PARTICLE DEPOSITION FROM TURBULENT DUCT FLOW

MR Sippola[1], WW Nazaroff[1] and TL Thatcher[2]

[1] Dept. of Civil and Environmental Engineering, University of California, Berkeley, CA USA
[2] Indoor Environment Dept., Lawrence Berkeley National Laboratory, Berkeley, CA USA

ABSTRACT

Particle deposition from turbulent duct flow is modeled and related to particle penetration of a ventilation system for a commercial office building. Three published turbulent deposition models capable of accommodating surface roughness are compared to experimental data and used to determine the penetration of 0.1–10 μm spherical particles through a sample duct run. Depending on the model employed, penetration fractions varied from 0.40-0.94 for 0.1 μm particles and 0.28-0.73 for 10 μm particles. Penetration is predicted to be independent of particle size for particle diameters less than 2 μm. Almost all the deposition is predicted to occur in short sections of the duct runs where the wall roughness is larger than in other duct sections because of the duct construction material.

INTRODUCTION

Exposure to airborne particles may contribute to human health effects including impairment of the respiratory system, lung tissue damage, and mortality. Particulate matter less than 10 μm in diameter (PM_{10}) is a criteria pollutant in the United States with an ambient air quality standard of 50 μg/m^3 on a yearly average basis and 150 μg/m^3 on a 24-hour average basis. No analogous U.S. standard exists for particles in indoor air. Epidemiological evidence suggests a positive correlation between outdoor PM_{10} concentrations and mortality in urban areas. This finding is surprising because most exposure to airborne particles occurs indoors and exposure does not correlate well with ambient concentrations [1]. In buildings with ducted air handling systems, particle deposition in ducts is a potentially important factor in influencing human exposure to particles.

A typical air supply system in a commercial building consists of an air handling unit which draws outside air through a filter and into a very large diameter duct, followed by a series of successively smaller, branched ducts which transport the air to different locations in the building. Generally, ducts are made of galvanized steel or aluminum and may be lined with fiberglass on the interior to reduce noise. Airflow in ventilation ducts is turbulent. Table 1 shows the range of duct dimensions and air velocities encountered in most commercial ventilation systems. Filter efficiencies at the air intake for particles less than 10 μm in diameter are low, commonly less than 10% for particle diameters ranging from 0.1 to 3.0 μm [2]. Thus, particle deposition from turbulent flow in the ventilation system is important for evaluating penetration into buildings and exposure of building occupants to outdoor particles.

Table 1. Approximate range of duct dimensions and flow conditions

	Duct Diameter	Wall Roughness	Air Velocity	Reynolds No.
Minimum value	0.15 m	0.001 mm	1 m/s	10^4
Maximum value	1.5 m	5 mm	10 m/s	10^6

Particle deposition to walls from turbulent airflow in a tube has significance in many engineering applications and has been widely studied. Experimentally, particle deposition has been observed to depend most strongly on particle size [3], surface roughness [4], and flow Reynolds number [5]. Mechanisms by which a particle may move in turbulent flow and can be captured at a solid surface include Brownian diffusion, turbulent diffusion, gravitational settling, inertial impaction, electrophoresis, thermophoresis, shear-induced (Saffman) lift, and interception. Several empirical and mechanistic models of deposition from turbulent duct flow have been proposed.

In this paper, three published models of particle deposition from turbulent pipe flow are evaluated and used to predict the fraction of particles which penetrate a single duct run of a ventilation system from a representative five-story commercial office building.

METHODS

The modeled duct run is from the ventilation system of a five-story commercial office building. The duct run begins at the air intake located on the roof of the building and terminates at a third floor office. Air traveling this path is carried in eight distinct duct sections, the characteristics of which are summarized in Table 2. Airflow rates are assumed to be constant at the designed rates. The flow path also includes two T-junctions, five 90° bends, and flow past numerous T-junctions and is selected to be representative of a typical duct run for a commercial office building. Analysis suggests that inertial impaction at the flow bends contributes a negligible amount to the overall deposition, thus, impaction at bends has been ignored in all simulations.

Table 2. Characteristics of modeled duct run

Section #	Orientation (-)	Material (-)	Roughness (mm)	Hydraulic Diameter (m)	Length (m)	Air Velocity (m/s)
1	Horizontal	Steel	0.15	1.50	1.1	10.6
2	Vertical	Steel	0.15	1.06	4.9	9.1
3	Horizontal	Fiberglass Liner	0.5	0.78	6.1	5.3
4	Horizontal	Steel	0.15	0.71	6.7	4.4
5	Horizontal	Steel	0.15	0.67	5.5	3.4
6	Horizontal	Steel	0.15	0.54	5.8	3.6
7	Horizontal	Steel	0.15	0.25	22.9	2.0
8	Horizontal	Flexible Aluminum	1.0	0.25	2.0	2.0

Three models have been used to evaluate particle penetration through the duct run: the modified free-flight model of El-Shobokshy and Ismail [6], the empirical free-flight model recommended by Wood [7], and the empirical correlation of the sublayer model presented by Fan and Ahmadi [8]. All three models predict dimensionless deposition velocity as a function of the particle dimensionless relaxation time to both smooth and rough surfaces. Input parameters are the particle diameter and density, duct diameter and roughness, and air velocity. Particle deposition velocity is defined as follows:

$$V_d = N / C \tag{1}$$

where N is the particle flux to the surface and C is the average particle concentration in the air stream. Deposition velocity is nondimensionalized by dividing by the friction velocity, u*:

$$V_d^+ = V_d / u^* \tag{2}$$

Particle dimensionless relaxation time is calculated by:

$$\tau^+ = \frac{C_c \rho_p d_p^2 u^{*2}}{18 \mu \upsilon} \tag{3}$$

where C_c is the slip correction factor, ρ_p is the particle density, d_p is the particle diameter, μ is the dynamic viscosity of air, and υ is the kinematic viscosity of air. For the airflow velocities and duct sizes of interest here, τ^+ is in the range of 5×10^{-5} to 5 for $0.1 < d_p < 10$ µm. If the deposition velocity is known, the fraction of a given sized particle penetrating a duct is:

$$f = \exp\left(-\frac{V_d PL}{UA} \right) \tag{4}$$

where f is the fraction of particles that pass through the duct, P is the duct perimeter, L is the duct length, U is the average air velocity, and A is the duct cross-sectional area.

All three models considered account for Brownian diffusion, turbulent diffusion and interception, and ignore electrophoresis and thermophoresis. The effect of gravity in horizontal ducts has been accounted for by the method outlined in Anand and McFarland [9]. The models of El-Shobokshy and Ismail [6] and Wood [7] are based on the free-flight concept which theorizes that particles attain a radial velocity while entrained in turbulent eddies, then deposit to the tube wall after being ejected from the eddy and coasting across the laminar boundary layer due to inertia. The sublayer model of Fan and Ahmadi [8] involves solving the Lagrangian equations of particle motion in a turbulent flow field, which accounts for turbulent bursts and fluid downsweeps at the tube wall. Fan and Ahmadi's model includes the shear-induced lift force. This phenomenon is theorized to account for the rapid increase in deposition with particle size which has been observed for particles in the range $1 < \tau^+ < 10$. Surface roughness elements shorten the distance for inertial coasting in the free flight models and increase the fraction of particle trajectories that encounter the wall in the sublayer model.

For the simulations, the duct wall is assumed to be a perfect sink for particles, and all roughnesses are assumed to be three-dimensional sand-grain type roughness. Turbulence is assumed to be fully developed. The particles considered are spherical with a density of 1.0 g/cm^3 and a diameter range from 0.1 to 10 µm.

RESULTS AND DISCUSSION

Comparisons of the three models to experimental data on particle deposition from turbulent pipe flow are presented in Figures 1 and 2. Figure 1 shows data collected from flow through small diameter (≈ 1 cm),vertically oriented, smooth and rough tubes at a Reynolds number of 10^4. The data of Liu and Agarwal [3] are considered the best available data for deposition in smooth tubes and the investigation by El-Shobokshy [4] is one of the few to thoroughly investigate and report the effects of surface roughness. The data collected by Shimada and Okuyama [5] are for very small diameter particles (d_p = 0.01-0.04 µm) that are influenced by Brownian motion. All deposition models show a general U-shaped trend. Starting at the left, the initial decrease in deposition velocity is due to the decreasing importance of Brownian diffusion as particle size, or τ^+, increases. As particle size increases further, deposition is expected to increase as a result of turbulent diffusion and interception. All the models show a decrease in the particle size dependence of deposition velocity as roughness increases, and all models predict roughness has less influence on particle deposition as particle size increases. The models of El-Shobokshy and Ismail [6]and Wood [7] show good agreement with the smooth pipe data over the entire range of τ^+, while that of Fan and Ahmadi [8] underpredicts V_d^+ in the range $0.1 < \tau^+ < 10$. All three models predict a dramatic increase in V_d^+ with surface roughness in the range $5 \times 10^{-3} < \tau^+ < 3$, with the model of Fan and Ahmadi [8] predicting the strongest effect. All model predictions for deposition to rough surfaces lie below the bulk of the equivalent experimental data. The model of El-Shobokshy and Ismail [6] agrees most closely with the experimental data over the range of roughnesses considered.

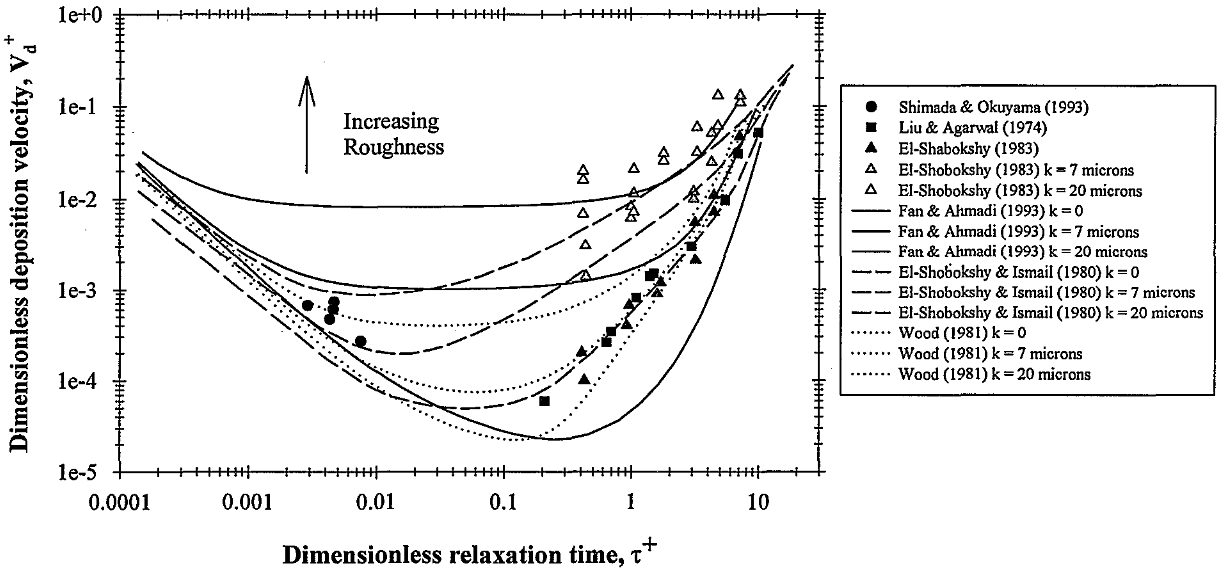

Figure 1. Model comparison to experimental data collected in vertical, small diameter tubes at Re = 10,000 and various wall roughnesses

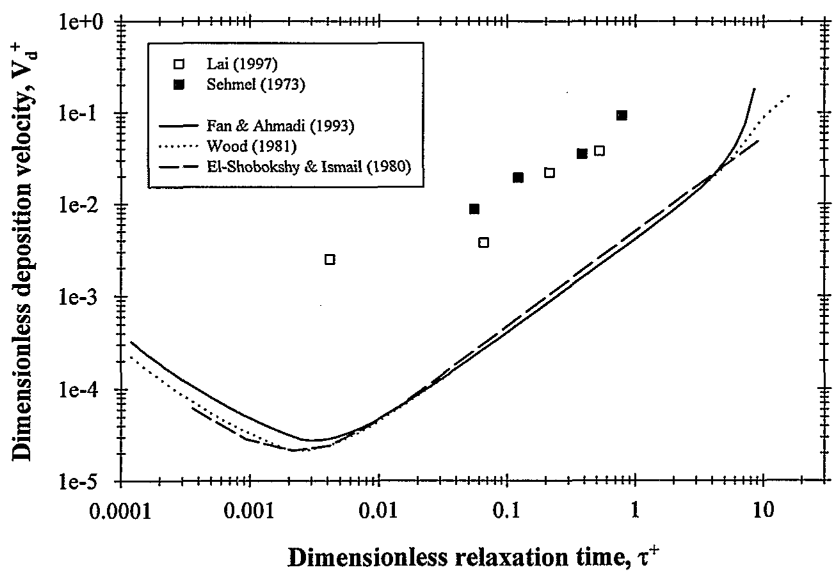

Figure 2. Model comparison to experimental data collected in large, smooth, horizontal ducts at $4.4 \times 10^4 < Re < 10^5$

Figure 2 displays data obtained from smooth, larger diameter (15-60 cm), horizontally oriented ducts at Reynolds numbers ranging from 4.4 x 10^4 to 10^5 [10, 11], which is more representative of conditions in a real ventilation duct. The models give similar predictions over the range $10^{-4} < \tau^+ < 4$. The agreement between models in the range $0.01 < \tau^+ < 4$ is the result of gravitational settling being the controlling deposition mechanism. The effect of the shear-induced lift force is seen to be important in Fan and Ahmadi's [8] model only for $\tau^+ >$ 4. All three models are observed to underpredict the experimental values of V_d^+ by one to two orders of magnitude. In addition to smooth wall deposition data, Lai [11] collected deposition data for different roughness arrangements in a large, horizontal duct. However, because the models are only able to accommodate sand-grain type roughness, a valid comparison between model and experiment is not possible.

The fractional penetration of particles through the modeled duct run as calculated by each model is shown in Figure 3. All three models predict that penetration is essentially independent of particle size for particles less than 2 μm in diameter. A decrease in particle penetration due to the effect of gravitational settling is predicted for particles greater than 2 μm by all three models. The model of Fan and Ahmadi [8] yields the lowest penetration fractions and the model of Wood [7] yields the highest penetration fractions for all particle sizes. All three models predict the majority of particle deposition to occur in sections 3 and 8 of the duct run. These ducts have higher surface roughness than the rest of the system because section 3 is acoustically lined with fiberglass and section 8 is a flexible aluminum duct with repeated ribbed roughness elements. Although these two duct sections comprise only 15% of the total length of the duct run, deposition in these ducts is expected to account for almost 99% of the total deposition in the system for particles smaller than 2 μm. These results indicate that deposition may significantly modify the particle concentrations in air flowing through ventilation ducts. In general, deposition models are observed to agree poorly with one another and with the experimental data, especially when rough surfaces are considered. More experimental data on deposition to large duct walls with quantified roughness are required for more complete model validation.

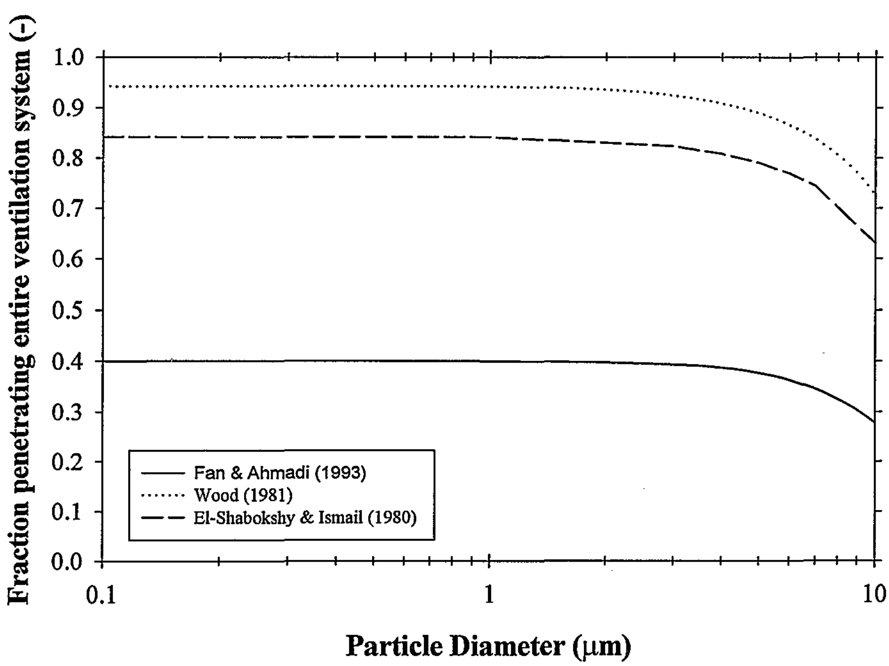

Figure 3. Fraction of particles penetrating the entire ventilation system versus particle diameter.

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