Venturi and Other Atomizing Scrubbers Efficiency and Pressure Drop

SEYMOUR CALVERT

University of California, Riverside, California

Particle collection efficiency and gas pressure drop for venturi and other atomizing scrubbers can be predicted by means of equations developed in this paper. The significance of the details of the liquid atomization process, the collection of particles on single drops, and the uncertainty regarding them are discussed. The role of drop holdup in the scrubber throat is also important.

Atomizing scrubbers have been used for small particle removal from gas in a variety of applications and are a very important type of air pollution control device. Their operation is based on a gas stream atomizing liquid which is either introduced into the gas or is entrained from a pool upon which the gas impinges. In either case, the liquid is broken into small drops upon which the small particles (called *dust* to distinguish them from atomized drops) collect. Small particles refer to the size range 0.1- to 1.0-μ diameter.

Venturi, orifice, and wetted disk scrubbers are examples wherein the liquid is introduced as a stream. Usually the liquid enters the venturi throat through several nozzles, and the jets of liquid are shattered into drops by the high velocity gas. Impingement of gas upon a pool of liquid can also cause the atomization and entrainment of liquid drops, and this principle is used in several types of commercial apparatus. Some scrubbers may appear to operate by impingement of the gas on solid surfaces but may actually obtain higher collection efficiency due to the atomization of liquid from the edges of the solid surfaces.

The growing importance of atomizing scrubbers hinges on their flexibility and simplicity. High collection efficiency is attainable, and yet the same device can be adjusted to give lower efficiency and require less power. A decrease in either liquid rate or gas velocity will decrease efficiency and power. Simplicity of design makes these devices relatively inexpensive to build or buy. Whether the removal of collected dust as a slurry represents an advantage or not will depend on the relative ease of disposing of it or a dry dust in a specific situation.

Despite the importance of this kind of scrubber, there has not previously been an adequate rational design method. Johnstone (*2*) and Brink's (*4*) work substantiates this. The following paper presents new methods for predicting pressure drop and particle collection efficiency. These methods are compatible with the reliable data which were available at the time of writing.

PRESSURE DROP

Pressure drop for gas flow through scrubbers is caused by friction with stationary surfaces and by the acceleration of liquid. Frictional loss is very dependent upon the geometry of the scrubber and must generally be determined experimentally. Acceleration loss is fairly insensitive to scrubber geometry and is frequently the predominant cause of pressure drop. It can be accounted for by use of Newton's law describing the force required to change the momentum of liquid at a given rate:

$$F_a = \frac{d(Mv)}{g_c dt} = \Delta P_a A \tag{1}$$

The relationships defined in Equation (1) may be derived by determining the rate of change of liquid momentum from the plane of introduction to the plane where it has reached the gas velocity. If it is assumed that the gas velocity is constant throughout this process, then

$$\Delta P_a = \frac{(v_g - v_l)}{g_c A} \frac{dM}{dt} \tag{2}$$

For pressure drop $\Delta P_a''$, in inches of water, and water flow rate L', in gallons per thousand cubic feet of gas flow, the following dimensional equation is approximately equivalent to Equation (2) when $V_l = 0$:

$$\Delta P_a'' = 5 \times 10^{-5} (v_g)^2 L' \tag{3}$$

The velocity squared term suggests that the pressure drop could be expressed in terms of velocity heads for comparison with the empirical correlation of data for venturi scrubbers shown in Figure 1. In terms of velocity heads for air density = 0.075 lb./cu.ft. and $v_l = 0$

$$\frac{\Delta P_a}{\Delta P_{VH}} = \frac{\Delta P_a}{\dfrac{\Delta (v)^2 \rho_g}{2g_c}} = 0.22\, L' \tag{4}$$

Equation (4) predicts a higher pressure drop than experimentally measured except at low liquid rates, where the frictional losses for the gas alone are significant. Predicted values are compared with the experimental results of various investigators (*1* to *4*) in Figure 1. At higher liquid rates, it appears that 80 to 90% of the momentum of the liquid is lost rather than serving to recompress the gas. This is in keeping with the observation (*5*) that the pumping efficiency of an ejector venturi is generally less than 15%.

ATOMIZATION

Liquid drop size must be known if dust collection efficiency is to be predicted. Our principal tool for describing the results of liquid atomization by a gas jet is the empirical correlation of Nukiyama and Tanasawa (*6*). Because their correlation, expressed as Equation (5), is valid for a wide variety of atomizer configurations, it is assumed to be an acceptable generalization

$$d_0 = \frac{585}{v_r}\sqrt{\frac{\sigma}{\rho}} + 597\left(\frac{\mu}{\sqrt{\sigma\rho}}\right)^{0.45}\left(\frac{1{,}000\, Q_w}{Q_g}\right)^{1.5} \tag{5}$$

Seymour Calvert is with Seymour Calvert Associates, Riverside, California.

which becomes for standard air and water:

$$d_0 = \frac{5{,}000}{v_r} + 29\left(\frac{1{,}000\, Q_w}{Q_g}\right)^{1.5} \quad (6)$$

We may also convert Equation (6) to

$$d_0 = \frac{16{,}400}{v_g} + 1.45\,(L')^{1.5} \quad (7)$$

A solution of Equation (7) for the region of most interest is plotted in Figure 2 as mean drop diameter vs. air velocity, with liquid flow rate and predicted pressure drop as parameters. Air pressure drop is computed by means of Equation (3).

Another way of predicting the stable drop for a given gas velocity is to use the fact that drops will shatter at a critical value of the Weber number:

$$N_{We} = \frac{\rho_g\, u^2 r}{g_c \sigma} \quad \text{(dimensionless)}$$

Experiments on the drop shatter of several liquids (7) give critical values of Weber number ranging from 5 to 12. If we use the properties of standard air and water with a critical Weber number of 6 and a drop radius of 0.1 cm., the required air velocity is 1,820 cm./sec.-60 ft./sec. To shatter a 0.2-cm. radius drop, which is on the order of raindrop size, would take an air velocity of about 42 ft./sec.

Comparison of the critical drop size, predicted by the Weber number criterion with the mean drop diameter predicted by Nukiyama and Tanasawa (see Figure 2) for lowest water rate, shows that the former is much larger at low velocities. The two methods approach agreement at velocities higher than 300 ft./sec. Because the range of Nukiyama and Tanasawa's experiments went down to about 200 ft./sec., we would probably be safer to use Goldshmid's Weber number criterion for velocities below about 100 ft./sec. However, this refinement has not been included in the treatment which follows.

COLLECTION ON SINGLE DROPS

Particle collection by liquid drops may be under the influence of several mechanisms, but inertia is the force most commonly effective in scrubbers. Prediction of scrubber performance requires that the interaction between a large population of drops and an aerosol be accounted for over the flight time of each drop. Given drop size, velocity, and concentration at each instant, one can apply the factors governing collection by single drops and sum up the contribution of the entire population.

Inertial impaction efficiency for spherical collection elements and liquid drops behaving much the same as solid spheres has been studied by several investigators (*7, 8*). While the data of Walton and Woolcock (*8*) are good for values of the inertial parameter K larger than a few tenths, Goldshmid and Calvert (*7*) elucidated some facts of importance for dealing with liquid drops and low values of K. Goldshmid found that drop shape and oscillation have a negligible effect on collection. Interfacial tension as measured by contact angle has an influence in the region of K between 0.1 and 0.4, with efficiency being lower for nonwetting combinations of particle and liquid-consistent with the observations of a crust being formed on the drop by nonwetting particles.

Of special significance for submicron particles was Goldshmid's discovery that particle collection on the back of the drop becomes substantial for low values of K. Figure 3 shows the collection efficiencies determined for monodisperse sulfur particles by water drops compared with Walton and Woolcock's experimental curve. The absence of a critical value of K, below which efficiency is zero, is clear and contradicts the existing published theory based only on collection on the front of the sphere.

A simple inertial model predicts a linear relationship between efficiency and K but does not account for the different lines shown in Figure 3, which probably are due to variation of transport into and retention in the wake as a function of particle size. This model also shows that particles larger than about a micron will be spun out of the wake and not be captured on the rear of the drop, as is observed experimentally.

Whether or not this mechanism persists at the very high velocities (> 200 ft./sec.) present in venturi scrubbers is a question of obvious importance for submicron particle collection. For the present, we will use an approximation to the experimental results of Walton and Woolcock, as these will give conservatively low values of efficiency:

$$\eta = \frac{K^2}{(K + 0.7)^2} \quad (8)$$

OVERALL COLLECTION MECHANISM

With the addition of some information regarding drop aerodynamics, we will be able to describe the overall mechanism of dust collection in an atomizing scrubber. First, let us consider the mechanism in general terms, as illustrated in Figure 4. The drop holdup, volume fraction drops, in the differential volume shown is

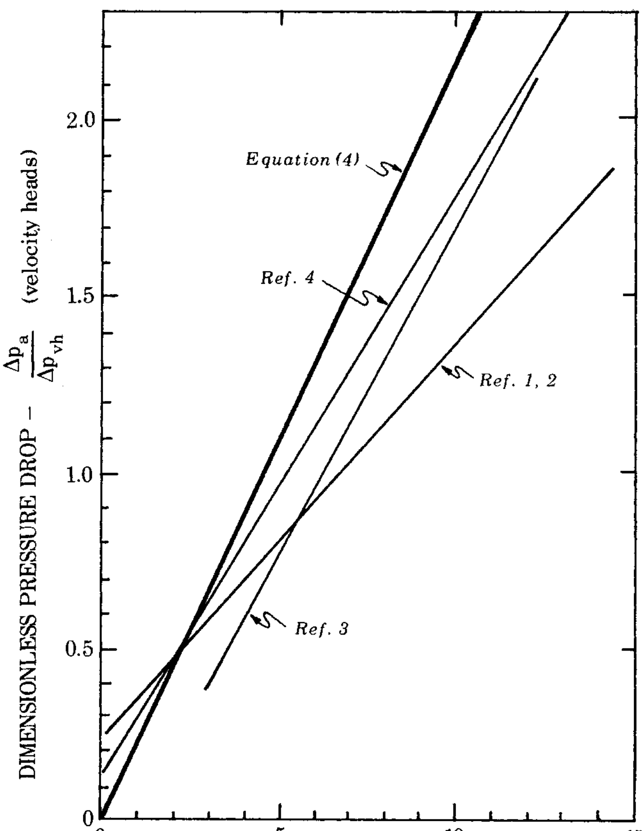

Fig. 1. Comparison of predicted and experimental pressure drops in venturi scrubber.

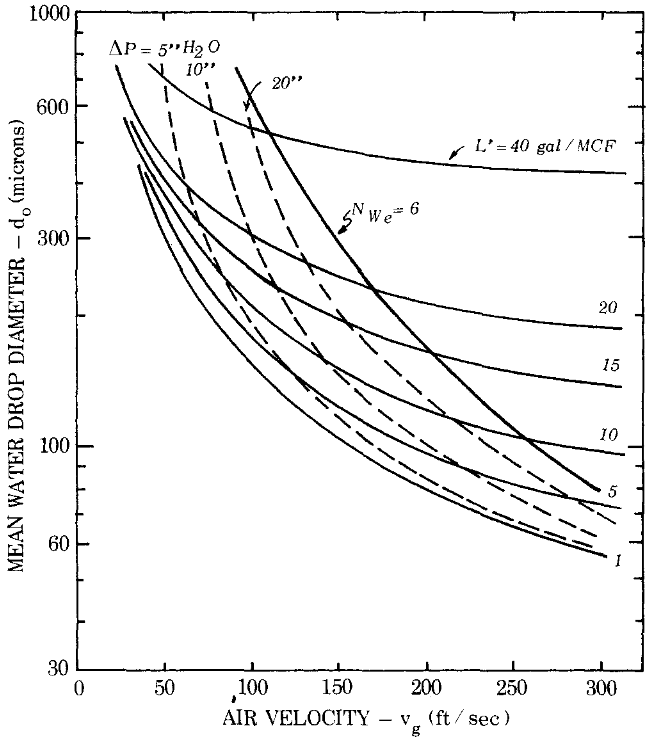

Fig. 2. Predicted drop diameter and Δ *P* vs. air velocity with *L'* as parameter.

$$H_d = \frac{Q_w}{(v_g + v_r)A} = \frac{Q_w}{v_d A} \tag{9}$$

A material balance for dust over the differential volume gives

$$v_g cA - v_g(c + dc)A - |v_r|\, H_d\left(\frac{3}{4r}\right) A\eta c dz = 0 \tag{10}$$

or

$$-\frac{dc}{c} = \frac{3|v_r| H_d \eta dz}{4r\, v_g} \tag{11}$$

If we define the magnitude of drop velocity relative to the gas as a fraction of the gas velocity relative to the duct, we get

$$|v_r| = f' v_g \tag{12}$$

Then

$$-\frac{dc}{c} = \frac{3f'\, Q_w\, \eta dz}{4r\, v_g(1 - f')A} \tag{13}$$

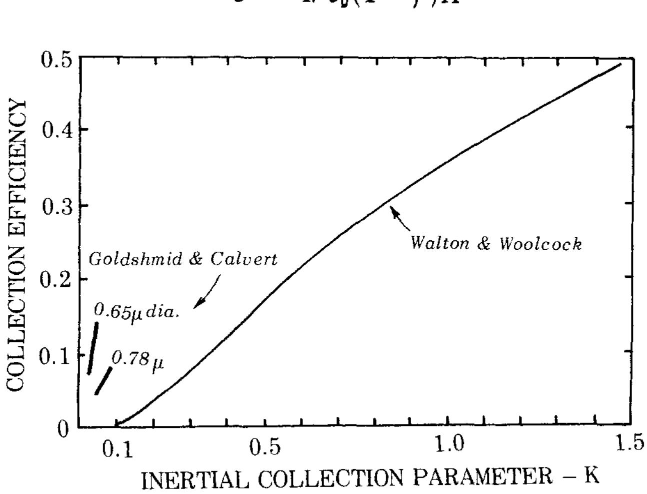

Fig. 3. Particle collection efficiency for sulfur aerosol as a function of inertial parameter.

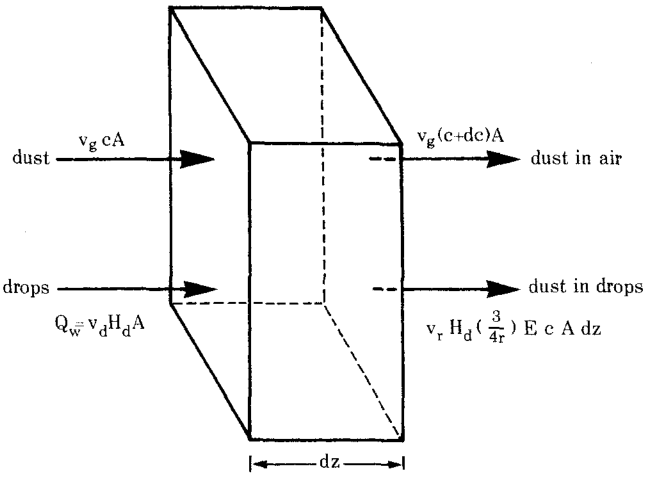

Fig. 4. Schematic diagram for material balance in concurrent scrubber.

We still need to know drop velocity and collection efficiency as a function of distance the drop travels, z. For this purpose, the findings of Ingebo (9) on the acceleration of liquid drops by air drag are useful. His drag coefficient data, are different from those for steady state motion and are represented by

$$\Psi = 27\,(N_{Re})^{-0.84} \tag{14}$$

The drag coefficients for the accelerating drop lie between the steady state drag coefficients for laminar and turbulent flow. For simplification of equations we will use a linear approximation of Ingebo's data within the range of Reynolds numbers of interest for atomizing scrubbers:

$$\Psi = \frac{55}{N_{Re}} \tag{15}$$

Equation (15) applies for Reynolds number of 100 to 500. It is also a fairly good approximation up to Reynolds number of 1,000. Unsteady drop motion relative to the gas z', due only to drag and inertial forces, is described by

$$\int_{N_{Re_1}}^{N_{Re_2}} \frac{dN_{Re}}{\Psi N_{Re}} = \frac{3\rho_g(z_2' - z_1')}{8r\rho_l} \tag{16}$$

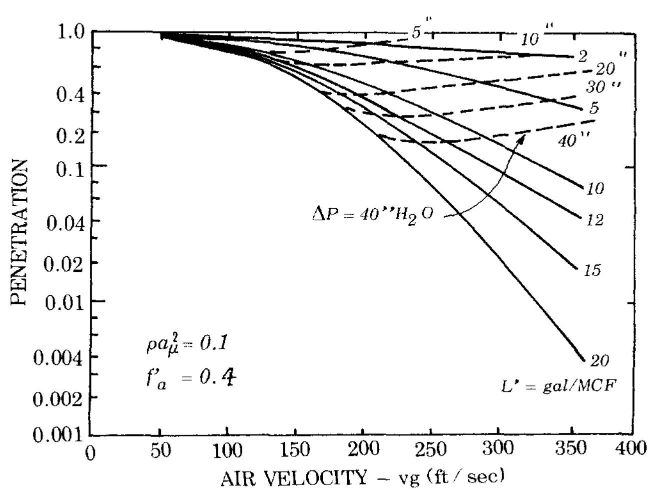

Fig. 5. Predicted penetration and pressure drop vs. air velocity with *L'* as parameter.

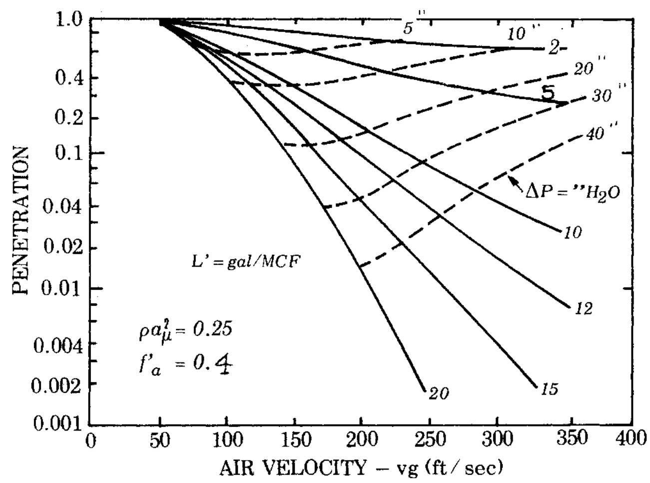

Fig. 6. Predicted penetration and pressure drop vs. air velocity with L' as parameter.

Substituting Equation (15) in (16) and integrating, we obtain

$$\frac{3z'\rho_g}{8r\rho_l} = \frac{N_{Re1} - N_{Re2}}{55} = \frac{N_{Re1}(1-f')}{55} \qquad (17)$$

Note that $dz = -(1-f')/f'\,dz'$. Differentiating Equation (17), we obtain a relationship between dz and df which may be substituted into Equation (13) to give

$$\frac{dc}{c} = \frac{\eta_a Q_w 4\rho_l r}{A\,55\mu}\,df' \qquad (18)$$

and, upon definite integration with η_a, considered constant:

$$\ln\frac{c_o}{c_i} = -\frac{\eta_a Q_w 4\rho_l r}{A\,55\mu}\,[f']_1^2 \qquad (19)$$

An approximate representation of the change in η_a is provided by assuming that it varies linearly with f' so that

$$\eta_a = \left(\frac{f'}{f_a'}\right)\eta_a' \qquad (20)$$

If we substitute this in Equation (18) and then integrate, we will obtain

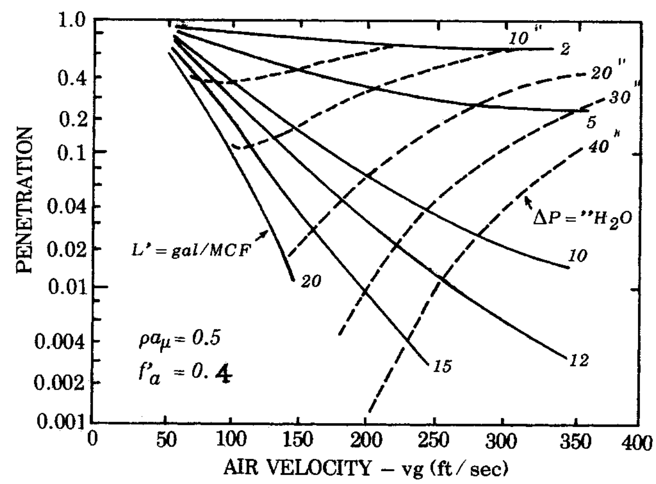

Fig. 7. Predicted penetration and pressure drop vs. air velocity with L' as parameter.

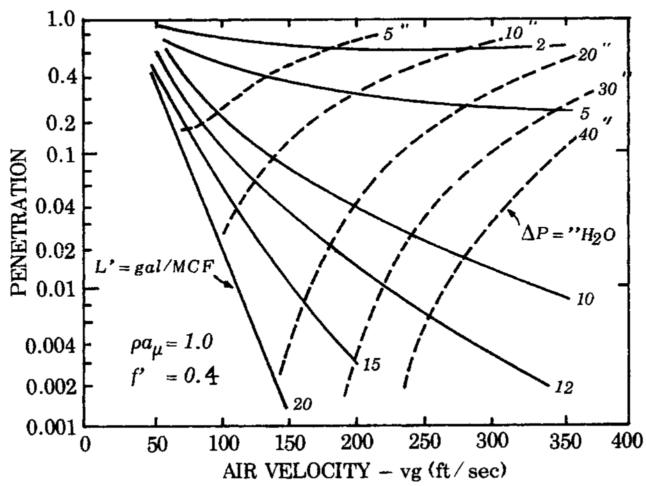

Fig. 8. Predicted penetration and pressure drop vs. air velocity with L' as parameter.

$$\ln\frac{c_o}{c_i} = -\left(\frac{4\,Q_w\,\rho_l\,r}{55\,A\mu}\right)\eta_a'\left(\frac{f_a'}{2}\right) \qquad (21)$$

An exact solution of Equation (18) can be obtained by a graphical integration by utilizing the point values of η_a. This refinement, however, is hardly warranted in view of the inaccuracy of our knowledge of drop size, velocity, collection efficiency, and other factors.

Plots which are very convenient for estimating collection efficiency can be prepared by using Equations (6), (21), and (3). On this one plot we can relate penetration, air velocity, water rate, pressure drop, and particle properties. The final forms of the relationships for standard air and water are

$$K_a = \frac{2\,v_g\,\rho_p\,a^2}{9\mu\,R_c} = 7.5\,\frac{v_g}{D_{c\mu}}\,(\rho_p a_\mu^2) \qquad (22)$$

$$\ln\frac{c_o}{c_i} = -\,[13{,}500\,(L') + 1.2\,L'^{2.5}\,v_g]\;\eta_a'\left(\frac{f_a'}{2}\right)\times 10^{-4} \qquad (23)$$

Figures 5, 6, 7, and 8 are based on predicted pressure drops and the assumptions of linear variation of efficiency with velocity and $f_a' = 0.4$. These assumptions are used because the predicted efficiency will fit best with the ex-

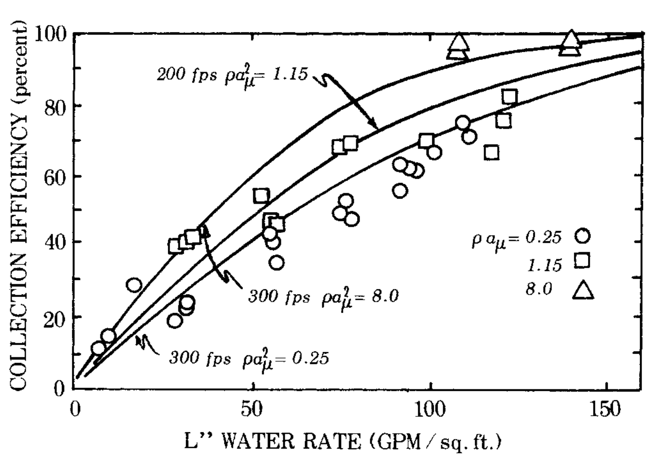

Fig. 9. Experimental and predicted collection efficiency vs. L'' with air velocity and particle properties as parameters.

perimental data available (*1, 4*). Figure 9 shows the comparison between predictions and experiment as efficiency vs. L'' (gallons per minute square feet). This manner of plotting is not very sensitive to changes in air velocity.

DISCUSSION

The predictions of Figures 5, 6, 7, and 8 show a minimum penetration for a given pressure drop for small dust. For larger dust, this is not so, and the penetration decreases with increase in liquid rate for a given pressure drop. Since most of the problem is usually the removal of small particles, it would be expected that there will be an optimum liquid rate in most practical cases.

The amount of data used in Figure 9 to establish the value for f_a' and the form of the efficiency relationship is admittedly small, but there is a scarcity of reliable data.

The two sets of points for $\rho a_\mu^2 = 0.25$ and 8.0 are Ekman and Johnstone's data (*1*) for the collection of dioctyl phthalate mist of 1.0- and 5.5-μ mean diameter in an experimental venturi scrubber with a 1 3/16-in. diameter throat at velocities ranging from 226 to 488 ft./sec. and water rates from 0.35 to 8.9 gal./1,000 cu.ft. The points for $\rho a_\mu^2 = 1.15$ are Brink's (*4*) data for the collection of phosphoric acid mist (mean diameter = 1.7μ) in a venturi scrubber with a 6-in. × 34-in. throat cross section at air velocities of about 200 ft./sec. and water rates of 8.9 to 11.8 gal./1,000 cu.ft.

The predictions are somewhat high for the 1.0-μ D.O.P. and low for the 1.7-μ acid mist. That we are not in a position to do much better will become apparent after we consider several points. Large venturi scrubbers give better performances than small ones, and phosphoric acid is more wettable than D.O.P. Therefore, the acid collection should be relatively more efficient.

The experimental data also show that efficiency increases slightly with increasing air velocity on this kind of plot, while the prediction runs in the opposite direction. The most obvious explanation for this is that f_a' must vary with air velocity, if not also with water rate, and must be larger for higher air velocity. We may also note that the predictions are based on average drop and dust sizes in addition to several other simplifying approximations. With its limitations, the foregoing is the only rational design method available for atomizing scrubbers. It is clear that some careful study must be given to this class of scrubbers, and that it must include a better definition of the atomization process. We must also explore the diffusional collection range and the drop wake collection mechanism because particles a few tenths micron diameter and smaller are collected at higher efficiency than predicted for impaction.

ACKNOWLEDGMENT

The assistance of Dr. Richard H. Boll in revising part of the derivation is gratefully acknowledged.

NOTATION

a = particle radius, cm. or ft.
a_μ = particle radius, μ
A = cross-section area, sq.ft. or sq.cm.
c = concentration of particles in gas, lb./cu.ft. or g./cc.
c_i = concentration of particles in inlet gas
c_o = concentration of particles in outlet gas
d_0 = Sauter (surface/volume ratio) mean drop diameter, μ
D_c = diameter or width of collector, ft. or cm.
$D_{c\mu}$ = diameter or width of collector, μ
f' = velocity ratio = v_r/v_g
f_a' = velocity ratio for atomization
F_a = force required for acceleration, lb.
g_c = conversion factor in Newton's law of motion = 32.17 (lb.)(ft.)/(sec.)^2(lb. force)
K = inertial impaction parameter = $\dfrac{2v_r \rho_p a^2}{9\mu R_c}$
K_a = inertial impaction parameter at atomization velocity
L' = ratio of liquid to gas flow rates, gal./1,000 cu.ft.
L'' = liquid flow rate per unit of scrubber cross section, gal./(min.)(sq.ft.)
M = mass of liquid
N_{Re} = Reynolds number, dimensionless
N_{We} = Weber number, dimensionless
ΔP = pressure difference, lb./sq.ft. or in. water
ΔP_a = pressure difference due to acceleration, lb./sq.ft.
ΔP_{vh} = pressure drop equivalent to one velocity head, lb./sq.ft.
ΔP_t = penetration of collector by particles = c_o/c_i, fraction
Q = volumetric flow rate, cu.ft./sec. or cu.m/sec.; Q_w, liquid; Q_g, gas
r = radius of drop, ft. or cm.
R_e = radius of particle collector, ft. or cm.
t = time
u = velocity in the horizontal direction, ft./sec. or cm./sec.; u_d, u_g, and u_l have similar meanings as V_d, V_g, and V_l, ft./sec. or cm./sec.
v = velocity
v_d = drop or particle velocity relative to duct, ft./sec.
v_g = gas velocity relative to duct, ft./sec.
v_l = liquid velocity relative to duct, ft./sec.
v_r = drop velocity relative to gas
z = distance traveled by drop relative to duct
z' = stopping distance of a drop, cm., z_1 initial position, z_2 final position
Z = height or length of scrubber, ft.

Greek Letters

η = particle collection efficiency of drop for particles of one size, fraction
η_a = collection efficiency for particles of diameter a
η_a' = average over a velocity range
μ = viscosity, poises or lb./(sec.)(ft.)
ρ = density lb./cu.ft. or g./cc.; ρ_g, gas; ρ_l, liquid; ρ_p, particle
σ = surface tension, dynes/cm.
Ψ = drag coefficient, fraction

LITERATURE CITED

1. Ekman, F. O., and H. F. Johnstone, *Ind. Eng. Chem.*, **43**, 1358 (1951).
2. Johnstone, H. F., and M. H. Roberts, *ibid.*, **41**, 2417 (1949).
3. Yocum, J. E., and S. Chapman, *Air Repair*, **4**, 154 (1955).
4. Bring, J., and C. E. Contant, *Ind. Eng. Chem.*, **50**, 1157 (1958).
5. Harris, L. S., *J. Air Pollution Control Assoc.*, **15**, 302 (1965).
6. Nukiyama, S., and Y. Tanasawa, *Trans. Soc. Mech. Engrs. (Japan)*, **4**, 86 (1938).
7. Goldshmid, Yhuda, and S. Calvert, *AIChE J.*, **9**, 352 (1963).
8. Walton, W. H., and A. Woolcock, *Intern. J. Air Pollution*, **3**, 129 (1960).
9. Ingebo, R., *NASA Tech. Note 3762* (1956).

Manuscript received February 1, 1968; revision received October 16, 1968; paper accepted October 25, 1968. Paper presented at AIChE New York meeting.