiring numerical solution.

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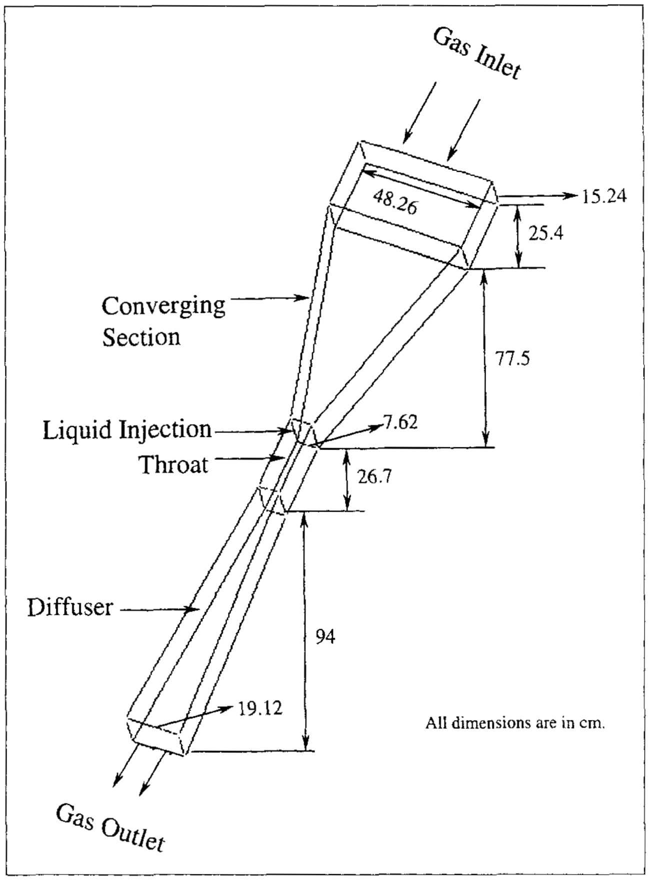

Figure 1. Venturi scrubber used for simulation.

Several important mathematical models to predict particle collection efficiency in a Venturi scrubber (Azzopardi and Govan, 1984; Behie and Beeckmans, 1973; Boll, 1973; Calvert, 1970; Ekman and Johnstone, 1951; Fathikalajahi et al., 1996; Placek and Peters, 1981, 1982; Viswanathan et al., 1984) use one of these approaches. Most of the earlier design approaches are based on the analytical model developed by Boll (1973), considering drop motion and particle impaction on drops. In this approach, the flux distribution was assumed to be uniform across the scrubber and there was no turbulent mixing between drops and particles. However, it has been proven that Boll's approach overpredicts the collection efficiency since it does not account for maldistribution of drops within the scrubber (Viswanathan, 1997b). Goel and Hollands (1977) first used Boll's design approach to devise an optimization scheme for the design of Venturi scrubbers, but without considering such issues as nonuniform flux distribution and film flow on the walls. Cooper and Leith (1984) proposed a 1-D model that does not account for film flow and assumes uniform throat coverage by liquid drops. Based on the analysis, they concluded that the conditions necessary to obtain optimum Venturi performance change with particle diameter, throat gas velocity, and scrubber geometry. Their assumptions are still unrealistic for a real scrubber. The importance of nonuniform distribution of droplets was recognized by Haller et al. (1989), when they proposed a two-zone model: droplet-laden and droplet-free zones. They proved experimentally that the occurrence of an annular flow within the scrubber system determines the efficiency and pressure drop. Although they proved that the collection efficiency could be improved experimentally, their model is too simplistic to determine flux distribution over a wide range of operating conditions. Fathikalajahi et al. (1996) recently proposed a 3-D model that takes into account the nonuniformity of flux distribution by considering liquid jet penetration developed by Viswanathan et al. (1983). Several details on the initial treatment of drops, such as initial drop velocity, were not mentioned. Viswanathan (1997b) recently proposed a 2-D model considering key variables affecting scrubber performance. This model, although detailed, required enormous computer time to solve and, hence, its applications may be somewhat limited. This article presents a new design procedure developed to estimate maximum particle collection efficiency in a Venturi scrubber. The model accounts for initial liquid momenta, drag forces, and turbulent diffusion. It also incorporates two important parameters, jet penetration and drop size, which are physically well defined and can be correlated with such variables as gas velocity, nozzle diameter, liquid injection velocity, and scrubber geometry.

Theoretical Model

The performance of a Venturi scrubber greatly depends on the liquid injection, drop size, liquid flux distribution, and initial liquid momenta. The majority of the collection process occurs in the throat because of the presence of a high degree of turbulence in the region caused by large relative velocities between the drops and particles. Hence, it is important for the theoretical model to predict the flux distribution as closely as possible within the throat. Recent models (Viswanathan, 1997b; Fathikalajahi et al., 1996) consider most of these conditions but at the expense of large computational requirements. This work is to develop a simplified model that factors jet penetration length, maldistribution of liquid drops, initial liquid momenta, drop movement in the axial direction by convection and in the lateral direction solely due to convective diffusion, nonuniform inlet dust size distribution, dust motion in axial direction through convective mechanism and in the lateral direction through convective diffusion mechanism, and particulate matter collection by droplets through inertial impaction. The model assumes uniform drop size, constant film flow, no drop-to-drop interactions, uniform inlet distribution of particles, and no interaction between particles. Only one-half of the scrubber is considered for simulation, assuming the system is symmetric. Since, in all practical applications, the separation distance between the liquid injection orifices is very small, negligible variation in the drop concentration can be assumed in the z-direction making the model 2-D (Viswanathan, 1984, 1997b). This makes the entire system axisymmetric with respect to the physical area to be considered in the simulation.

Droplet motion

The droplet motion in this model is predicted as a steady-state process. The 2-D steady-state continuity equation for liquid drops can be written as

$$\frac{\partial}{\partial x}(V_{dx}C_d) = \frac{\partial}{\partial y}\left(E_d\frac{\partial C_d}{\partial y}\right) + Q_d - Q_f \qquad (1)$$

In Eq. 1, the change in concentration due to bulk motion is equated to the change due to convective diffusion plus the drop source strength minus the amount of liquid flowing as film on the walls. The fraction of liquid flowing on the walls dimensionless, averaged over the entire scrubber , for known operating and design conditions was obtained from the correlation (Viswanathan et al., 1997a)

$$F = \frac{89.379}{\left(\frac{L}{G}\frac{R_0}{d_0}\right)^{1.007}(V_{Gth})^{0.888}}$$

Liquid droplet velocity

The drop velocity in the axial (x) direction can be determined from a force balance on the drops as shown by Viswanathan (1997b)

$$\frac{dV_{dx}}{dx} = \frac{3}{4} C_{DN}\mu_G \frac{(V_G - V_{dx})}{D_d^2 \rho_d V_{dx}} \tag{2}$$

The value for C_D is calculated using the equation (Fathikalajahi et al., 1995)

$$C_D = \frac{25.8}{N_{Re}^{0.81}} \tag{3}$$

Mean droplet diameter is calculated using Boll's Equation

$$D_d = \frac{42{,}200 + 5{,}776\left(\frac{L}{G}\right)^{1.932}}{V_{Gth}^{1.602}} \tag{4}$$

Eddy diffusivity

Eddy diffusivity of the drop and particle can be calculated using the concept that velocity fluctuations in turbulent flow are sinusoidal and Stokes' Law applies to the drag on drops

$$\frac{E_d}{E_G} = \frac{b^2}{\omega^2 + b^2}; \quad \frac{E_p}{E_G} = \frac{b^2}{\omega^2 + b^2} \tag{5}$$

The value of ω was taken as 300 and $E_G/(V_G D_{eq}) = 0.01$ (Viswanathan, 1997b).

Particle motion

The 2-D, steady-state, continuity equation describing the transport of particulate matter, neglecting longitudinal diffusion, has the form (Viswanathan, 1997b)

$$0 = -V_G \frac{\partial C_p}{\partial x} + \frac{\partial}{\partial y}\left[E_p \frac{\partial C_p}{\partial y}\right] - \sum_{i=1}^{m^*}\sum_{j=1}^{n^*} \frac{\pi \eta_{ij} F_i}{4} D_{dj}^2 (V_G - V_{dxj}) C_p C_{dj} \tag{6}$$

This steady-state equation is similar to Eq. 1 for droplet motion, except that the source term in Eq. 1 was replaced by a dust removal term. The principal collection mechanism in a Venturi scrubber is inertial impaction. The single drop collection efficiency η can be calculated from (Calvert et al., 1972; Taheri and Sheih, 1975; Fathikalajahi et al., 1996)

$$\eta_{ij} = \left(\frac{\Psi}{\Psi + 0.7}\right)^2 \tag{7}$$

Determination of overall collection efficiency

The overall collection efficiency at any axial location can be calculated by determining the concentration of particulate matter at that location by an integration process. The overall collection efficiency is given by

$$\eta_{ov} = 1 - \frac{\int C_{p(x,y)} dy}{\int C_{p(0,y)} dy} \tag{8}$$

Numerical Procedure

Since the system is axisymmetric, the total volume chosen for simulation accounts for one nozzle (z direction), the entire length of the scrubber (x direction), and one-half of the width of the scrubber (y direction). The physical space is divided into cells of a fixed Eulerian grid and the Lagrangian mass particles carry the fluid from cell to cell by the sum of bulk and turbulent velocities. In order to evaluate the movements of each mass particle, the bulk velocity, eddy diffusivity, gas stream drag, and initial liquid momenta are calculated. The initial position of the liquid drops (jet penetration) is very important, because it affects the flux distribution significantly. In this work, the initial position of the liquid drops is assumed to correspond to the point of jet atomization as measured by (Viswanathan et al., 1983)

$$\frac{l^*}{d_0} = 0.1145 \frac{\rho_j V_j}{\rho_G V_{G,th}} \tag{9}$$

The flux distribution at any axial position is obtained by applying a central difference formula on Eq. 1 and representing it in tridiagonal matrix form. Values of the drop concentration for each cell is then calculated by solving this matrix using Gaussian elimination and back substitution. Particulate matter is introduced as uniformly distributed dust particles moving with the same velocity as the gas stream. The particle distribution at any axial position is then determined in a way similar to the flux distribution. From the concentrations, the overall cleaning efficiency at any axial location is calculated using Eq. 8.

Results and Discussion

All the results discussed are evaluated at the throat end except for the industrial-scale scrubber, where they are evaluated at the end of the scrubber. Assumed changes in scrubber dimensions have been specified. Otherwise the original design specifications hold.

Model validation

The model is validated by first comparing theoretical flux distribution with experimental values measured in a pilot-

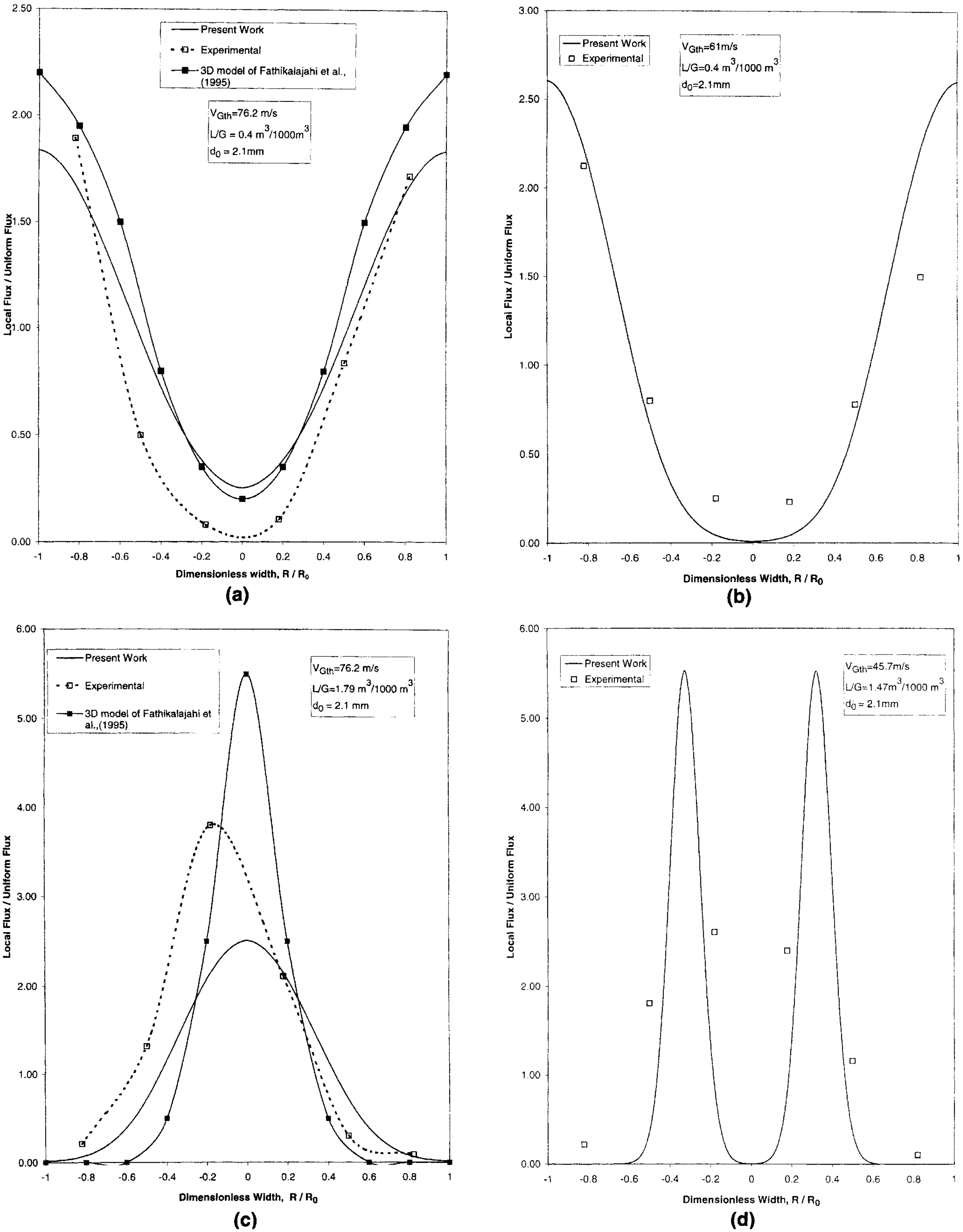

Figure 2. Experimental vs. predicted flux distribution in a pilot-scale scrubber.

scale Venturi scrubber (Viswanathan et al., 1984). Then, particulate collection efficiency measured in an industrial-scale scrubber is modeled before performing simulation for a wide range of operating and design conditions using the approach mentioned in this work.

Figures 2a to 2d provide a comparison of experimental and predicted flux distributions for a combination of gas velocities and L/G ratios. In addition, they also provide a comparison of the predicted values of flux distribution from a 3-D model of Fathikalajahi et al. (1995) wherever available. The model predictions using the proposed approach compare reasonably well with experimental values as that of Fathikalajahi et al. A very close match of flux distribution has not been demonstrated by any model until now. This is because the dispersion process is so complicated that there may be limitations in representing the various phenomena occurring within the system in the model equations and subsequently solving them using advanced computational methods. The flux distribution correlation developed in a pilot scrubber using a statistical fit of concentration distribution by Koehler et al. (1987) is scrubber specific and, hence, has limited use. The proposed approach, however, predicts consistent trends of flux distribution over a wide range of operating conditions. Hence, the proposed model predicts flux distribution in the scrubber well.

To validate the versatility of the model, the Brink and Contant industrial-scale scrubber was simulated. The efficiency data (Brink and Contant, 1958) are compared with the calculated values in Figure 3. This model predicts values that are in good agreement with the experimental data. Therefore, this 2-D model, although simplified, takes into consideration important factors, like nonuniform flux distribution and initial liquid momenta, that characterize a more realistic scrubber and predicts flux distribution and collection efficiency accurately.

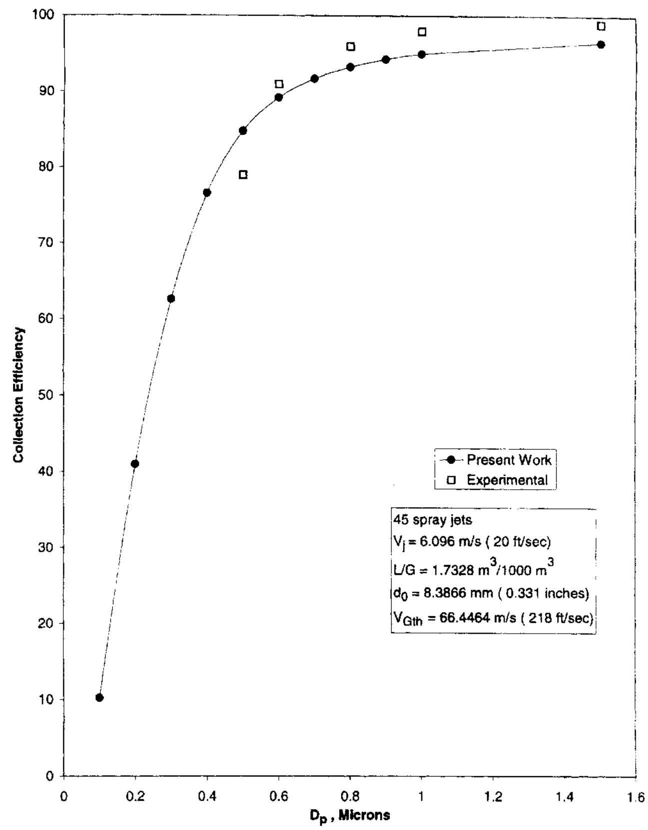

Figure 3. Model prediction vs. experimental data of Brink and Contant.

Estimating optimal parameters for maximum collection efficiency

To identify the effect of design and operating parameters on particulate collection efficiency, flux distribution values were predicted over an extensive range of operating and design conditions for the pilot-scale scrubber. Since the flux measurement in the pilot-scale scrubber is available only at the end of the throat, all comparisons are made at this location. In addition, most of the particulate collection occurs within the throat of the scrubber and flux distribution is expected to be best at this location within the throat. The operating parameters used for simulation include L/G ratio of 0.40–1.79 m^3/1,000 m^3 and throat gas velocity of 30–120 m/s.

Effect of Throat Gas Velocity. Figures 4a and 4b illustrate the effect of throat gas velocity on collection efficiency. Higher throat gas velocities give higher collection efficiency, when all conditions such as L/G ratio, nozzle diameter, and Venturi geometry remain the same. Increase in gas velocity for a constant liquid loading essentially increases the liquid rate. Higher gas velocities produce finer droplets. There is no change in jet penetration as the liquid injection velocity increases or decreases proportionally with the throat gas velocity. However, it is clear that the flux distribution does change as shown in Figure 4a. This effect is in agreement with observations reported by Viswanathan (1997b). However, Fathikalajahi et al. (1996) have reported that the flux distribution does not change as a function of throat gas velocity when L/G is constant. This observation is true only for gas velocities beyond 80 m/s, as shown in Figure 4a. Therefore, higher gas velocities result in a greater number of finer droplets (higher impaction efficiency), and uniformity of flux distribution, thereby giving rise to higher collection efficiency as has been previously observed by many researchers (Placek and Peters, 1981; Viswanathan, 1997b). This effect becomes minimal beyond a particular gas velocity resulting in no significant changes in the removal efficiency. This phenomenon could be explained by the fact that, although finer droplets are formed and more liquid is injected with increasing gas velocity, the flux distribution remains the same and the finer droplets are accelerated very quickly to the gas velocity giving the collector very little interaction time, thereby negating all other factors aiding the collection process.

Effect of Liquid to Gas Ratio. It can be seen from Figures 5a and 5b that there is an optimum L/G ratio at which the droplets are uniformly distributed and the collection efficiency is maximum, while all other parameters are fixed. Increasing L/G ratio, at a constant throat gas velocity, affects jet penetration due to changes in initial liquid momenta. This, in turn, affects the uniformity of flux distribution. Change in drop size with L/G ratio was noted for the range of L/G ratios chosen as reported by Fathikalajahi et al. (1996). Although a higher L/G ratio has more liquid available for scrubbing, bigger drops are formed, and the nonuniformity of

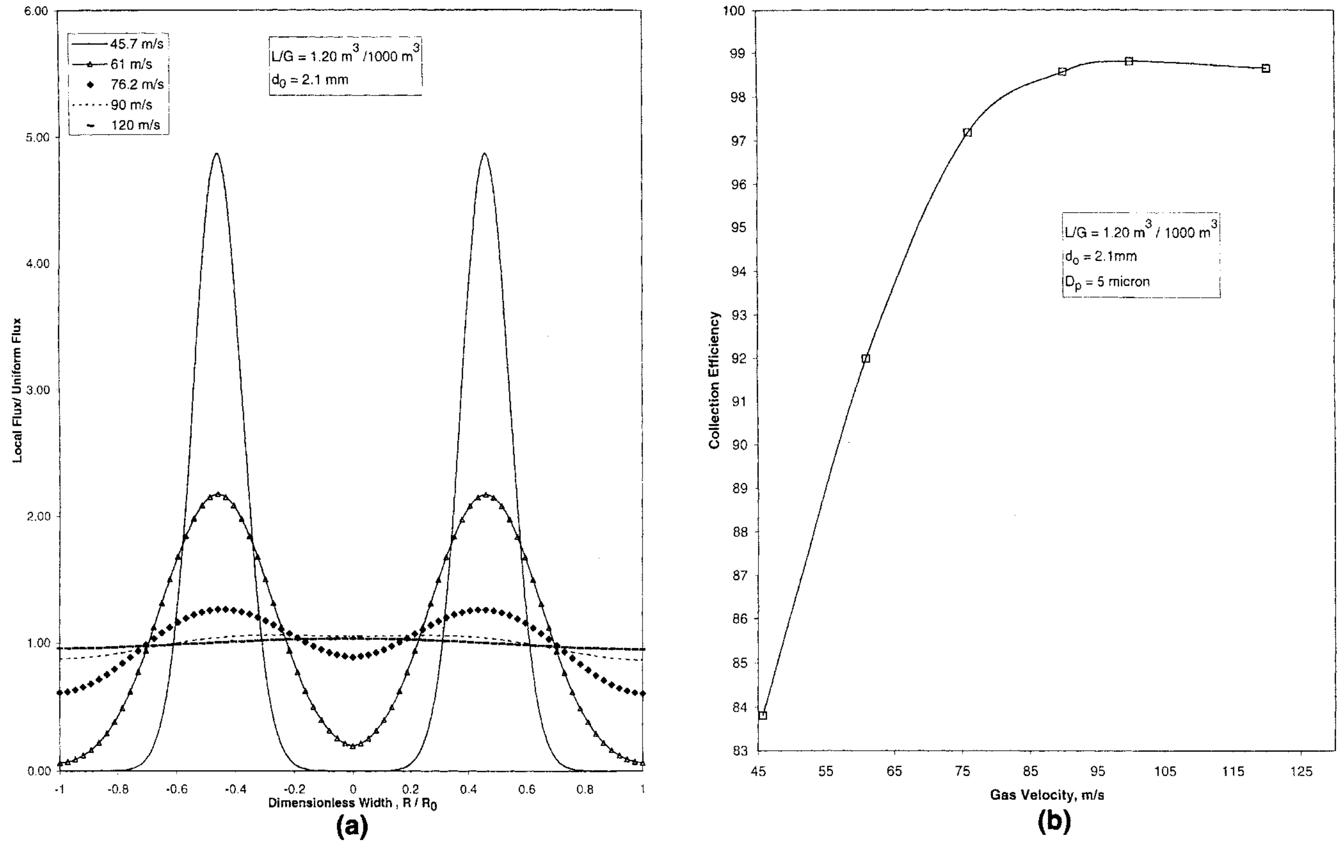

Figure 4. Pilot scrubber. (a) Effect of throat gas velocity on flux distribution; (b) effect of throat gas velocity on collection efficiency.

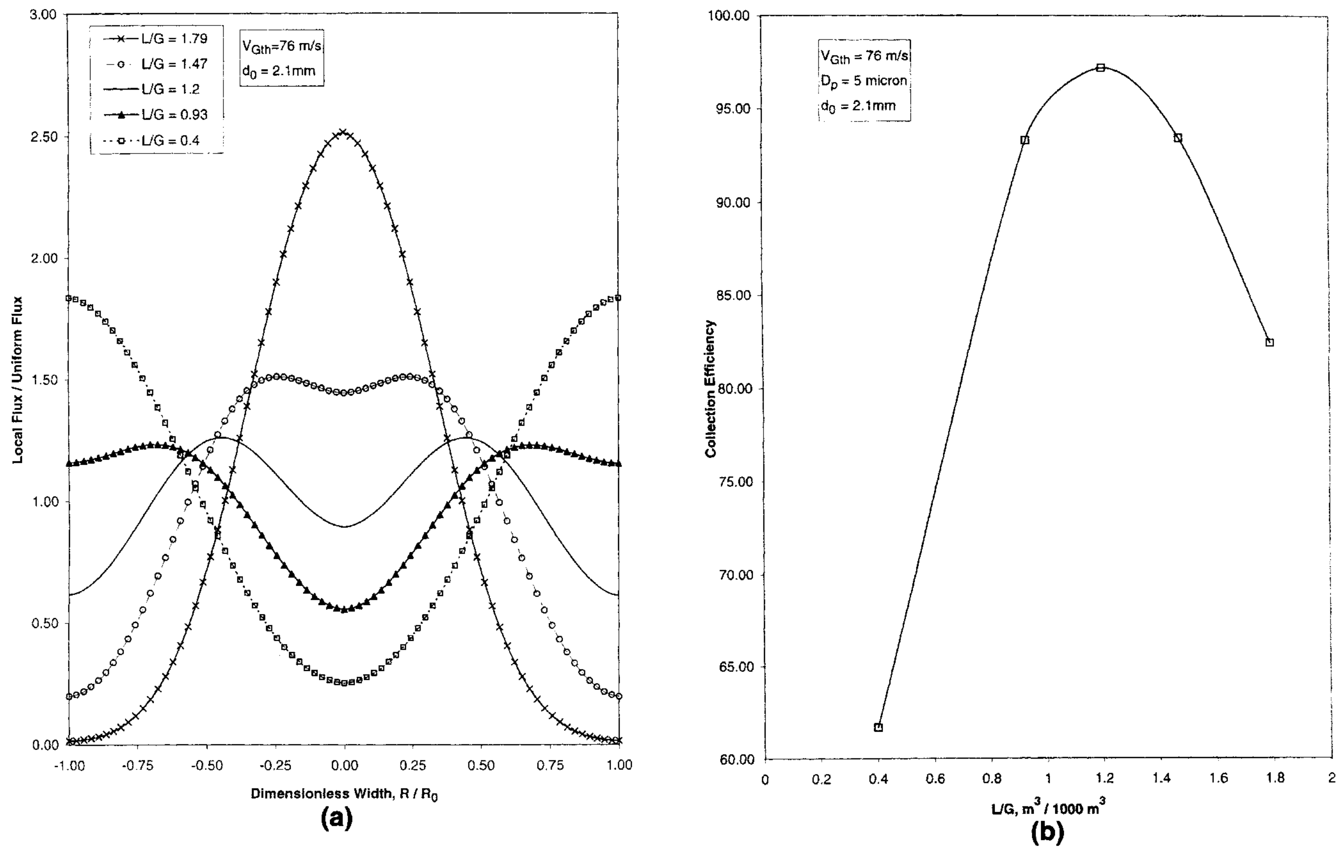

Figure 5. Pilot scrubber. (a) Effect of L/G ratio on flux distribution; (b) effect of L/G ratio on collection efficiency.

the flux distribution (Figure 5b) has a dominating negative effect on particle collection resulting in lower collection efficiencies. From Figure 5b, it is evident that maximum efficiency is obtained for an optimal L/G ratio of 1.20 m^3/1,000 m^3 which gives the most uniform throat coverage. This was found to be true for all operating conditions simulated. Throat gas velocity and L/G ratio are two operating parameters considered fundamental to any Venturi design model and their effects on flux distribution are well established. It is also known that the reasons for variations in flux distribution are not limited to these two variables. Other variables, such as the liquid injection system and throat dimensions that affect flux distribution, should be represented in the form of fundamental equations to merit a systematic and meaningful analysis. From Eq. 9, the jet penetration as a fraction of the throat radius can be written as

$$\frac{l^*}{R_0} = 0.1145 \frac{\rho_j V_j}{\rho_G V_G} \frac{d_0}{R_0}$$

Rewriting the above equation in terms of L/G ratio and substituting $A_{th} = W_0(2R_0)$ for rectangular cross-section and $A_{noz} = \pi/4(d_0)^2$ results in the following equation

$$\frac{l^*}{R_0} = 16 \frac{0.1145}{\pi} \frac{\rho_j}{\rho_G} \left[\frac{L}{G^*} \frac{R_0}{d_0} \frac{Z}{n_j} \right] \tag{10}$$

in which $Z = W_0/2R_0$. From Eq. 10, it is evident that l^*/R_0 is proportional to $[(L/G^*)(R_0/d_0)(Z/n_j)]$ and the nozzle diameter and aspect ratio can affect the flux distribution.

Since design of the throat dimensions and liquid injection arrangement are critical to the collection efficiency, the pilot scrubber is simulated for $0 < Z < 5$ and d_0 (mm) = 1.40, 2.10, 2.57, 3.18, 3.86.

Effect of Aspect Ratio. This effect on flux distribution is shown in Figures 6a and 6b. The flux was obtained at an L/G ratio of 1.20 m^3/1,000 m^3 and a throat gas velocity of 76 m/s. The aspect ratio was varied in such a way that the throat cross-sectional area remained the same. This ensured that certain operational parameters, like gas-flow rate and liquid rate, were not altered. The number of nozzles was fixed at 34 as per the design of the pilot scrubber. The distance between nozzles varies as a result of the change in aspect ratios. This distance was maintained within reasonable limits to maintain the assumed negligible flux distribution variation in the plane of injection. In this analysis, the nozzle to nozzle distance varied from 2.5–11.4 mm for the aspect ratios studied. Figure 6a shows that there exists an aspect ratio at which the flux distribution is most uniform. It was observed that changes in aspect ratio altered the jet penetration length resulting in different flux distribution. Figure 6b shows that the removal efficiency is maximum at aspect ratios between 2 and 3.

Effect of Nozzle Diameter. Changes in nozzle diameter affect the liquid injection velocity. A decrease in nozzle diameter increases the liquid injection velocity and *vice versa* for a scrubber geometry at constant L/G ratio and throat gas velocity. It alters the jet penetration length. Higher injection

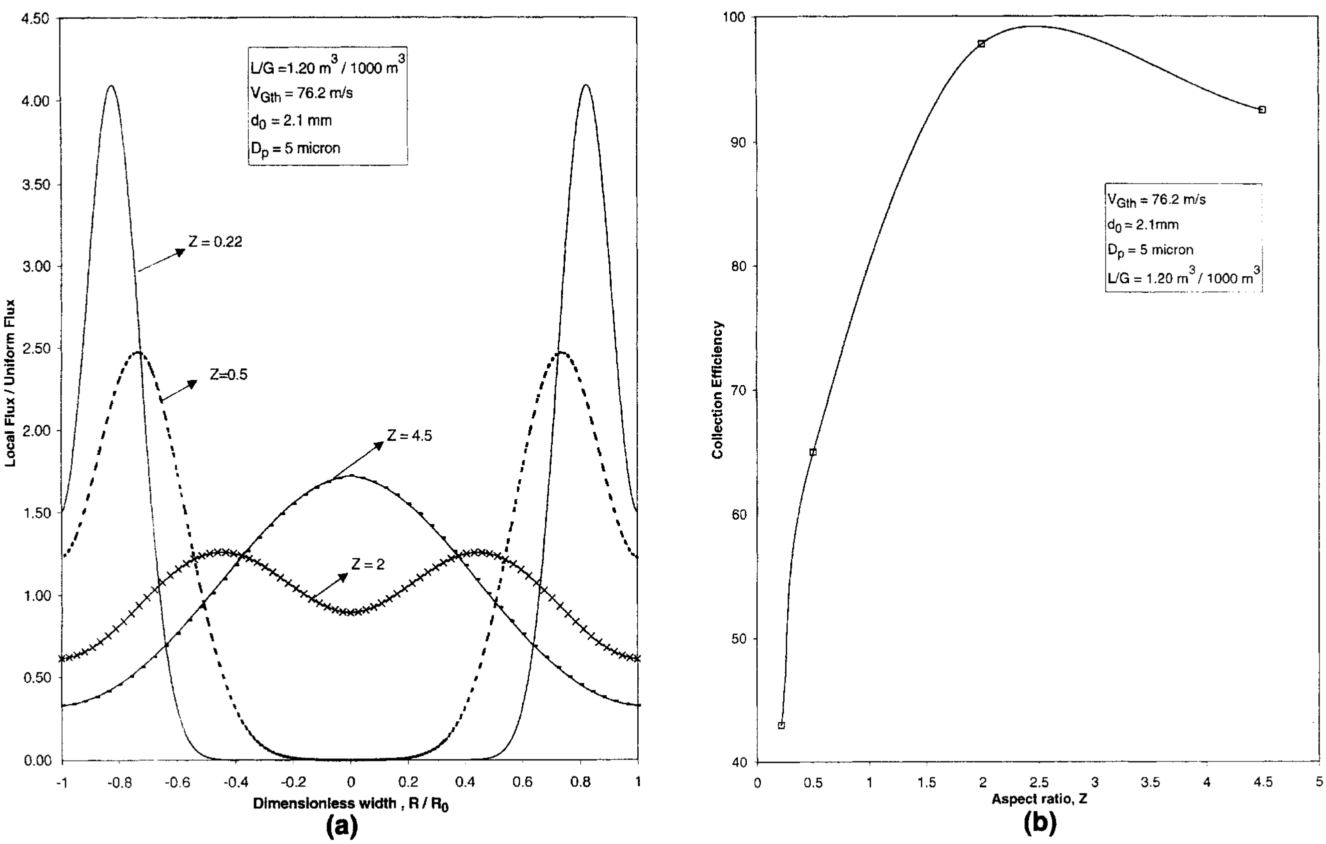

Figure 6. Pilot scrubber. (a) Effect of aspect ratio on flux distribution; (b) effect of aspect ratio on collection efficiency.

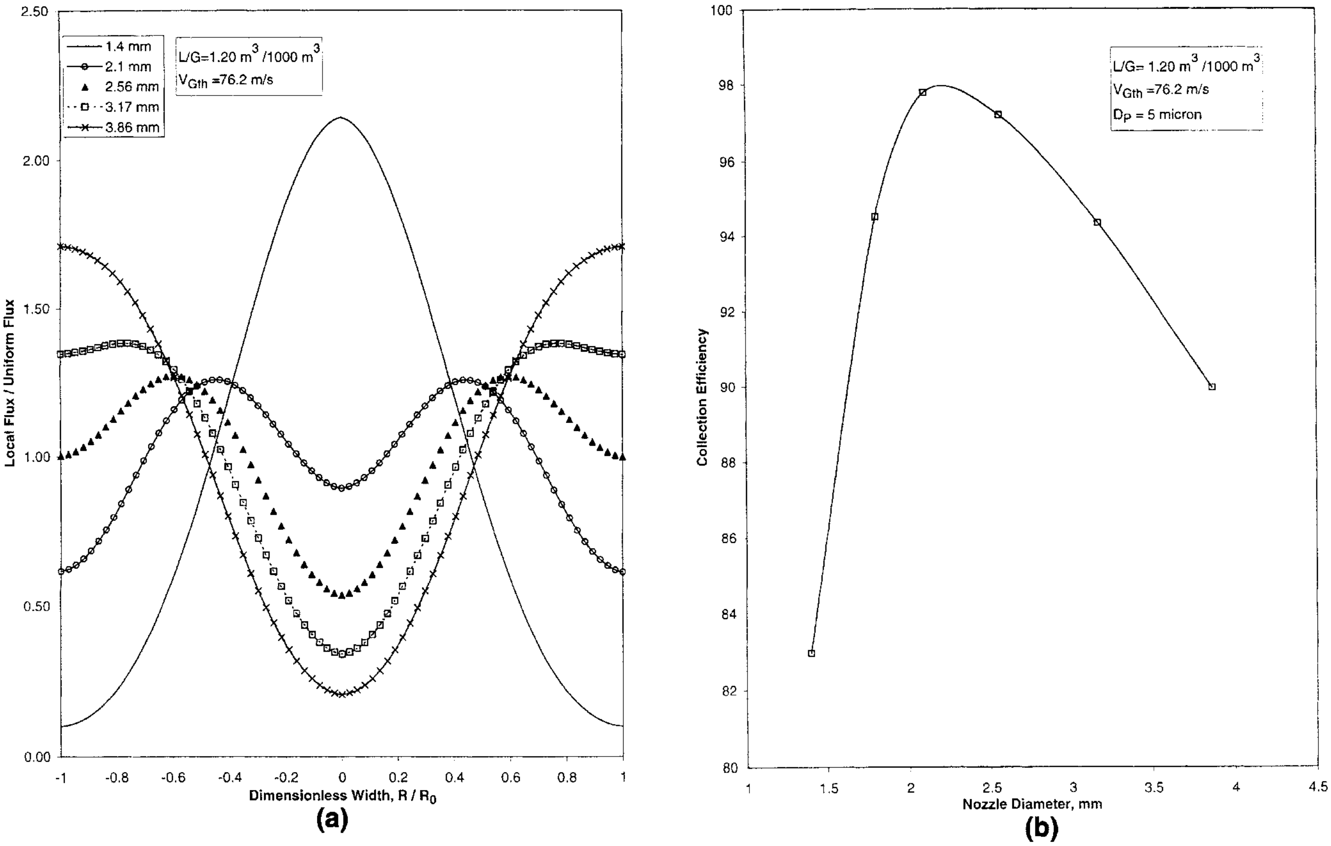

Figure 7. Pilot scrubber. (a) Effect of nozzle diameter on flux distribution; (b) effect of nozzle diameter on collection efficiency.

velocities increase the jet penetration length, thus atomizing the jets further away from the scrubber wall and making a lesser amount of liquid flow as film on the walls. However, a very high penetration length causes nonuniformity in droplet flux distribution and impedes the collection efficiency. Figures 7a and 7b show the variation in droplet flux and collection efficiency as a function of nozzle diameter. An increase in nozzle diameter from 1.4 to 2.1 mm gives a 15% increase in efficiency, and a further increase to 3.86 mm decreases the efficiency by 8%. Evidently, jet penetration length is critical to the removal efficiency since changes in nozzle diameter at constant throat gas velocity and L/G ratio affect jet penetration. Fathikalajahi et al. (1996) reported similar observations using a 3-D model approach for the Brink and Contant scrubber.

Venturi Number Concept. As the simulation shows, the flux distribution varies as a function of gas throat velocity, L/G ratio, nozzle diameter, and aspect ratio. Though smaller drop size and higher liquid loading help remove efficiency, the jet penetration length has a dominating effect on the uniformity of flux distribution and dictates the collection process. The parameters analyzed previously can be combined to form a dimensionless group identified as the Venturi number

$$\text{Venturi number, } V_N = \left(\frac{L}{G^*} \frac{R_0}{d_0} \frac{Z}{n_j} \right) \qquad (11)$$

Figures 8a to 8d show the effect of the Venturi number for a wide range of L/G ratios, throat gas velocities, nozzle diameters, and aspect ratios. The effect of number of nozzles was not considered in this work since the model assumes a negligible variation of flux in the plane of injection as a consequence of a good nozzle arrangement. From these figures, it can be seen that the maximum efficiency occurs within a constant range of the Venturi number for all operating conditions. At these conditions, it is found that the fractional jet penetration is between 25–35% of the throat width ($2R_0$). This was found to be the same by Fathikalajahi et al. (1996). Based on this analysis, the conditions that fix the jet penetration within these limits give the most uniform flux distribution and highest collection efficiency. It is important to note that the nozzle arrangement must be designed in such a way that there is a minimal variation due to dispersion of droplets, and, in turn, of flux distribution in the plane of injection. Moreover, for a fixed Venturi number, higher aspect ratios obtained by reducing the throat width results in higher collection efficiencies for the same L/G ratio and throat gas velocity. This effect becomes insignificant for higher aspect ratios, as shown in Figure 9. However, in this case, the throat cross-sectional area is not maintained constant. This affects the quantity of gas and liquid handled by the system. Now, the four parameters defining the Venturi number, namely, L/G ratio, nozzle diameter, aspect ratio, and number of nozzles can be chosen along with appropriate throat gas velocity to obtain maximum efficiency. Most optimal gas velocities are between 70–90 m/s, as can be seen from Figure 4b and as confirmed by Fathikalajahi et al. (1996) for the industrial scale

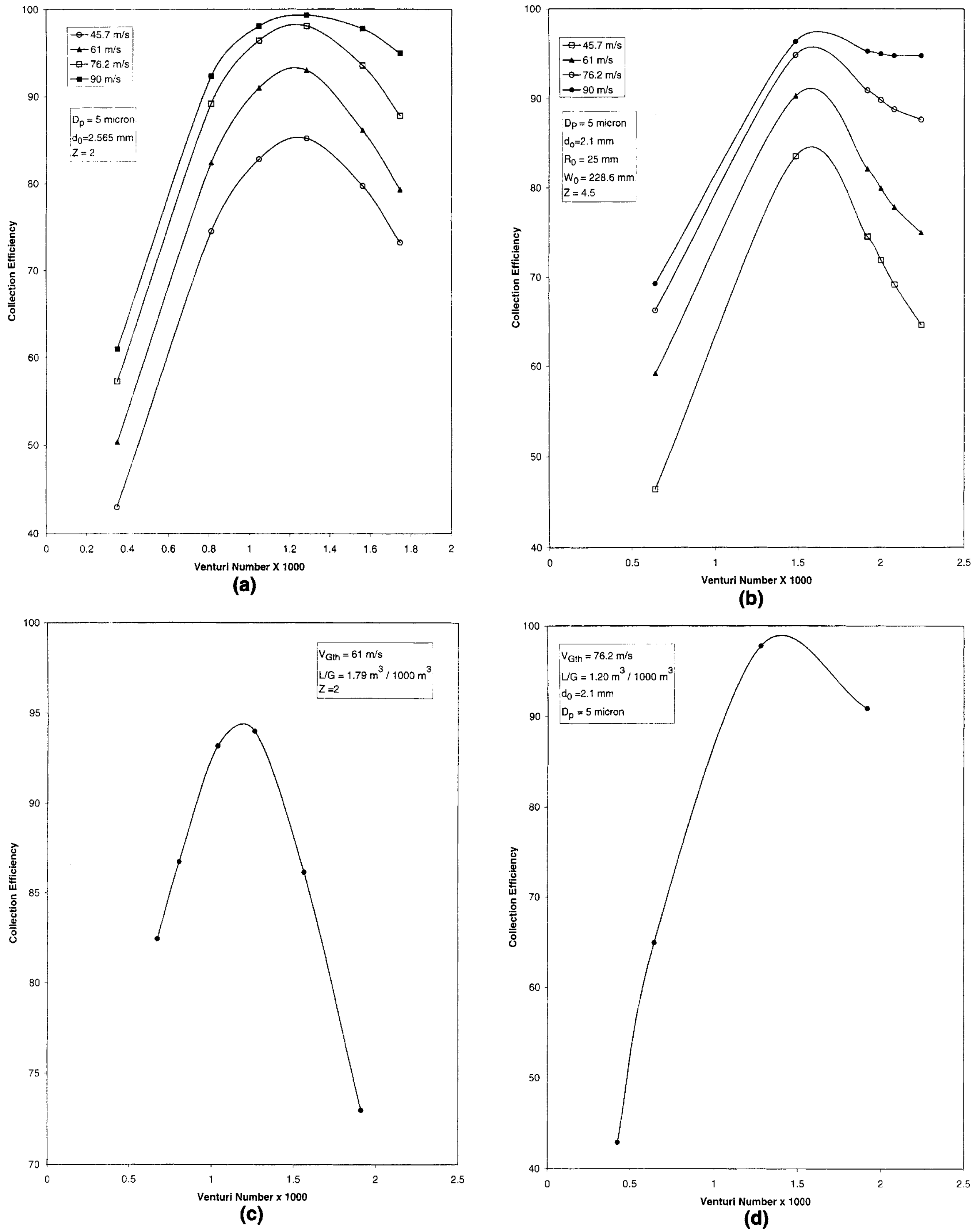

Figure 8. Venturi number with optimum conditions for the pilot-scale scrubber.

(a, b) Variation in L/G ratio and throat gas velocity for two widely varying conditions; (c) variation in nozzle diameter for the same L/G ratio; (d) variation in aspect ratio for the same L/G ratio.

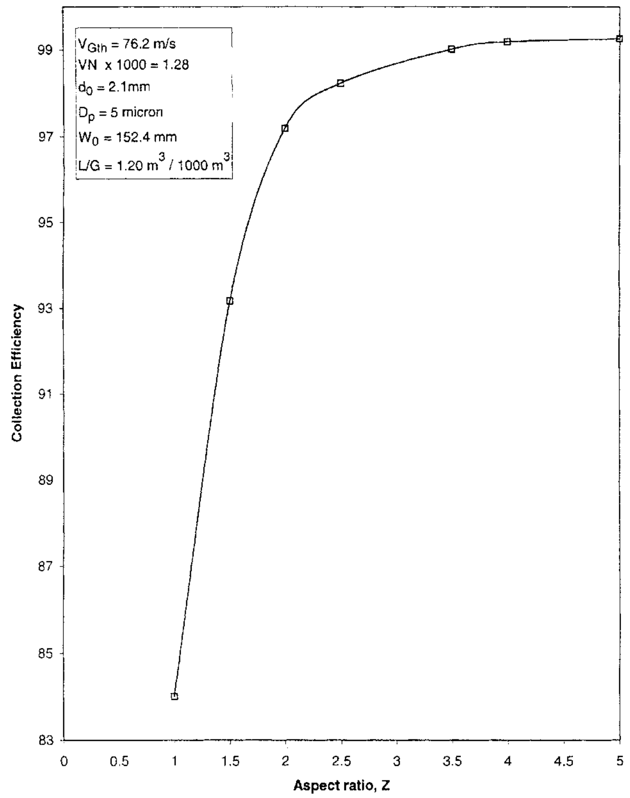

Figure 9. Effect of variation in aspect ratio on collection efficiency for a constant Venturi number.

scrubber. However, it is important to note that the ranges of variables selected to define the Venturi number should be practically feasible.

This analysis makes it clear that there is an optimal Venturi number which gives rise to maximum collection efficiency. Figures 4b, 5b, 6b and 7b show that the flux distribution under these conditions is most uniform at the end of the throat. However, the flux distribution changes along the length of the throat as the drops are accelerated by the gas stream. Figures 10a to 10c depict flux distribution along the throat length as contours of constant normalized flux. Flux distribution generated for the optimal Venturi number produced a near-uniform throat coverage along the entire throat. The two extreme conditions of the Venturi number yielded less than uniform coverage along the throat. Conditions in Figure 10c produced higher flux closer to the center, with zero/minimal flux closer to the walls due to higher jet penetration. However, lower flux values were observed closer to the center when the conditions resulted in lower jet penetration (Figure 10a). As the L/G ratio increases, the gas velocity and scrubber geometry being the same, the flux distribution changes significantly. This analysis also shows that the higher flux values at the beginning of the throat tend to distribute into lower flux values toward the end of the throat, thereby producing a relatively better coverage further downstream of the throat. Increase of liquid rate indiscriminately at constant gas velocity does not necessarily result in higher collection efficiencies since it may result in a high degree of maldistribution (Figure 10c). Haller et al. (1989) reported similar observations from their experimental studies on a pilot-scale Venturi scrubber. Hence, the optimal Venturi number not only gives the most uniform flux distribution at the throat end but ensures maximum throat coverage and liquid utilization. The optimization approach developed by Cooper and Leith (1984) does not consider key parameters that define flux distribution: nozzle diameter, initial liquid momenta, and nozzle arrangement. Since the jet penetration has been proved to be a very crucial factor in estimating maximum efficiency by this approach, their work could not be compared due to missing information such as nozzle diameter and the number of nozzles used. Note that their approach to optimization is scrubber-geometry specific, whereas the proposed Venturi number concept is readily applicable over a wide range of operating and design conditions.

The change in flux distribution along the throat makes the throat length another important design factor in the Venturi scrubber optimization problem. Even as the throat coverage becomes better as its length increases, the rate of change in collection efficiency is expected to be lower as the drop velocity approaches the gas velocity, generally toward the end of the throat. The throat has to be sufficiently long to ensure that the droplets reach near the throat gas velocity thereby assuring maximum collection efficiency. Too long a throat, beyond the above mentioned condition, will cause extra pressure drop with minimal gain in collection efficiency. A very short throat would not allow the drops to approach the throat gas velocity and would result in achieving less than desired collection efficiencies. Hence, a useful length of the throat exists, beyond which not much collection can be expected. The main collection mechanism in Venturi scrubbers is the inertial impaction with the relative velocity between the droplets and the gas stream being the driving force for the process. When the drops are at the throat upstream, where large relative velocities exist, the collection is expected to be maximum. Using as a reference the point at which the drop velocity equals the throat gas velocity, the useful throat length can be obtained by correlating L/G ratio, throat gas velocity, and useful length as

$$L_{th}^{*} = \left[\frac{369.561\left(\dfrac{L}{G}\right)^{0.293}}{V_{Gth}^{1.127}} \right] \tag{12}$$

Although the useful length as defined may be higher than the one normally required, an objective analysis of pressure drop with collection efficiency is necessary to estimate optimum throat length.

Conclusion and Recommendation

From this work, the following conclusions can be drawn:

- A 2-D model incorporating jet penetration can predict both flux distribution and collection efficiency accurately.
- Maximum efficiency is found to occur when penetration is around 25–35% of the throat width.
- Both gas velocity and L/G ratio affect uniformity of throat coverage. However, coverage seems to be less dependent on gas velocity than L/G ratio.

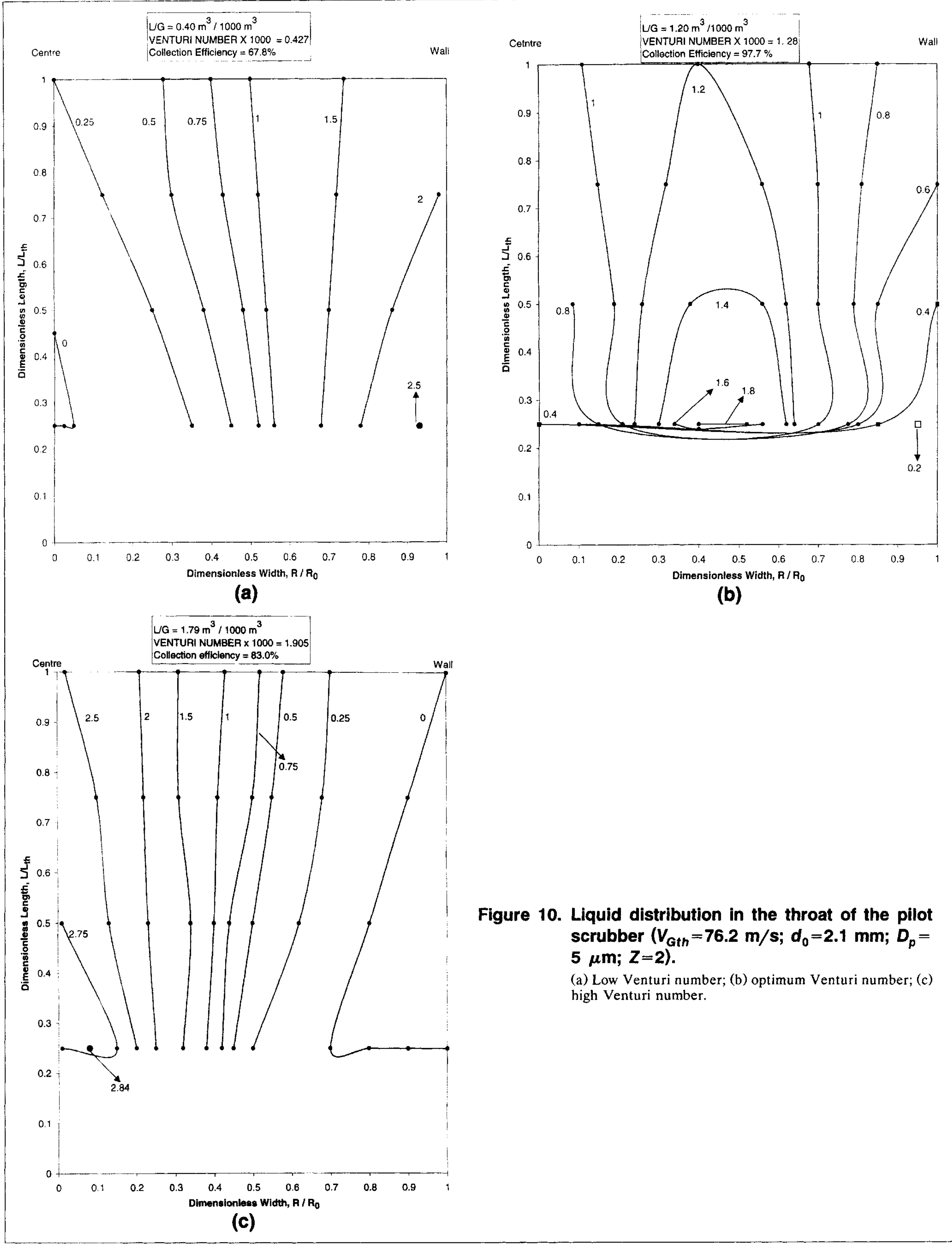

Figure 10. Liquid distribution in the throat of the pilot scrubber (V_{Gth}=76.2 m/s; d_0=2.1 mm; D_p= 5 μm; Z=2).

(a) Low Venturi number; (b) optimum Venturi number; (c) high Venturi number.

• The flux distribution is also a function of nozzle diameter and aspect ratio for which optimum values exist corresponding to maximum collection efficiency.

• A dimensionless group, Venturi number, derived from the jet penetration correlation, could define flux distribution and collection efficiency for changes in L/G ratio, aspect ratio, nozzle diameter, and number of nozzles. The Venturi number concept provides a concise and comprehensive method to optimize important operating and design parameters for maximum removal efficiency. Venturi numbers between $1.0–1.5\times10^{-3}$ offers the conditions for maximum efficiency.

• The useful length of scrubber throat could be obtained by using the L/G ratio defined by the Venturi number along with the appropriate throat gas velocity.

It is recommended that

• A simulation study be conducted to analyze the effect of multiple drop size on flux distribution and removal efficiency.

• Since specific nozzle configurations could affect the flux distribution, the effect of nozzle arrangement on collection efficiency should also be studied.

• To optimize scrubber performance, a correlation between Venturi number and pressure drop should be established.

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Notation

$\vec{a}$ = instantaneous drop acceleration, m/s^2
$b = 18\mu_G/\rho D^2$
C = concentration, no./m^3
C_D = standard drag coefficient
C_{DN} = modified drag coefficient, $C_{DN} = C_D * N_{Re}$
d_0 = orifice diameter, mm
D = diameter, m
E = eddy diffusivity, m^2/s
F_i = mass fraction of particulate matter belonging to the ith class
$\vec{g}$ = acceleration due to gravity, m/s^2
G = gas flow rate, 1,000 m^3/s
G^* = gas flow rate, m^3/s
L = liquid flow rate, m^3/s
L^* = useful length, m
l^* = jet penetration length at which the droplets form, mm
m^* = number of selected mean diameters describing particulate matter size range
n^* = number of selected mean diameters describing liquid drop size range
n_j = number of nozzles
N_{Re} = Reynolds number
Q_d = liquid drop source strength, no./m^3·s
Q_f = amount of liquid flowing as film on the wall, no./m^3·s
R_0 = half the Venturi throat, mm
V = velocity, m/s
W_0 = width of Venturi throat perpendicular to water injection, mm
x, y, z = rectangular coordinates, m
ρ = density, kg/m^3
η_{ij} = collection efficiency of particulate matter belonging to the ith class by droplets belonging to jth class
μ = fluid viscosity, kg/m·s
ω = frequency of air fluctuations, rad/s
ψ = impaction parameter, $|v_G - v_{dN}|P_p D_p^2/9\mu_G D_d$

Subscripts

d = drop
eq = equivalent
f = film
G = gas
j = jet or liquid
max = maximum
0 = orifice
ov = overall
p = particle/dust
th = throat

Literature Cited

Azzopardi, B. J., and A. H. Govan, "The Modelling of Venturi Scrubbers," *Filtration and Separation*, **23**, 196 (1984).
Behie, S. W., and J. M. Beeckmans, "On the Efficiency of a Venturi Scrubber," *Can. J. Chem. Eng.*, **51**, 430 (1973).
Boll, R. H., "Particle Collection and Pressure Drop in Venturi Scrubbers," *Ind. Eng. Chem. Fund.*, **12**, 40 (1973).
Brink, J. A., and C. E. Contant, "Experiments on an Industrial Venturi Scrubber," *Ind. Eng. Chem.*, **50**, 1157 (1958).
Calvert, S., "Venturi and Other Atomizing Scrubbers," *AIChE J.*, **16**, 392 (1970).
Calvert, S., D. Lungren, and D. S. Mehta, "Venturi Scrubber Performance," *J. of Air Pollution Control Assoc.*, **22**, 529 (1972).
Cooper, D. W., and D. Leith, "Venturi Scrubber Optimization Revisited," *Aerosol Sci. and Technol.*, **3**, 63 (1984).
Ekman, O. F., and H. F. Johnstone, "Collection of Aerosols in a Venturi Scrubber," *Ind. Eng. Chem.*, **43**, 358 (1951).
Fathikalajahi, J., M. R. Talaie, and M. Taheri, "Theoretical Study of Liquid Droplet Dispersion in a Venturi Scrubber," *J. Air Waste Mgmt. Assoc.*, **45**, 181 (1995).
Fathikalajahi, J., M. Taheri, and M. R. Talaie, "Theoretical Study of Non-uniform Droplets Concentration Distribution on Venturi Scrubber Performance," *Particulate Sci. and Technol.*, **14**, 153 (1996).
Goel, K. C., and K. G. T. Hollands, "Optimum Design of Venturi Scrubbers," *Atmos. Environ.*, **11**, 837 (1977).
Guntheroth, H., "Suspended Substance and Liquid Separation from Gases with Venturi Scrubber," Progress Reports, VDI Publication, Ser. 3, No. 13 (1966).
Haller, H., E. Muschelknautz, and T. Schultz, "Venturi Scrubber Calculation and Optimization," *Chem. Eng. Technol.*, **12**, 188 (1989).
Koehler, J. L. M., H. A. Feldman, and D. Leith, "Gas-Borne Liquid Flow Rate in a Venturi Scrubber with Two Different Liquid Injection Arrangements," *Aerosol Sci. Technol.*, **7**, 15 (1987).
Leith, D., and D. W. Cooper, "Venturi Scrubber Optimization," *Atmos. Environ.*, **14**, 657 (1980).
Placek, T. D., and L. K. Peters, "Analysis of Particulate Removal in Venturi Scrubbers—Effect of Operating Variables on Performance," *AIChE J.*, **27**, 984 (1981).
Placek, T. D., and L. K. Peters, "Analysis of Particulate Removal in Venturi Scrubbers—Role of Heat and Mass Transfer," *AIChE J.*, **28**, 31 (1982).
Viswanathan, S., A. W. Gnyp, and C. C. St. Pierre, "Jet Penetration Measurements in a Venturi Scrubber," *Can. J. of Chem. Eng.*, **61**, 504 (1983).
Viswanathan, S., A. W. Gnyp, and C. C. St. Pierre, "Examination of Gas-Liquid Flow in a Venturi Scrubber," *Ind. Eng. Chem. Fund.*, **23**, 303 (1984).
Viswanathan, S., A. W. Gnyp, and C. C. St. Pierre, "Estimating Film Flow in a Venturi Scrubber," *Particulate Sci. Technol.*, **15**, 65 (1997a).
Viswanathan, S., "Modeling of Venturi Scrubber Performance," *Ind. Eng. Chem. Res.*, **36**, 4308 (1997b).
Viswanathan, S., A. W. Gnyp, and C. C. St. Pierre, "Annular Flow Pressure Drop Model for Pease-Anthony-Type Venturi Scrubbers," *AIChE J.*, **31**, 1947 (1985).

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