PREDICTED DRY DEPOSITION VELOCITIES

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PARTICLE DRY DEPOSITION VELOCITIES*

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ABSTRACT

Particle deposition velocities are predicted from a steady-state one-dimensional mass transfer model. Dimensionless integral mass transfer resistances are used for the predictions. Predictions are made for a particle density of 1.5 g/cm³ and a reference concentration height of 1 m. Ranges of variables considered are for individual particle diameters from 0.01 to 100 μ m, roughness heights from 10⁻⁴ to 10 cm, friction velocities from 10 to 200 cm/sec, and Obukhov's stability length criteria of ± 10 m.

INTRODUCTION

Particle removal rates from polluted atmospheres to environmental surfaces have been described by dry deposition velocities which are a function of particle, surface, and air properties. These removal rates are important in considerations of air pollution removal if environmentally permissible upper limits of air pollutant concentrations are not to be exceeded. Deposition velocities have been summarized for several authors.⁽¹⁾ Unfortunately, many experimental deposition velocities have been determined with limited control of experimental conditions. Particle diameters have been inadequately known, and hence experimental results have usually been reported with insufficient information to generalize deposition velocities to other field conditions.

A second limitation is that particle and gaseous removal rates are non-steady-state processes dependent upon the delivery capability of the upper atmosphere as well as surface resistance. Historically, deposition velocities,

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v_d , have been defined as a deposition flux, N , divided by an airborne concentration, χ . That is,

$$v_d = \frac{N}{\chi} \quad (1)$$

which has units of length/time usually reported as cm/sec. Airborne concentrations have often been measured at 1 m above the deposition surface.

There is a fallacy in this deposition velocity concept. It is the exception rather than the rule that non-steady-state mass transfer can be adequately described by a single point concentration measurement. If mass transfer occurs, airborne concentration profiles must, of necessity, be developed to act as the driving gradient for mass transfer in a diffusion controlled process. Only in the nominal case of simple gravity settling will concentration profiles be constant.

In mass transfer processes the airborne concentration at any point results from the capability of the atmosphere to deliver pollutant from regions of higher concentrations to regions of lower concentrations. Consequently, most field determined deposition velocities only approximate surface mass transfer removal rates for the particular plume test conditions above the reference concentration height. To extrapolate field deposition velocities to new situations requires similitude between pollutant plume shape, particle diameters, wind shear, etc.

The objective of this paper is to present a generalized technique for predicting particle removal rates by dry deposition from any airborne plume. Inherent in applying the method is that one can completely describe a pollutant plume at some initial point in time.

GENERAL MODEL

Pollutant motion in the atmosphere is described by the non-steady-state continuity equation. Conceptually, pollutant transport is idealized in Fig. 1 by a three-box model using the continuity equation. In box 1, airborne pollutant plume movement is described by standard meteorological equations. In this atmospheric turbulent layer, mass transfer processes are described by micro-meteorological eddy diffusivities. In the overall deposition process, the plume approaches and interfaces with box 2. This idealized layer of box 2 is just above the vegetative canopy or surface elements in a region where transfer processes are modified by the presence of the canopy or surfaces. As illustrated, this interface region can extend to all scales from small vegetation and trees, to scales as large as cities.

Deposition velocities will be predicted through calculating integral diffusional resistances in each of the three boxes. Unfortunately predictions must be limited to surface elements with small roughness heights since diffusional resistance correlation exists only for small surface roughness. Perhaps as additional data are obtained, further model generalization to both larger roughnesses and sub-boxes within box 3 will be predictable.

Model predictions of deposition velocities using boxes 2 and 1 will also be for the simplest case -- steady state one dimensional flow from a uniform pollutant source. Extension of model concepts to other pollutant plumes is limited only by the reader's requirements and ability to describe pollutant concentration profiles caused by diffusion and transport at significant elevations above environmental surfaces. If the user has a plume surface depletion model available to predict concentrations at the interface of boxes 2 and 3, the user will not need the proposed simple model. Rather, the user should directly use the mass transfer resistance integral for box 3 in that more complex model.

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Fig. 1 Conceptual Three Box Model

Most diffusion transport equations still use a deposition velocity rather than a mass transfer integral for a boundary condition. Consequently, deposition velocities K_{1-M} will be presented. The deposition velocity, K , is defined as

$$K_1 = \frac{N}{C} \quad (2)$$

In this case, the concentration, C , is for monodispersed particles and is measured 1 cm above the deposition surface. The deposition velocity nomenclature K , rather than v_d , reflects that deposition velocities are a function of particle diameter. The subscript 1-M indicate a uniform pollutant concentration above a 1 m reference height.

SIMPLE MODEL

Deposition velocities K assume particle deposition is described by a one-dimensional, steady-state continuity equation. Basic assumptions in this model are that particles diffuse at a constant flux from a uniform concentration of particles, that a relationship for particle eddy diffusivity can be determined, that the effect of gravity can be described by the terminal settling velocity, that particle agglomeration does not occur, and that particles are completely retained by the surface. Based upon these assumptions, the deposition flux to a surface is described by

$$N = -(\epsilon + D) \frac{dC}{dz} - v_t C, \quad (3)$$

in which v_t is the absolute value of the terminal settling velocity.

The deposition velocity is predicted from a dimensionless integral form of Eq. (3).

$$-\int_{C_z}^0 \frac{u_* dC}{N + v_t C} = \int_{z^+}^{r^+} \frac{dz}{\epsilon/v + D/v} = \text{Int} \quad (4)$$

in which ϵ is the particle eddy diffusivity, D is the Brownian diffusivity, ν is the kinematic viscosity of air, u_* is the friction velocity, $z^+ = zu_*/\nu$ is the dimensionless distance above the surface, and v_t is the terminal settling velocity. Integration limits are that particle concentration is a constant C_z at a reference height of z cm and above and that particle concentration is zero at a dimensionless particle radius, r^+ , from the deposition surface. The right-hand integral is a resistance integral (negative in value) abbreviated as Int . Int contains the dimensionless eddy diffusivity, ϵ/ν , and Brownian diffusivity and hence Int quantifies only diffusional resistance between the integration limits. This integral Int can be subdivided into

$$\text{Int} = \int_{z^+ \text{ at } C_z}^{z^+} \frac{dz^+}{\epsilon/\nu + D/\nu} + \int_{z^+}^{z^+} \frac{dz^+}{\epsilon/\nu + D/\nu} + \text{Int}_3 \quad (5)$$

where the first integral is Int_1 and the second integral is Int_2 . The limit z^+_{1-2} is the distance at which boxes 1 and 2 interface. Similarly, boxes 2 and 3 interface at z^+_{2-3} . These integrals will be evaluated after a relationship between deposition velocity and Int is shown.

The deposition velocity is obtained from an integrated form of Eq. (4) for the deposition flux in which

$$N = \frac{v_t C_z \alpha}{1 - \alpha} \quad (6)$$

in which

$$\alpha = \exp(-v_t \text{Int}/u_*). \quad (7)$$

Now the deposition velocity is defined in terms of the reference concentration, C_z at z cm height,

$$K_z = \frac{(-N)}{C_z} \quad (8)$$

Thus, the deposition velocity at height z is

$$K_z = \frac{v_t}{1 - (1/\alpha)} \quad (9)$$

As shown by Eq. (9), the lower limit of predicted deposition velocities is v_t . The reason for this limit is that if the diffusional resistance were large (Int is a negative number), α would approach infinity and $1/\alpha$ would approach zero. However, as diffusional resistance became relatively less, the deposition velocity would become increasingly greater than the gravitational settling velocity.

Int₃

Surface integral resistances Int_3 were evaluated by Sehmel and Hodgson⁽²⁾ from wind tunnel determined deposition velocities. Deposition velocities, K_1 , were determined for deposition of monodispersed particles onto four different surfaces. These were an artificial grass 0.7 cm in height, a smooth brass surface, crushed gravel 0.5 to 1.6 cm in diameter, and a water surface with wave heights up to 2.5 cm. Particle diameters were from 0.03 μm up to 30 μm for a particle density of 1.5 g/cm³. Friction velocities, u_* , ranged from 11 to 144 cm/sec and roughness heights, z_o , from 0.004 to 0.4 cm. In all cases, the reference concentration height for defining K_1 was 1 cm above the deposition surface which corresponds to a box 3. Consequently, values of Int_3 were evaluated from the K_1 's by

$$\text{Int}_3 = - \frac{u_*}{K_1} \ln \left(\frac{1}{1 - v_t/K_1} \right) \quad (10)$$

Least squares techniques were used to determine a dimensionless correlation for predicting Int_3 from the wind tunnel deposition velocity data for the

four surfaces for non-reentrainment conditions. The dimensionless correlation is

$$\begin{aligned} \text{Int}_3 = - \exp \left\{ -23.667 + 5.555 \ln \frac{d}{z_o} \right. \\ - 0.07681 \left(\ln \frac{d}{z_o} \right)^2 + 0.9722 \ln \frac{u_*}{v_t} \\ + 0.03799 \left(\ln \frac{u_*}{v_t} \right)^2 - 2.254 \ln \frac{D}{u_* z_o} \\ \left. - 3.724 \ln \frac{\rho u_* d^2}{18 v z_o} \right\} \end{aligned} \quad (11)$$

in which d is particle diameter, z_o is roughness height, and ρ is particle density of 1.5 g/cm^3 .

Int₂ and Int₁

Resistance integrals Int_2 and Int_1 for heights greater than 1 cm were evaluated using Eq. (5) and Businger⁽³⁾ et. al, atmospheric diffusion correlations for stable, neutral and unstable conditions. The assumption was that particle eddy diffusivity was equal to the eddy diffusivity of air momentum. Since these correlations do not include any canopy effect on eddy diffusivity in box 2, Int_2 and Int_1 were combined into a single resistance integral. Resistance integrals were calculated from 1 cm up to 10 m.

Resistance integrals are shown in Fig. 2 as a function of height and stability. Since eddy diffusion is least in stable atmospheres, mass transfer resistance integrals are also largest for stable atmospheres. The largest shown is -30. For unstable atmospheres, mass transfer resistance integrals are least. For instability, the largest resistance integral shown is -15.5. In contrast in magnitude, Int_3 surface resistance integrals ranged from -1 to -10^5 .

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Fig. 2 Resistance Integral from 1 cm to Indicated Height

FUNCTION OF HEIGHT

Predicted deposition velocities were calculated from the box 3 Int_3 correlation Eq. (11) and integral resistances above 1 cm to 10 cm, to 1 m, and to 10 m from Fig. 2. Predicted deposition velocities shown in Fig. 3 were calculated at each height for both unstable and stable atmospheres. The upper bound for each height is for an unstable atmosphere with Obukhov's length equal to -10 m. All predicted deposition velocities are greater than particle terminal settling velocities indicated by the $u_* = 0$ line for a particle density of 1.5 g/cm^3 .

Deposition velocities are a function of particle diameter and have their smallest values in the 0.1 to 1 μm particle diameter range. For larger particles, both increased effective eddy diffusion in box 3 and increased gravity settling rates tend to increase predicted deposition velocities above the minimum. For smaller particles, deposition velocities increase with decreasing particle diameters because of increased mass transfer by Brownian diffusion.

Relative resistances or controlling resistances can sometimes be inferred from the changes in deposition velocity with height. Deposition velocities for $10^{-2} \mu\text{m}$ particles are almost insensitive to changes in particle diameter at elevated heights of 10 cm, 1 m, and 10 m. In contrast, deposition velocities at 1 cm are extremely large in box 3. Consequently in this size range, deposition rates are controlled by atmospheric diffusion in boxes 2 and 1.

Predicted deposition velocities are most sensitive to the reference concentration height for particle diameters at $10^{-2} \mu\text{m}$. However, sensitivity appears to be less pronounced at 1 m and above. Due to this insensitivity, a 1 m reference height has been selected for presentation in the other deposition velocity figures. We must remember that even with a relative insensitivity to

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Fig. 3 Predicted Deposition Velocity at Indicated Height
for $u_* = 20$ cm/sec and $z_0 = 3$ cm

height at 1 m, deposition velocities are only an approximation to describe the unsteady state diffusion-transport boundary limits. It is fortunate that deposition velocities are relatively insensitive to height at 1 m since field experiments and predictions have often used a similar height.

DEPOSITION VELOCITIES AT 1 M

Deposition velocities, K_{1-M} , have been predicted for a 1 m reference concentration height in Fig. 4 through 11. In each figure, ranges of deposition velocities for stable and unstable atmospheres are shown. Parameters in each figure are either friction velocity ranging from 10 to 200 cm/sec or roughness height ranging from 10^{-3} to 10 cm.

In Fig. 4, deposition velocities are shown as a function of friction velocity for a constant roughness height of 3 cm. This is a typical height for the Hanford Reservation. Deposition velocities, K_{1-M} , increase rapidly with an increase in friction velocity and are a function of particle diameter. Minimum deposition velocities occur for particle diameters from about 0.2 to 0.4 μm .

In Fig. 5 through 11, deposition velocities are shown for a constant friction velocity in each figure. These figures encompass typical values for friction velocities. Curves are shown for roughness heights of 10^{-3} , 10^{-1} , 3, and 10 cm. Also shown in Fig. 5 is a $u_* = 0$ curve including particle diameters less than 10^{-1} μm . In this case, this lower curve predicts combined mass transfer by Brownian diffusion and gravity settling in the final 1 cm adjustment to a smooth deposition surface.

In general, deposition velocities increase with an increase in either friction velocity or roughness height. However, some predicted curves cross at particle diameters around 6 μm and larger. This crossing should not occur and consequently is indicative of limitations in the resistance integral correlation for Int_3 .

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Fig. 4 Predicted Deposition Velocities at 1 Meter Height
for $z_0 = 3.0$ cm
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Fig. 5 Predicted Deposition Velocities at 1 Meter for $u_* = 10$ cm/sec

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Fig. 6 Predicted Deposition Velocities at 1 Meter for $u_* = 20$ cm/sec

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Fig. 7 Predicted Deposition Velocities at 1 Meter for $u_* = 30$ cm/sec

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Fig. 8 Predicted Deposition Velocities at 1 Meter for $u_* = 50$ cm/sec

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Fig. 9 Predicted Deposition Velocities at 1 Meter for $u_* = 100$ cm/sec

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Fig. 10 Predicted Deposition Velocities at 1 Meter for $u_* = 150$ cm/sec

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Fig. 11 Predicted Deposition Velocities at 1 Meter for $u_* = 200$ cm/sec

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For all combinations of friction velocity and roughness height that were calculated, minimum deposition velocities occur in the range of 0.04 to 0.4 μm . As most readily seen in Fig. 5, the particle diameter at each minimum deposition velocity increases with an increase in roughness height.

CONCLUSIONS

Deposition velocities have been determined for field conditions, but data have never been organized into a unified approach for extending predictions to other test conditions. This paper develops a predictive method for field conditions for a particle density of 1.5 g/cm^3 . If other particle densities are to be considered, the recommendation is that the integral resistance Int_3 be linearly adjusted as a function of particle density.

There are problem areas in applying deposition velocities. Deposition velocities are a function of particle diameter even when all other variables are constant. Thus in either applying or interpreting deposition velocities to field conditions, one must adequately describe the particle size distribution.

Deposition velocities are nearly independent of particle diameter only in the 0.1 to 1 μm size range. Since deposition velocities increase rapidly above one μm , even a few percent of particles being greater than one μm in diameter can significantly alter the average deposition velocity.

Usage of a three box mass transfer model and the dimensionless resistance integral require that sufficient experimental data should always be recorded when experimentally evaluating deposition velocities. Required data include at least friction velocity, roughness height, particle size distributions, and atmospheric stability. In addition, airborne concentration should be measured at several heights in order to determine the vertical concentration profile. If the profile is known, one can determine if airborne concentration is nearly

insensitive to height at the height selected for defining the deposition velocity. If airborne concentration is dependent on height, a better approximation than a single deposition velocity must be developed to include the atmospheric delivery capability. These data will be required if more realistic deposition velocity predictions or correlations are ever to be made with multi-box mass transfer models.

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