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PARTICLE DEPOSITION AND DIFFUSIVITIES ALONG SMOOTH SURFACES

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MASTER

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PARTICLE DEPOSITION AND DIFFUSIVITIES ALONG SMOOTH SURFACES*

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ABSTRACT

Particle mass transport and deposition mechanisms of eddy diffusion, particle inertia, and lift forces are described by "effective" eddy diffusion coefficients, ϵ , directed toward the deposition surface. Of principal concern is the eddy diffusion coefficient in the region very close to a surface in which the turbulence scale and intensity decrease rapidly as the surface is approached. These eddy diffusion coefficients are predicted from particle deposition velocity measurements through the use of a model which describes particle deposition in terms of eddy diffusion, Brownian diffusion, and the terminal settling velocity.

INTRODUCTION

The turbulent deposition of aerosol particles from an air stream onto a surface is one means by which airborne particulates are removed from the polluted atmosphere. Aerosol particles will deposit on a surface due to the action of the turbulent air motions of the carrying stream. The particle mass transfer at the surface has been characterized by a deposition velocity, K , defined as

$$K = \frac{\text{amount deposited/cm}^2 \text{ of surface/sec}}{\text{airborne particle concentration above the surface}} \quad (1)$$

* This paper is based on work performed under United States Atomic Energy Commission Contract No. AT(45-1)-1830.

which has units of cm/sec. This deposition velocity is the combined effect of all processes contributing to particle deposition. In laboratory experiments, K has been defined in terms of a particle concentration within a cm of the surface. For these experiments, K has been directed toward measuring the controlling mass transfer resistance at the deposition surface. In contrast for field experiments, K has been defined in terms of particle concentrations 1 to 2 m above the vegetative cover. Consequently, the K for field experiments includes both the controlling mass transfer resistance at the surface as well as the mass transfer resistance to about the 2 m height.

Particle deposition velocities were predicted in the pioneering work of Friedlander and Johnstone (4) by eddy diffusion transport followed by a final free flight. Subsequently, others (1, 2, 3, 5, 11) have attempted to improve upon the basic assumption for the particle velocity at the start of the free flight. This model approach has subsequently been shown to be erroneous by both Sehmel (8) and Rouhiainen and Stachiewicz (6) by using two different approaches. The conclusion is that the equality of particle eddy diffusivities to the eddy diffusivities of air momentum is untenable adjacent to a surface. In the present paper, the effective eddy diffusivity approach of Sehmel will be used to include a larger data base for calculation of eddy diffusivities near a floor surface and will be extended to include eddy diffusivities near a ceiling surface.

MODEL DEVELOPMENT

The purpose of using effective eddy diffusivities for particles is to establish a procedure for predicting deposition velocities to smooth surfaces. In reality, this eddy diffusivity procedure first predicts the overall mass transfer resistance and subsequently predicts the deposition velocities. Although only the overall mass transfer resistance can be predicted, reasonable estimates of particle eddy diffusivities and comparison with air eddy diffusivities can be made.

Particle deposition near a surface is assumed in the model to occur by diffusion and gravitation effects. The basic model assumptions are that there is a constant flux of particles from a uniform concentration source C_1 at 1 cm, that particle eddy diffusivities can be predicted, that the gravitational force can be described by the terminal settling velocity, and that the particles are completely retained by the surface after contact. Based upon these assumptions, the deposition flux to a floor surface is

$$N = -(\epsilon + D) \frac{dC}{dy} - v_t C. \quad (2)$$

Working Size Type Area: $3\frac{1}{2} \times 52$ inch (To be shot at 90°)

Shot Size Type Area: $3\frac{1}{2} \times 52$ inch

Find Trim Size: $3\frac{1}{2} \times 52$ inch

Similar equations (10) can be set up for deposition on wall and ceiling surfaces. Prediction of the deposition velocity

$$K_1 = -N/C_1 \quad (3)$$

is from a dimensionless integral form of Equation (1) in which

$$-\int_{C_1}^0 \frac{u_* dC}{N + v_t C} = \int_{y^+ \text{ at } 1 \text{ cm}}^{r^+} \frac{dy^+}{\epsilon/v + D/v} \quad (4)$$

The right-hand integral is termed the resistance integral Int. Once Int is predicted, the deposition velocity can be predicted from

$$K_1 = \frac{y_t}{1 - (1/\alpha)} \quad (5)$$

where

$$\alpha = \exp(-v_t \text{Int}/u_*). \quad (6)$$

EXPERIMENTAL

The experimental techniques for measuring deposition velocities have been previously described (9). The essential features are that monodispersed uranine particles [density of 1.5 g/cm³ (7)] were introduced into a 61 × 61 cm cross section wind tunnel. Downstream, the particle deposition flux and airborne concentration profiles were measured. Particle concentration was measured by impaction on cylindrical wires or by collection on filters. The closest concentration measured was 1 cm from the surface. The mass balance of the uranine was determined by dissolving the uranine in water and fluorometric analysis of the wash solutions.

DATA ANALYSIS

Particle effective eddy diffusivities were calculated to predict the observed deposition velocities. The constants in the final eddy diffusivity correlations were selected to minimize the sum of squares of the logarithms of the ratios of the predicted to experimental deposition velocities. The final correlations for eddy diffusivities are shown in Fig. 1.

The eddy diffusivities are a function of the dimensionless distance y^+ from the surface, the particle relaxation time, τ^+ ,

and are also different for vertical surfaces (8), floor surfaces, and ceiling surfaces. The different diffusivity equations are applied to the shaded region to calculate the diffusional resistance Int. For instance, typical calculations for floor deposition might start from either

$$\text{Int} = \int_{y^+ \text{ at } 1 \text{ cm}}^{\infty} \frac{dy^+}{140 + D/v} + \int_{\infty}^{\infty} \frac{dy^+}{0.002 \left(\frac{y^+}{10}\right)^3 + D/v} \quad (7)$$

$$\text{or} \quad \int_{y^+ \text{ at } 1 \text{ cm}}^{\infty} \frac{dy^+}{\psi(y^+)^{2.6} (\tau^+)^{1.2} + D/v}$$

or

$$\text{Int} = \int_{y^+ \text{ at } 1 \text{ cm}}^{\infty} \frac{dy^+}{140 + D/v} + \int_{\infty}^{\infty} \frac{dy^+}{1.1y^+ + D/v} + \int_{\infty}^{\infty} \frac{dy^+}{\psi(y^+)^{2.6} (\tau^+)^{1.2} + D/v} \quad (8)$$

The limits of integration would depend upon where the line representing the eddy diffusivities intercepted the upper and lower boundary of the shaded area. Also shown in the shaded area are dashed lines which were used by Sehmel in the original development of effective eddy diffusivities.

DEPOSITION VELOCITY COMPARISON

Deposition velocities to floor, wall, and ceiling surfaces were calculated from Equation (5) using the appropriate form of Equation (7). The resulting deposition velocities are shown in Fig. 2 for a nominal velocity of 6.7 m/sec. As expected, the ceiling deposition is least, wall deposition intermediate, and floor deposition the greatest. For particles smaller than about 0.8 μm , the predicted deposition velocities are all the same. The reason for this identical curve is that for each geometry the eddy diffusivities were small and were represented by the lower boundary limit of the shaded region of Fig. 1. Even though small, the eddy diffusivities were large enough to predict a greater deposition velocity than for particle transport caused by only Brownian diffusion and gravity settling to a floor surface which is shown by the $u_* = 0$ curve.

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Working Size Type Area: 10 1/2 x 12 inches (To be shot at 90%)

Final Size Type: 10 1/2 x 12 inches

Final Trim Size: 10 1/2 x 9 1/2 inches

FIGURE 2

COMPARISON OF DEPOSITION VELOCITIES TO SMOOTH FLOOR, WALL, AND
CEILING SURFACES FOR A $u_* = 34.1$ CM/SEC AND $y_0 = 0.004$ CM

From Table 1 of Text

Working Size Type Area: $33\frac{1}{2} \times 52$ Picas (To be shot at 90%)
Final Size Type Area: 30×47 Picas
Final Trim Size: $6\frac{1}{2} \times 9\frac{1}{3}$ inches

A further comparison of deposition velocities is made for a larger nominal air velocity of 13.4 m/sec in Fig. 3. The greater turbulence has caused the three curves to be closer together. However, improvement in the eddy diffusivity correlations appears to be needed since a portion of the wall deposition velocity curve is greater than for the floor deposition velocity curve.

CONCLUSIONS

Much remains to be learned about particle deposition. Nevertheless, a model is developed to estimate particle sampling losses in smooth straight lines as well as the lower limit of deposition velocities expected for atmospheric surfaces. The real practical problem now is determining methods for predicting particle deposition to environmental surfaces in which factors such as surface roughness, particle agglomeration, impaction, interception, electrical, and phoretic effects are more important in the eddy deposition process.

NOMENCLATURE

- C = local particle concentration, particles/cm³
- C_1 = average particle concentration at reference height of 1 cm, particles/cm³
- d = particle diameter, cm
- D = Brownian diffusivity, cm²/sec, see Sehmel (1971)
- Int = diffusional resistance integral, see Equation (4)
- k = von Kármán's constant equal to 0.4
- K_1 = deposition velocity, cm/sec (number of particles depositing/(cm² sec)/average number concentration/cm³ of air at reference height of 1 cm)
- N = particle flux, particles/(cm²sec)
- r = particle radius, cm
- r^+ = ru_*/ν , dimensionless
- u = local horizontal air velocity, cm/sec
- u_* = friction velocity, $u = (u_*/k) \ln[(y+y_0)/y_0]$
- v_t = settling velocity, $\rho d^2 g / (18 \mu)$, cm/sec
- y = height above surface, cm
- y^+ = yu_*/ν , dimensionless
- y_0 = roughness height, cm
- $\alpha = \exp(-v_t \text{ Int} / u_*)$, see Equation (6)
- ϵ/ν = ratio of [(inertial + diffusivity + lift)/viscous] forces for particles
- μ = gas viscosity, gm/(cm sec)
- μm = micrometer, which is 10^{-4} cm
- ν = kinematic viscosity, μ/ρ_g , cm²/sec
- ρ = particle density, gm/cm³

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FIGURE 3

COMPARISON OF DEPOSITION VELOCITIES TO SMOOTH FLOOR, WALL
AND CEILING SURFACES FOR A $u_* = 34.1$ CM/SEC AND $y_0 = 0.004$ CM
(Nominal Velocity of 13.4 m/Sec or 30 MPH)

Last Line of Text

Working Size Type Area: 83 $\frac{1}{2}$ x 52 Picas (To be shown at 90%)
Print Size Type Area: 30 x 4 Picas
Total Print Size: 6 $\frac{1}{2}$ x 10 $\frac{1}{2}$ Inches

ρ_g = gas density, gm/cm³
 τ = particle relaxation time, $\rho_d^2/(18 \mu)$
 $\tau^+ = \tau u_*^2/\nu$, dimensionless

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