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Parameterization of aerosol dry deposition velocities onto smooth and rough surfaces

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ABSTRACT

The velocities of aerosol deposition onto vertical and horizontal surfaces are needed for 2D and 3D calculations of aerosol transport and deposition in the urban and indoor environments. This paper analyzes the experimental results and semiempirical and theoretical models on dry deposition velocities. The features of the solution obtained by Zhao and Wu [(2006a). Modeling particle deposition from fully developed turbulent flow in ventilation duct. *Atmospheric Environment*, *40*, 457–466] for the velocity of aerosol deposition onto smooth surfaces are analyzed, the integrals are approximated analytically. To treat the deposition onto rough surfaces, the results of Sehmel [(1973). Particle eddy diffusivities and deposition for isothermal flow and smooth surfaces. *Journal of Aerosol Science*, *4*, 125–138]; Sehmel and Hodgson [(1978). A model for predicting dry deposition of particles and gases to environmental surfaces. PNL-SA-6721. Richland, WA: Battelle, Pacific Northwest Laboratory] are modified and represented in a unified manner for vertical and horizontal surfaces. Cross-comparison with data of Slinn [(1978) Parameterization for resuspension and for Wet and Dry Deposition of Particles and Gases for Use in Radiation Dose Calculations. *Nucl.Safety*, 19(2), 205–219.] and the model of Lai and Nazaroff [(2000). Modeling indoor particle deposition from turbulent flow onto smooth surfaces. *Journal of Aerosol Science*, *31*, 463–476] allowed reconciliation between the theoretical and semiempirical approaches. Finally, an approximation to the aerosol dry deposition velocities is obtained in the form of convenient parameterization formulas covering a wide range of particle sizes $0.01\,\mu\mathrm{m} \leqslant d \leqslant 1000\,\mu\mathrm{m}$ and surface roughnesses $z_0 \leqslant 10$ cm.

1. Introduction

The calculation of aerosol deposition in the urban environment (Jonsson, Karlsson, & Jönsson, 2008; Kosovic et al., 2005; Yang & Shao, 2008) and indoors (Chen, Yu & Lai, 2006; Gao & Niu, 2007; Zhao & Wu, 2007) requires expressions for the dry deposition velocity which must satisfy rather diverse requirements:

- possibility of calculating the deposition onto vertical walls and horizontal surfaces;
- possibility of calculating different degrees of surface roughness z_0 ranging from 0 to 1 m and arbitrary particle size d ranging from 10^{-8} to 10^{-3} m;
- simple formulas allowing real-time computations.

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Nomenclature

C	aerosol concentration
C_c	Cunningham correction coefficient: $C_c = 1 + 2\frac{\lambda}{d}\left[1.257 + 0.4\exp\left(-\frac{1.1d}{2\lambda}\right)\right]$
C_D	particle drag coefficient: $C_D(Re) = 24/Re + C^0$, where $C^0 = 0.42$
d	particle diameter
D	coefficient of Brownian diffusion of aerosol particles: $D = kTC_c/3\pi\mu d$
g	gravitational acceleration
g^+	dimensionless gravitational acceleration $g^+ = g\nu/(u^*)^3$
k	Boltzmann constant
j	aerosol particle flux
k^+	dimensionless roughness parameter $k^+ = z_0u^*/\nu$
L	Monin–Obukhov parameter
Re	Reynolds number $Re = d\rho u_s/\mu$ for particle deposition
Sc	Schmidt number $Sc = \nu/D$
T	ambient temperature
u^*	friction velocity in the surface (near-wall) layer
u_d, α	pollutant dry deposition velocity
u_d^+	pollutant dry deposition velocity in dimensionless units, $u_d^+ = u_d/u^*$
u_s	particle gravity sedimentation velocity $u_s = \frac{12\mu}{C^0C_c\rho d}\left(\sqrt{1 + \frac{C^0C_c^2\rho\rho_p}{108\mu^2}d^3\left(1 - \frac{\rho}{\rho_p}\right)g} - 1\right)$
y	distance to the surface (wall)
y^+	dimensionless distance to the surface (wall) $y^+ = yu^*/\nu$
z_0	surface roughness parameter
α, u_d	pollutant dry deposition velocity
λ	air molecular path
μ	air dynamic viscosity
ν	air kinematic (molecular) viscosity $\nu = \mu/\rho$
ν_t	air turbulent viscosity
ρ	air density
ρ_p	particle density
τ_p	characteristic time of particle relaxation (deceleration) $\tau_p = u_s/g$
τ_L	Lagrangian timescale of turbulence
τ^+	dimensionless relaxation time $\tau^+ = \tau_p u^{*2}/\nu$

Numerous papers (Davies, 1966; Fan & Ahmadi, 1993; Johansen, 1991; Kharchenko, 1997; Liu & Agarwal, 1974; Nho-Kim, Michou, and Peuch, 2004; Sehmel, 1973, 1980; Sehmel & Hodgson, 1978; Sippola & Nazaroff, 2002; Slinn, 1978, 1982; Valentine and Smith, 2005; Wood, 1981a, 1981b; Zaichik and Alipchenkov, 2007) describe semiempirical relations for the velocities of deposition onto vertical and horizontal walls. These were determined mainly from experimental data on turbulent deposition in ducts and channels. The most complete set of data was obtained by Sehmel (1973) and by Sehmel and Hodgson (1978), including those from open-surface experiments. Note that in the various semiempirical formulas it is not always possible to determine their range of validity or take into account the complete set of the physical effects within the turbulent boundary layer.

Most attractive are the theoretical models considering the physical pattern of the particle motion and deposition in the near-wall layer formed near a surface. With these models it becomes possible to include particle motion in a heterogeneous turbulence field (turbophoresis), including the particle lag in turbulent pulsations. One of the most complete models of this kind is the generalized Eulerian theory presented by Guha (1997). However, this theory is difficult to close and use within the numerical complexes computing the 2D and 3D pattern of turbulent flows in the urban environment. It would be most helpful to have a self-contained technique for computing the deposition velocity with a minimum of input parameters.

An important step in this direction is the paper by Lai and Nazaroff (2000), who consider the particle deposition onto horizontal and vertical surfaces of rooms, when turbophoresis can be neglected. Since its application requires a detailed description only of the respirable aerosol fraction dangerous in inhalation, this model can serve as a simple, easy-to-use tool.

A very important contribution to the development of easy-to-use deposition models which at the same time include the entire set of factors important in practice has been made by Zhao and Wu (2006a, 2006b). Zhao and Wu (2006a) suggest an improved Eulerian model to predict the particle deposition velocity onto walls in a developed turbulent flow. The model partitions the boundary layer into three areas and includes the description of turbophoresis, Brownian and turbulent diffusion as well as sedimentation. A relation between the turbophoresis velocity to the deceleration time, friction velocity and normal distance to the surface is used. The predicted results agree well with the measured data for the internal surfaces of buildings and for vertical walls of channels. The model is easy to use and operates with a combination of dimensionless quantities. The only input parameters required are the friction velocity, particles diameter and density. The model was further improved by Zhao and Wu