Optimization of Aerosol Penetration through Transport Lines*

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When aerosol particles are transported through tubing systems for near-real-time monitoring purposes, there will be losses of particles on internal surfaces of the transport system that will render the monitoring process less accurate. Herein we consider three aspects of modeling particle penetration: an analytical solution for the effective particle depositional velocity in inclined tubes; the optimum diameter of a straight tube for maximum aerosol penetration; and the concept of maximum penetration, P_{max}, between two points in space. P_{max} is the upper bound, and the ratio of the actual penetration, P, to P_{max} gives the scope for improving the transport line design to increase penetration.

INTRODUCTION

In the workplace of nuclear plants and nuclear waste disposal facilities, near-real-time measurements of radioactivity associated with aerosol particles are made with continuous air monitors (CAMs). Often these CAMs may be physically remote from the sampling location, in which case aerosol particles are transported from the sampling location to the CAM through a transport system. Typically these transport lines consist of straight tubes, elbows, and an inlet nozzle. The straight tube may be vertical, horizontal, or inclined. Any two straight sections of tubes are usually connected with 45° or 90° elbows. If prohibitively high levels of radioactivity are recorded by a CAM, an alarm will be triggered to initiate emergency procedures. In order for the CAMs to provide meaningful signals, the loss of aerosol particles through transport lines should be at a minimum. This study is concerned with modeling of the particle losses, and its objectives are as follows:

1. To present an analytical expression for calculating the effective particle deposition velocity in straight tubes.
2. To present a procedure for predicting an optimum tube diameter for an existing transport line.
3. To introduce a concept of "maximum penetration" for aerosol transport through a line connecting two points in three-dimensional space.

PREVIOUS WORK

In the past, several models have been developed to predict particle deposition in straight tubes. Friedlander and Johnstone (1957) and Davies (1966) modeled particle deposition caused by turbulent diffusion. According to Fuchs (1964), Natanson derived an analytical solution for gravitational settling in horizontal tubes with viscous flow.

Experiments conducted by Sehmel (1970) indicated that the particle turbulent eddy diffusion is greater than that for air momentum transfer in turbulent flow. Strom (1972) experimentally studied the particle deposition in a transport system that included elbows and vertical and horizontal straight

*Aerosol Technology Laboratory Publication 6441/02/01/91/NKA.

0278-6826/92/$5.00

tubes. Minimum losses were noted at an optimum flow Reynolds number (Re) of 2800 and he suggested the optimum was independent of particle size. Particle deposition in the size range of 2–15 μm in horizontal tubes was found to be significantly higher than in vertical tubes due to gravitational settling. Charuau (1982) investigated losses in tubes due to particle charge, gravitational settling, turbulent deposition, and Brownian diffusion. He recommended that sampling systems should be designed to operate in the transitional Re range of 2500–5000. Liu and Agarwal (1974) measured particle deposition in vertical tubes as a function of particle diameter for Re (based on tube diameter) values of 10,000 and 50,000. Liu and Ilori (1974) proposed a model to calculate the effective particle diffusivity, and the comparison with their experimental data was good. Onda (1977) reviewed and compared various models and experimental data for particle deposition in straight tubes due to turbulent diffusion in fully developed flows. His results suggested that predictions based on the model of Beal (1970) compared best with the experimental data over a wide range of dimensionless particle relaxation times.

In the supramicrometer size range of particles, the contribution of Brownian motion toward particle deposition velocity is negligible. Also, in the absence of electric and thermal fields, the two important mechanisms responsible for particle deposition in tubes are turbulent diffusion and gravitational settling. Although gravitational settling and turbulent deposition are not independent, the two mechanisms are frequently treated as if they were by multiplying the penetration for gravitational settling with that for turbulent deposition (e.g., Schwendiman, 1976).

Recently, Anand and McFarland (1989) developed a numerical model to predict the particle deposition in inclined tubes by considering the combined effect of turbulent diffusion and gravitational settling. Numerical calculations were made for vertical, horizontal, and 45° inclined tubes for a range of particle sizes and flow rates. It was noted that there exists an optimum tube diameter for which the penetration is maximum in nonvertical tubes. Based upon analyses of the numerical results, the optimum tube diameter was observed to be independent of tube length; however, it was observed to be a function of particle size and flow rate. The optimum diameter was not associated with a constant value of tube Re, as had been noted by Strom (1972). For horizontal tubes a correlation was established relating optimum tube diameter to air flow rate and particle size. The turbulent diffusion velocity was calculated using the model of Agarwal (1975).

In the present study, the parameter P is used to represent the penetration of aerosol through a component of a tubing system (straight tube, elbow, or inlet). We assume the total penetration through the transport system, P_T, is the product of penetration through each of the individual components. The numerical model for calculating penetration through straight tubes is obtained by extending the work of Anand and McFarland (1989). Where needed, the penetration model of Vincent et al. (1986) for an inlet nozzle and the penetration expression of Pui et al. (1987) for elbows are used. Beal's model (1970) is employed to represent the combined effects of turbulent and Brownian diffusion mechanisms.

ANALYTICAL EXPRESSION FOR EFFECTIVE DEPOSITIONAL VELOCITY IN STRAIGHT TUBES

When gravitational settling and diffusional mechanisms occur simultaneously in a straight nonvertical tube the mechanisms do not act independently. Anand and McFarland (1989) employed a numerical technique to combine the particle velocities due to gravitational settling and turbulent diffusion; however, we will show in this section that there is an analytical solution for the effective velocity when sedimentation and diffusion (turbulent and thermal) occur simultaneously in a straight tube.

The physical model considered for the purpose of analysis is shown in Figure 1a, where the sampling tube is inclined at an angle ϕ from the horizontal. At any given tube cross section the concentration of aerosol particles is assumed to be uniform. In addition, the flow is assumed to be fully developed and turbulent. If the aerosol concentration is C_o at the tube inlet ($x = 0$) and

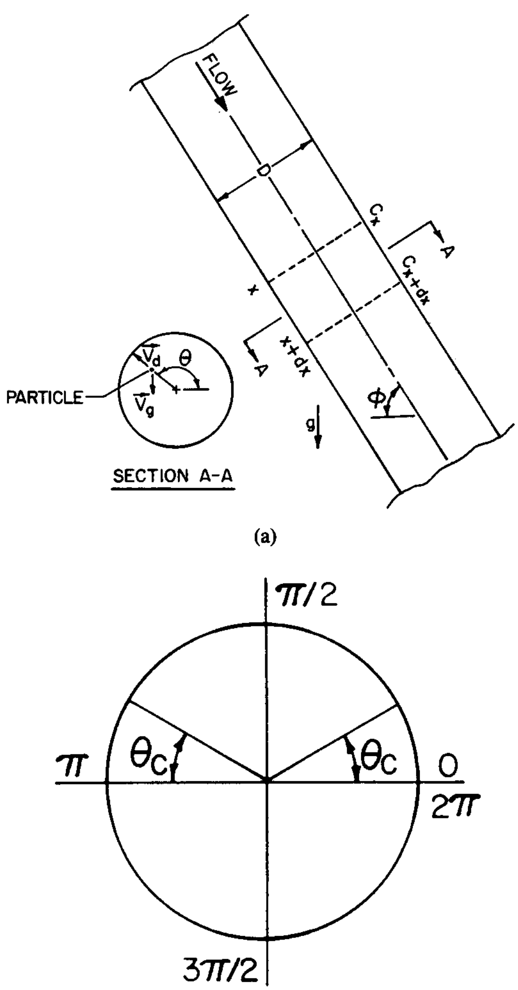

FIGURE 1. Layout of inclined tube.

C is at a distance X from the tube inlet, then P is given by the exponential relationship

$$P = \frac{C}{C_o} = \exp\left(-\frac{\pi d V_e X}{Q}\right) \tag{1}$$

where Q = volumetric flow rate of air, d = tube diameter, and V_e = effective velocity of particle deposition. The effective depositional velocity V_e is the vector sum of velocities due to turbulent diffusion (V_t), Brownian diffusion (V_b), and gravitational settling (V_g). The sum of V_t and V_b is defined as V_d, and the vector sum of the depositional velocities directed normally toward an area element $dx \cdot d\theta \cdot d/2$ at an angle θ is $(V_d - V_g \sin\theta)$. This expression can be integrated along the circumference of a tube to give

$$V_e = \frac{1}{2\pi}\int_0^{2\pi}\left(V_d - V_g \sin\theta\right) d\theta \tag{2}$$

The above integral is subjected to the constraint

$$\left(V_d - V_g \sin\theta\right) > 0 \tag{3}$$

V_e is set equal to zero when $(V_d - V_g \sin\theta) < 0$; otherwise it would be implied that aerosol mass could be transported from the outside environment into the tube through a part of the tube's upper half. A point along the circumference where $(V_d - V_g \sin\theta) = 0$ is defined as the critical angle θ_c and is given by

$$\theta_c = \sin^{-1}\frac{V_d}{V_g} \tag{4}$$

The integral (Eq. 2) can be solved in a closed form sense by splitting the integration range $[0, 2\pi]$ into several parts, viz., $[0, \theta_c]$, $[\theta_c, (\pi - \theta_c)]$, $[(\pi - \theta_c), \pi]$, and $[\pi, 2\pi]$, as shown in Figure 1b. Setting the integral in $[\theta_c, (\pi - \theta_c)]$ to zero to satisfy the constraint and evaluating Eq. 2 yields

$$V_e = \frac{V_d \theta_c}{\pi} + \frac{V_d}{2} + \frac{V_g \cos\theta_c}{\pi} \tag{5}$$

Although results calculated from use of Eq. 5 are the same as those obtained earlier by Anand and McFarland (1989) through numerical integration of Eq. 2 with the constraint (Eq. 3), the closed form solution presented herein is more versatile.

OPTIMUM TUBE DIAMETER FOR AN EXISTING TRANSPORT LINE

A typical transport line consists of straight tubes, elbows, and an inlet nozzle. Straight tubes can either be vertical, inclined, or horizontal. The P_T for a transport line given by

$$P_T = \prod_i P_i \tag{6}$$

where P_i is the penetration for each individual component.

For nonvertical tubes there is an optimum tube diameter (d_{opt}), which is the tube diameter that corresponds to the maximum penetration for a given particle size and flow rate. A computer algorithm has been developed to calculate penetration for a particular geometrical configuration (tube size, number and type of elbows, inlet size as related to aspiration efficiency, and orientation of various straight tube sections), particle size, and flow rate. The program is initiated at a particular tube diameter and incremented with steps of 1 mm. The tube diameter is declared to be optimal when the penetration value shows a decrease for the next step. However, it should be noted the concept of optimum tube diameter does not apply to a sampling line that has no nonvertical tubes, since without gravitational settling there will be no maximum penetration value. The maximum results from a trade-off between a small tube diameter with lower gravitational losses but higher turbulent depositional losses and a larger tube diameter with lower turbulent depositional losses but higher gravitational settling losses.

Calculations have been made for a wide range of conditions; however, only representative conditions with straight tubes are given here. The efficacy of the program was tested by comparing the predicted results with experimental observations from wind tunnel tests for a special transport system (McFarland et al., 1991). For the calculations shown herein, the flow rate was fixed at 56.6 L/min (2 cfm) since this is a commonly used value for aerosol transport systems in nuclear facilities. Also, only straight tubes are considered to illustrate the concepts.

Figure 2 shows particle penetration as a function of tube diameter for different particle sizes in vertical tubes. The gravitational contribution is zero, with the mechanisms contributing to the particle deposition being turbulent and Brownian diffusion. For this example the only significant reduction in penetration of a supramicrometer particle is associated with turbulent diffusion. No optimum tube diameter exists for maximizing penetration of particles in the inertial range (≥ 1 μm aerodynamic equivalent diameter, AED). However, a designer could select tubing by adopting a criterion for wall losses

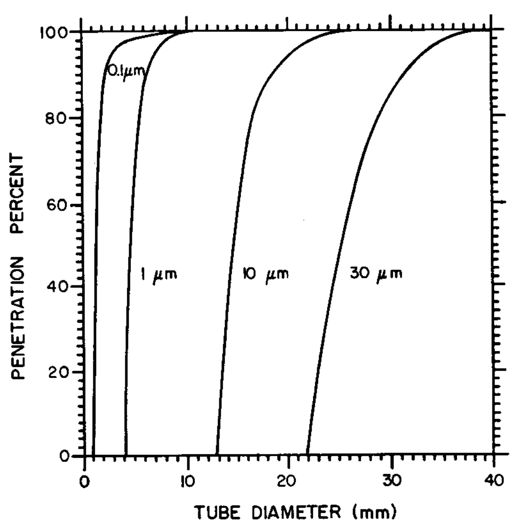

FIGURE 2. Aerosol penetration through 10 m long vertical tubes.

associated with a certain particle size and calculating the corresponding tube diameter.

Figure 3 depicts the variation of penetration with tube diameter for horizontal tubes. For nonvertical tubes the gravitational component contributes to particle deposition with the gravitational component playing a significant role for the case of large particles (≥ 3 μm AED) in horizontal tubes. It is evident that, for sizes in which gravitational settling is important, there is a d_{opt} for which the penetration is a maximum. Also, it should be noted that the decrease in penetration is steeper on the lower side of the optimum diameter than on the higher side. Hence, it is recommended that the design tube diameter for aerosol transport lines be slightly larger than the optimum diameter if the overall losses are controlled by deposition in the straight tubes (as opposed to elbows or inlets). For very small particle sizes the tube orientation does not influence the penetration, since the dominant depositional mechanism is Brownian diffusion.

The variation of penetration of 10 μm AED aerosol particles at a flow rate of 56.6 L/min with d for different lengths of horizontal tube is shown in Figure 4. These numerical calculations demonstrate that d_{opt} is independent of tube length.

In Table 1 d_{opt} calculated from the present model is compared with the values calculated from Eq. 12 of Anand and McFarland (1989). The comparison is good for particle sizes ≥ 1 μm AED. For particle sizes ≤ 1 μm, the optimum diameters calculated from the present model and that of Anand and McFarland are noticeably different. This is attributed to the fact that for small particle sizes (≤ 1 μm) the contribution of Brownian diffusion toward particle deposition is significant and the earlier model of Anand and McFarland did not include this mechanism. Except for extremely long tubes, very small diameter tubes, or extremely small particle sizes, the penetration of submicrometer aerosol particles will be high and the concept of the optimum diameter is less important than for supramicrometer aerosol particles. For optimizing the tube diameter for transport of submicrometer aerosol particles, judgment of the designer based on

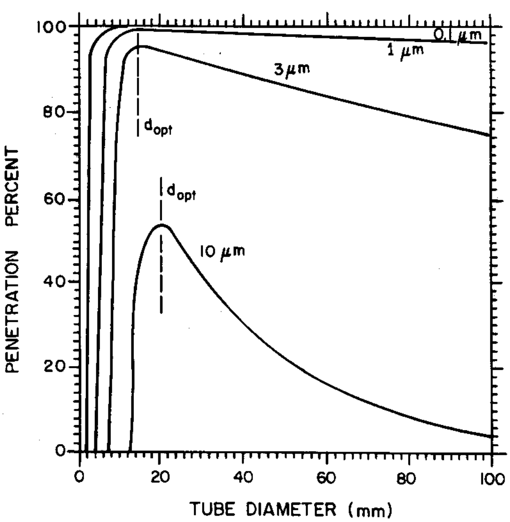

FIGURE 3. Aerosol penetration through 10 m long horizontal tubes. d_{opt} is the tube diameter associated with maximum penetration.

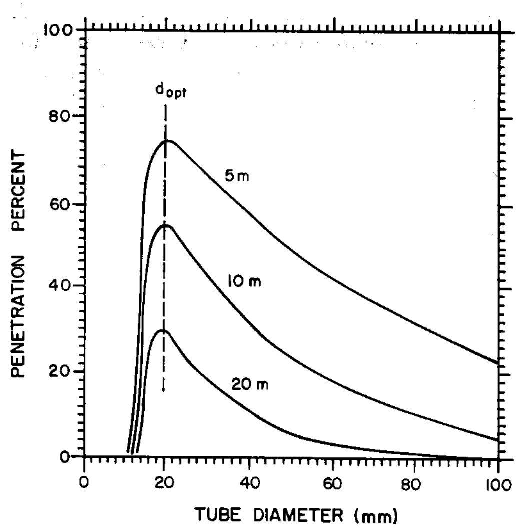

FIGURE 4. Penetration of 10 μm AED aerosol particles through horizontal tubes. The value of d_{opt} is independent of tube length.

TABLE 1. Optimum Tube Diameter

Particle diameter (μm)	d_{opt} (mm)[a]	d_{opt} (mm)[b]
0.1	7.194	>100
0.3	9.061	32
1.0	11.668	12
3.0	14.695	14
10.0	18.923	18
30.0	23.833	24

Flow rate = 56.6 L/min, tube length = 2 m, particle density = 1000 kg/m^3.
[a] Eq. 12 of Anand and McFarland (1989).
[b] Model prediction.

review of a curve of penetration versus tube diameter may be more appropriate than use of the optimization model.

Similar optimal results are obtained when elbows and inlets are included in the calculations, although the effect of elbow losses is to produce an optimum tube diameter that is less well defined than that for straight tubes.

THE CONCEPT OF MAXIMUM PENETRATION

In practice, a real-time aerosol sampler is often physically displaced from the sampling location. For example, in a nuclear plant the sample acquisition point may be located in a flow duct while the instrument (CAM) is remotely situated; or, in a clean room application, an optical particle counter may be located outside of the room while the inlet is in the controlled environment. Due to construction constraints the sampling point and the sampler are usually connected by a transport line with a number of straight tubes having different inclination angles and connected with elbows. However, for a given flow rate, particle size, and tube diameter, the penetration will be a maximum for a straight tube connecting the sampling location and the sampler. Thus the penetration in an actual transport line will always be less than P_{max}. This concept of P_{max} is useful for an engineering viewpoint because the comparison between P_T and P_{max} gives an indication of the possible scope for improvement. Also, note that P_{max} is the upper bound of aerosol penetration through transport lines between two points in a three-dimensional space.

In order to calculate P_{max}, the length L_{max} and the inclination of the transport line with the horizontal, ϕ_{max}, are needed. The origin is located at the sampler and coordinates of the sampling location (X, Y, Z) are established. Here, Z is the difference in elevation between the sampler and the sampling location. The L_{max} of such a transport line is given by

$$L_{max} = \sqrt{X^2 + Y^2 + Z^2} \qquad (7)$$

and the angle of inclination, ϕ_{max}, of the sampling line with respect to the vertical is given by

$$\phi_{max} = \sin^{-1}\frac{Z}{L_{max}} \qquad (8)$$

A designer should configure transport lines such that (P_T/P_{max}) is maximized within the constraints imposed by practical design considerations.

ILLUSTRATION OF MAXIMUM PENETRATION

The concept of maximum penetration is illustrated with the help of the example shown in Figure 5. For the purpose of simplicity, both sampling point and sampler are chosen to be in one plane (y-z). Following the previous discussion, the straight line connecting the two points (the path entitled "maximum penetration") will yield the maximum penetration. The penetration along other paths, labeled 1–8 in Figure 5, will be less than the maximum penetration. In the case of path 1, the horizontal and vertical portions are equal in length and the two tubes are connected with an elbow. Path 2 consists of an inclined tube and a vertical tube. As one moves from path 2 to path 4 the vertical segment length decreases, and finally the vertical segment length is zero for

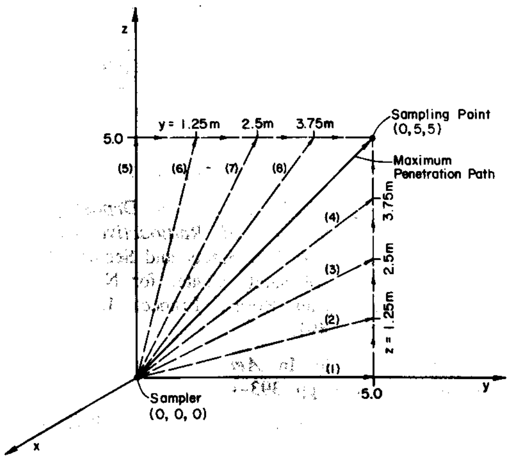

FIGURE 5. Two-dimensional arrangement used to illustrate the concept of maximum penetration for a tubing system.

the path of maximum penetration. Similarly, for path 5 the vertical and horizontal tubes are equal. As one moves from path 5 to path 8 the horizontal segment length decreases and finally is zero for the path of maximum penetration.

Table 2 shows the comparison of penetration for the various paths. The losses of aerosol in the straight sections of tubing were calculated from Eqs. 1 and 5, and the losses in elbows were determined from the model of Pui et al. (1987). It is evident that

TABLE 2. Illustration of the Maximum Penetration Concept

	Penetration			
Path no.	Tube 1, P_1	Elbow, P_{el}	Tube 2, P_2	Overall penetration $P_T = P_1 * P_{el} * P_2$
1	0.7982	0.8199	0.9543	0.6245
2	0.7976	0.8458	0.9655	0.6513
3	0.7959	0.8694	0.9769	0.6760
4	0.7933	0.8894	0.9883	0.6973
P_{max} path	—	—	—	0.7901
5	0.9543	0.8199	0.7982	0.6245
6	0.9260	0.8458	0.8445	0.6614
7	0.8796	0.8694	0.8934	0.6832
8	0.8340	0.8894	0.9452	0.7011

Flow rate = 113.2 L/min, particle diameter = 10 μm, particle density = 1000 kg/m^3.

the penetration along the path of maximum penetration is the upper bound, thus illustrating the concept of maximum penetration. It should be noted that this concept is applied for aerosol transport situations with the identical particle size and flow rate for the actual and the maximum penetration paths.

SUMMARY AND DISCUSSION

A model is developed to calculate monodisperse particle penetration through aerosol transport lines considering Brownian diffusion, gravitational settling, and turbulent diffusion. An analytical expression for effective depositional velocity particle is derived. The analytical expression should be of use in characterizing particle losses in inclined tubes where gravitational settling is of consequence.

A numerical procedure is given for calculating the optimal tube diameter for maximizing penetration through transport tubes. It should be noted that the calculations were carried out under the assumption of fully developed flow. If entrance effects were included, the value of optimal diameter would change somewhat. In addition, if other components (e.g., elbows and inlet) were included, the optimum would exist but the reduction in penetration for suboptimal tube diameters would be less pronounced than for straight tubes. Also, the code does not take into account the effects of particle charge; however, Liu et al. (1985) have shown that transport losses of micrometer-sized aerosol particles are not significantly influenced by charge provided the tube is a conductor. Effects of charge on aerosol transport have also been investigated by Charuau (1982). Details of our numerical code and its application have recently been reported (Anand and McFarland, 1991).

With respect to the concept of maximum penetration for an aerosol transport tube connecting two points in space, we feel the approach should be useful in the design and analysis of aerosol transport systems because it gives an upper bound on the penetration and shows the user the potential for improvement.

NOMENCLATURE

d	tube diameter, mm or m
C	particle concentration, m^{-3}
L	tube length, m
P	penetration
Q	airflow rate, L/min
V	particle deposition velocity, m/s
X	Distance measured from the tube entrance, m
X, Y, Z	Cartesian coordinates
ϕ	angle of inclination of the tube relative to the horizontal direction
θ	angle measured in the radial direction in a plane normal to the direction of flow

Subscripts

b	Brownian diffusion
c	critical
d	combined turbulent and Brownian diffusion effects
e	effective
el	elbow
g	gravitational effects
max	maximum
o	tube entrance
opt	optimal conditions
t	turbulent diffusion
T	total

This work was performed under the auspices of U.S. National Research Center Grant Contract NRC-04-89-353. The project monitor was Dr. Stephen A. McGuire.

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Received April 18, 1991; accepted September 12, 1991