Prediction of particle deposition on to rough surfaces

Andrew Michael Reynolds*

Silsoe Research Institute, Wrest Park, Silsoe, Bedford MK45 4HS, UK

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Abstract

Lagrangian stochastic models applicable to the prediction of particle deposition onto hydraulically smooth surfaces are extended to account for the effects of surface roughness. Within the modelling approach, roughness elements are treated as mass ‘sinks’ volumetrically distributed within the flows. The extreme sensitivity of the deposition of micron and sub-micron sized particles to the micro-roughness of hydraulically smooth surfaces is shown to be very well predicted. This suggests that the models can be used to predict the deposition of particles onto leaves and other natural surfaces with micro-roughness elements correctly. Model predictions for the deposition velocities of spores and pollens onto completely rough sticky surfaces are shown to be in very close agreement with the experiment. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Despite there being considerable interest in the rates at which particles are transported from turbulent air flows to rough surfaces, relatively little progress has been made in the formulation of predictive models. Instead, attention has been focused largely upon particle deposition to hydraulically smooth surfaces, i.e. to surfaces where the roughness elements do not protrude beyond the laminar sub-layer (see e.g. Hahn et al., 1985; Oron and Gutfinger, 1986; Fan and Ahmadi, 1993). A notable exception, however, is the work of Fernandez de la Mora and Friedlander (1982), and Schack et al. (1985) who developed a general correlation for particle deposition onto ‘completely’ rough surfaces, i.e. to surfaces having a roughness length $l^+ > 70$ (Schlichting, 1968) where, as throughout the manuscript, the superscript + is used to denote quantities which have been rendered non-dimensional using the friction velocity, $u_\text{\kappa}$, and the kinematic viscosity, $\nu$. Although, the ability of this correlation to describe the available experimental data over nine orders of magnitude of deposition velocity and covering three orders of magnitude in particle size, is impressive, the correlation contains two empirical factors which depend on the structure of the roughness layer and which can only be determined experimentally.

In this paper, a new, non-empirical, approach to predicting particle deposition onto rough surfaces is presented. The new approach is based upon the Lagrangian stochastic (LS) models of Reynolds (1999a,b) for the deposition of ‘heavy’ and ‘Brownian’ particles onto hydraulically smooth surfaces. The first model is applicable to the prediction of particle deposition in the inertia-moderrated and diffusion-impaction regimes. In these regimes, the deposition process is dominated by the effects of particle inertia and gradient diffusion and so the effects of Brownian motion can be neglected. The second model is applicable...
to the diffusion-deposition regime, where Brownian motion dominates the deposition process. It will be shown that these models are readily extendable to the prediction of particle deposition onto rough surfaces. The new modelling ingredients are the inclusion of a mass ‘sink’ volumetrically distributed within the flow field and the off-setting of the fluid velocity profile to account for the shift in the origin due to the presence of the roughness elements. The applicability of the models is thereby extended to include, for example, the deposition of spores and pollens onto grass and the capture of smaller particles by the micro-roughness elements on leaves and other natural surfaces. This ability will be demonstrated through detailed comparisons with existing data from wind-tunnel and laboratory-scale experiments (Chamberlain, 1967; Wells and Chamberlain, 1967). In contrast with Eulerian approaches to particle deposition (see e.g. Legg and Price, 1980; Slinn, 1982; Ferrandino and Aylor, 1985), the Lagrangian approach does not require the ad hoc specification of turbulent diffusivity and remains valid even when the length scale of the scalar field is much less than that of the turbulence. This occurs in the near-field of localized sources, in strongly inhomogeneous turbulence and in convective boundary layers. The Lagrangian approach has therefore the potential to find application in a diverse range of situations including the prediction of the dispersion and subsequent deposition, over complex terrain, of pollens from genetically modified crops and droplets from agricultural sprays, the prediction of acid deposition and predicting environmental aspects of safety in the nuclear and chemical industries.

2. Description of the LS model for heavy-particle deposition

The basis of the model is to regard the trajectories of ‘heavy’-particles in turbulent air flows as being like that of fluid-particles in a virtual fluid which has heavy-particle velocity statistics. That this, heavy-particle velocity statistics are regarded as being, in some sense, perturbed fluid velocity statistics. Details of this approach to modelling the dispersion and deposition of heavy-particles are given in Reynolds (1999a) and are described only briefly here.

The heavy-particle velocity statistics, required here as model inputs, can be deduced from the fluid velocity statistics and the equation of motion for a particle. The general equation of motion of a small, rigid particle in a turbulent flow contains many terms which can be justifiably neglected in most incompressible air–particle systems when the particle density is much greater than the air density (Maxey and Riley, 1983). These neglected terms include the pressure gradient force, virtual mass, Basset history integral and Faxen’s modification to Stokes’ drag force. For heavy-particles, Brownian motion can also be ignored. The equations of motion of the particle in a turbulent flow then reduce to a balance of Stokes’ drag force, particle inertia and any body forces which may be present

$$\frac{du_p}{dt} = \frac{u_I - u_p}{\tau_p} + a_B$$

where $u_p$ is the particle velocity, $u_I$ is the local fluid velocity, $a_B$ is the acceleration due to body forces and $\tau_p$ is the particle aerodynamic response time, which according to Stokes’ drag law is given by

$$\tau_p = \left(\frac{\rho_p}{\rho_f}d_p^6\right)/18v$$

where $\rho_p$ is the particle density, $\rho_f$ is the fluid density, $d_p$ is the particle diameter and $v$ is the kinematic viscosity. The dominant body forces acting on a heavy-particle are lifted due to mean shear (Saffman lift) and turbophoresis which is a convective drift down gradients of velocity variance and gravity. These are described by

$$F_L = 1.62 \sqrt{v \frac{du}{dy} (v_p - v_I)}, \quad F_T = -\frac{\pi}{6} \rho_p d_p^3 \frac{\partial \sigma_p^2}{\partial y},$$

$$F_G = \frac{\pi}{6} \rho_p d_p^3 g$$

where $du/\partial y$ is the gradient in the local mean streamwise air velocity, $v_p$ and $v_I$ are the components of fluid velocity and particle velocity in the direction normal to the streamwise direction, respectively, $\sigma_p^2$ is the root-mean-square (rms) value of $v_p$ and $g$=9.81 m s$^{-2}$ is the acceleration due to gravity. Other forces such as lift caused by free rotation can be shown to be at least an order of magnitude less than the shear lift and so they can be ignored (Kallio and Reeks, 1989).

Provided that the fractional changes in $\Delta \sigma_p/\sigma_p$ during time increments of size, $\tau_p$, are much less than unity, Eq. (1) implies that the mean value of normal particle velocities $\overline{v_p} = \tau_p a_B$, and that the rms normal particle velocities are related to the rms normal fluid velocities by $\sigma_p^2 = \sigma_f^2/(1 + \tau_p/T'_f)$, where $T'_f$ is the
timescale associated with fluid velocity fluctuations along a particle trajectory. This timescale is shorter than the Lagrangian timescale, \( T_L \), for fluid-particles along a fluid-particle trajectory. This is simply because of the effects of particle-inertia and gravity which cause the trajectory of a heavy-particle to deviate from that of the fluid-particle containing it at any instant, with the consequence that fluid-velocity correlations along a heavy-particle trajectory decay more rapidly than those along a fluid-particle trajectory (Csanady, 1963). Here, following Sawford and Guest (1991), this ‘crossing-trajectories effect’ is parameterized by

\[
T_L' = T_L (1 + (\beta \pi_p / \sigma_r)^2)^{-(1/2)},
\]

where \( \beta \) is an empirical constant of \( \mathcal{O}(1) \) relating Lagrangian and Eulerian turbulence scales. Sawford and Guest (1991) determined the value of \( \beta \) by optimizing the agreement between the predicted and measured dispersion of tracers in decaying grid turbulence. They estimated that \( \beta = 1.5 \), which is the value adopted here. Other values of \( \beta \sim \mathcal{O}(1) \) were not found to lead to significantly different predictions for particle deposition. The Lagrangian timescale \( T_L = 2 \sigma_p^2 / C_0 \varepsilon \), where \( \varepsilon \) is the mean rate of dissipation of turbulent kinetic energy divided by fluid density and \( C_0 \) is the Lagrangian velocity structure function constant. Here we take \( C = 5 \) (Reynolds, 1998a).

It is not necessary to consider third- and higher-moments of the heavy-particle velocity statistics, as these are of secondary importance in determining the trajectories of heavy-particles in turbulent shear-layers. More important are the effects of the strong gradients in Reynolds-stress (Reynolds, 1999a). Consequently it is sufficient to regard the heavy-particle velocities as being Gaussian. Furthermore, because root-mean square turbulent velocity fluctuations in the streamwise direction are typically small compared to the mean streamwise velocity, it is sufficient to consider only turbulent particle motions in the direction normal to the surface.

The one-dimensional LS model which satisfies the well-mixed condition (Thomson, 1987) for Gaussian heavy-particle velocity statistics is given by

\[
\frac{dx_p}{dt} = u_p, \quad dy_p = v_p \, dt, \quad \frac{du_p}{dt} = \frac{u_t - u_p}{\tau_p}, \quad dv_p = a_p \, dt + \sigma_p \frac{2}{T_L^p} \, d\xi
\]

where \( T_L^p = T_L' + \tau_p \) is the timescale characterizing particle velocities along the particle trajectory, \( d\xi \) are increments of an independent Wiener process with mean of zero and variance of \( dt \), and where

\[
a_p = \frac{v_p - \bar{v}_p}{T_L^p} + v_p \frac{d\bar{v}_p}{dy} + \frac{1}{2} \left[ 1 + \frac{v_p(v_p + \bar{v}_p)}{\sigma_p^2} \right] \frac{d\sigma_p^2}{dy}
\]

(Reynolds, 1999a).

The generalization of Eqs. (3) and (4) to two and three dimensions gives rise to the so-called ‘non-uniqueness problem’, familiar in the context of LS models for tracer-particles. This non-uniqueness is non-trivial because different LS models produce different predictions for mean particle concentrations (Sawford and Guest, 1988). Criteria in addition to the well-mixed condition which can resolve this non-uniqueness have yet to be established (Reynolds, 1998b,c; Sawford, 1999).

Particle trajectories were simulated by numerical integration of Eqs. (3) and (4). Following Thomson (1987) the size of the time-step, used in this integration, is taken to be

\[
dt = \text{min} \left( 0.01 T_L^p, \frac{0.1 \sigma_p}{|a_p|}, \frac{0.01 \sigma_p}{|v_p \partial \sigma_p / \partial y|}, \frac{0.01 T_L^p}{|v_p \partial T_L^p / \partial y|} \right)
\]

(5)

which ensures that the simulated trajectories resolve any inhomogeneities in \( \sigma_p \) and \( T_L^p \). In the numerical simulations, particles were perfectly reflected when they reached the top of the boundary-layer. This does not result in any violation of the well-mixed condition when the particle velocity statistics are taken to be Gaussian (Wilson and Flesch, 1993) and is equivalent to the imposition of a no-net-flux boundary-condition.

3. Lagrangian stochastic model for Brownian particle deposition

In this model the effects of particle inertia in determining the dispersion and deposition of sub-micron sized particles are assumed to be negligible compared to the combined effects of turbu-
lent dispersion and Brownian motion. The basis of the model is to partition turbulent and Brownian motions. This is justifiable because the timescales governing Brownian motion are much smaller than the smallest timescale, the Lagrangian dissipation timescale, \( t_d \), associated with turbulent motions. Details of this model can be found in Reynolds (1999b).

The model, which satisfies the well-mixed condition for the joint turbulent–Brownian process, is given by

\[
\frac{dx_p}{dt} = u_f, \quad dy_p = v_p \, dt + \sqrt{2D} \, d\xi,
\]

\[
dv_p = -\frac{v_p dt}{T_L} + \frac{1}{2} \left( 1 + \frac{v_p^2}{\sigma_p^2} \right) \frac{d\sigma_p^2}{dy} \frac{d\xi}{\sigma_p},
\]

\[
+ D \left[ \left( \frac{d\sigma_v}{dy_v} \right)^2 \left( 2v_p - \frac{v_p^3}{\sigma_p^2} \right) \right] + \left( \frac{d^2\sigma_v}{dy_v^2} \right) v_p + \sigma_v \frac{2}{T_L} d\xi',
\]

where \( d\xi \) and \( d\xi' \) are components of independent Wiener processes with means of zero and variances of \( dt \), \( D = kT_p/m_p \) is the Brownian diffusion constant, \( k \) is the Boltzmann constant, \( T \) is absolute temperature and \( m_p \) is the particle mass. Turbulent and Brownian particle motions in the streamwise direction are taken to be negligible compared to advection by the mean air flow. The Lagrangian timescale is taken to be \( T_L = 2\sigma_v^2/C_0'\epsilon \), where the difference between \( C_0' \) and \( C_0 \) accounts for Reynolds number effects, which are of importance in determining the trajectories of Brownian particles close to surfaces. The two constants, \( C_0' \) and \( C_0 \), are related by \( C_0' = C_0/(1 + Re_\epsilon^{-1/2}) \) where \( Re_\epsilon \) is the Lagrangian Reynolds number (Sawford, 1991). The Lagrangian Reynolds number \( Re_\epsilon = (T_L/T_d)^2 \), where \( T_d = C_0/2\sigma_0 \), \( T_d \) is the Eulerian dissipative timescale, \( \sigma_0 = 0.13 Re_\kappa^{0.64} \) is a constant related to the rms of fluid-particle accelerations and \( Re_\kappa \) is the Reynolds number based on the Taylor micro-scale. Here, because different fluid-particle trajectories contribute to the trajectory of a Brownian particle, \( C_0 \) is not the Lagrangian velocity structure function constant. The value of \( C_0 \), the only adjustable model parameter, was determined by optimizing model agreement with the experiment deposition data of Wells and Chamberlain (1967). This gave \( C_0 = 5 \).

The trajectories of micron and sub-micron sized particles were simulated by numerical integration of Eq. (6) using a time-step analogous to that given in Eq. (5) for heavy-particles. By following the approach adopted in Section 2, the model could be readily extended to include the effects of gravity but this is not necessary here since model predictions will later be compared with experimental data for deposition from vertical pipe flow. Gravity is known (see e.g. Young and Leeming, 1997) to have a negligible effect upon deposition from the vertical flows. The generalization of the model to two and three dimensions of problematic because of the non-uniqueness problem.

4. Mass sink and velocity off-set

The predominant effect of surface roughness is to shift the virtual origin of the velocity profile by a distance, \( e = 0.55l \), away from the surface, where \( l \) is the length of the protrusions (Wood, 1981). Now, because much of the area available for particle deposition is at the protrusions themselves rather than the bottom surface of the boundary-layer and because the turbulent motion of particles is more intense around the protrusions than at the bottom surface, a large fraction of particle deposition is expected to occur at the effective roughness height. In the modelling approach, it is therefore assumed that particles are captured when they reach the level of the effective roughness height \( b = l - e = 0.45l \) above the origin, \( e \), of the velocity profile.

The capture efficiency is taken to be unity and once captured particles are assumed not to rebound or to subsequently become detached. This is appropriate to situations where the deposition surface has been made ‘sticky’, as is the case in some of the wind-tunnel studies of deposition by Chamberlain (1967), against which models will be validated. It is also applicable to the micron and sub-micron sized particles which on making contact with a surface are likely to be deposited and remain deposited.

Extending the model to surfaces having capture efficiencies less than unity is problematic because rebound is determined, in part, by the streamwise velocity variance of the air flow and incorporating this quantity into LS models leads the non-uniqueness problem. This difficulty could be circumvented by
simply ignoring any contributions to rebound from streamwise velocity fluctuations and retaining a one-dimensional LS model but without a rigorous means for determining capture efficiencies and bounce back velocities the resulting model will be ad hoc in character.

5. Prediction of deposition velocities

In the simulations, as in the experiments of Wells and Chamberlain (1967), and Chamberlain (1967), the velocity of deposition, $V_{dep}$, is taken to be the ratio of the flux of particles to the mass sink, $j$, divided by the mean concentration of particles, $\langle c \rangle$. The prescription for the calculation of this flux from the particle trajectories simulated by the LS models is described below and illustrated schematically in Fig. 1.

The one-dimensional form of the particle deposition flux through an incremental length $\Delta X$ is given by $j=(dN/dt)/\Delta X$ where $N=\langle c \rangle \Delta X H$ is the number of particles within a ‘volume’ $\Delta X H$ of a boundary-layer of height $H$. Therefore, $dN/dt=-V_{dep}N/H$ which upon integration yields $N(t)=N(0) \exp(-V_{dep}t/H)$. This expression could be used to calculate deposition velocities once the numbers of airborne particles, $N(0)$ and $N(t)$, within the sample volume at times 0 and $t$ have been predicted from the trajectories of particles simulated using the LS models described in Sections 2 and 3. However, it is more natural to calculate deposition velocities from the number of airborne particles, $N_{in}$ and $N_{out}$, flowing into and out of the sample volume. This is readily achieved by expressing time $t$ in terms of the average streamwise velocity across the boundary-layer, $U$, and the length $X$. Substituting $X/U$ for $t$ into the expression for $N(t)$ and rearranging gives $V_{dep}=HU/X \ln(N_{in}/N_{out})$, which is the expression used here to calculate the deposition velocity, $V_{dep}$. It is identical to that utilized by Swailes and Reeks (1994) in their numerical simulations of particle deposition from turbulent duct flows and is directly analogous to $V_{dep}=RU/2X \ln(N_{in}/N_{out})$ which has been much used in the prediction of particle deposition in pipes of radius $R$ (Kallio and Reeks, 1989; Uijttewaal and Oliemans, 1996).

Strictly, the deposition velocity, $V_{dep}$, is only applicable to an equilibrium particle concentration. Although a true equilibrium in particle concentration does not occur in this problem because the total number of particles is continually being depleted along the boundary layer, a quasi-equilibrium is achieved when the normalized concentrations, $c(y)/\langle c \rangle$, no longer varies in the streamwise direction. Such a quasi-equilibrium corresponds to a unique deposition velocity. The development of this quasi-equilibrium was assured in the simulations by monitoring the
particle concentration profile and deposition as a function of streamwise location until steady values were attained. That is, the equilibrium deposition rate was determined from the deposition velocities calculated for 20 segments of length \( X^+ = 500 \) of a sample volume of the boundary-layer located between \( X^+ = 10,000 \) and \( X^+ = 20,000 \) downwind of the source. To promote the establishment of the quasi-equilibrium concentration particles were released from 20 equispaced positions between the deposition surface and the top of the boundary-layer. It was further promoted by releasing particles with velocities drawn from the local equilibrium Gaussian velocity distributions. It is assumed that the introduction of particles into the boundary-layer does not affect the statistical properties of the airflow required here as model inputs.

6. Comparisons of predicted and measured deposition velocities

6.1. Wind tunnel experiments of Chamberlain (1967)

Chamberlain (1967) measured the deposition velocities of spores and smaller particles in a wind-tunnel neutral boundary-layer to a variety of surfaces which were, depending on the value of \( u_* \), either ‘completely’ rough or in the transition regime between being hydraulically smooth and completely rough. The geometry of Chamberlain’s experiment is similar to that shown in Fig. 1. The particles were tagged with a radioactive marker and the numbers of particles deposited was measured from the radioactivity on the deposition surfaces. The radioactivity of the particles in the airstream was determined from the average radioactivity of particles caught in a sampler. The deposition surfaces included Italian rye grass grown to a height of 60 mm, artificial grass made of strips of PVC of length 80 mm and treated with a sticky solution, and rough glass with pyramidal roughness elements about 3 mm high, made sticky with stopcock grease. The corresponding values of roughness length \( z_0 \) are 10, 0.65 and 0.2 mm.

The ‘sticky’ surfaces are of particular interest because the number of particles striking these surfaces, a quantity which can be predicted directly by the LS models, can be equated with the number of particles being deposited.

In the experiments of Chamberlain, the source effectively extended across the boundary-layer, which here is taken to be homogeneous in the cross-wind direction. It is, therefore, appropriate in the numerical simulations of these experiments to neglect particle motions in the cross-wind direction and use a one-dimensional LS model for particle motions in the vertical direction along with the one-dimensional calculation of deposition velocities described in Section 5. The LS models require the mean streamwise velocity, \( u_t \), and root-mean-square fluctuating velocity, \( \sigma_v \) and the mean dissipation rate of turbulent kinetic energy as model inputs. The boundary-layer had a logarithmic mean velocity profile. Therefore,

\[
u_t = \frac{u_*}{\kappa} \ln \left( \frac{z_0}{y} \right), \quad \varepsilon = \frac{u_*^3}{\kappa y} \quad (7)
\]

where \( z_0 \) is the roughness length and \( \kappa = 0.4 \) is von Kármán constant. Chamberlain (1967) did not report upon profiles of rms normal velocities. However, for the larger particles considered by Chamberlain (1967), the Lycopodium spores and ragweed pollen, which have mean diameters of 32 and 19 \( \mu \)m and density \( \rho = 1175 \) kg m\(^{-3} \), gradient-diffusion plays little or no part in determining deposition as these particles, by acquiring sufficient momentum from the large turbulent eddies in the turbulent core of the flow, reach the deposition surfaces directly. That is, for all the values of \( u_* \) appropriate to the experiments of Chamberlain (1967), the Lycopodium spores and ragweed pollen have non-dimensional relaxation timescales \( \tau_p^+ > 20 \), which corresponds to the ‘inertia-modulated regime’ of particle deposition. Consequently for these particles it is appropriate to treat the rms normal fluid velocity as a constant throughout the boundary-layer. Following Pasquill (1974), this constant is taken to be \( \sigma_z = 1.3 u_* \).

It should be noted, however, that even when \( \sigma_z \) is constant, there is a weak turbophoretic force because of the dependency of \( \sigma_p \) on \( \tau_p^+ \)(\( \gamma_p \)).

Comparisons of measured and predicted deposition velocities of Lycopodium spores and ragweed pollen for the artificial sticky grass and the sticky rough glass are shown in Figs. 2–4. Predictions were obtained using the LS model for heavy-particle dispersion and deposition. The model is seen to predict well the dependencies of deposition velocities on friction...
Fig. 2. Comparison of predicted (○) and measured (●, Chamberlain, 1967) deposition velocities, $V_{dep}$, as a function of friction velocity, $u_*$, for Lycopodium spores from a wind-tunnel neutral boundary-layer to sticky artificial grass.

Fig. 3. Comparison of predicted (○) and measured (●, Chamberlain, 1967) deposition velocities, $V_{dep}$, as a function of friction velocity, $u_*$, for ragweed pollen from a wind-tunnel neutral boundary-layer to sticky artificial grass.
velocity, $u_a$, the length of the protrusions, $l$, and particle size, $d_p$.

The good agreement between the model and experimental measurements of deposition is already understood. The wind spread at the height of the tips of the artificial grass is equal to approximately $2u_a$ and if $u_a$ is say 0.5 m s$^{-1}$ then the stopping distance of Lycopodium spores travelling at this speed is 3 mm which is comparable with the width, 5 mm, of the artificial grass. The efficiency of collection of the tips of the grass will therefore be quite high at high wind speeds. At low wind speeds the efficiency will be small, but the corresponding reduction in deposition by impaction is masked because sedimentation then becomes relatively more important. The same remarks also apply to deposition onto rough glass because in this case the roughness length (3 mm) is less than the stopping distance of the Lycopodium spores when $u_a \geq 0.2$ m s$^{-1}$.

Slinn (1982) obtained comparable agreement with the deposition data of Chamberlain (1967) using an Eulerian approach with a turbulent-eddy diffusivity closure; an approach which was later refined by Ferrandino and Aylor (1984). However, as noted earlier, such closures are essentially ad hoc in character and their validity is severely restricted. A further difficulty is that, unlike in the Lagrangian approach where deposition velocities are calculated directly, in Eulerian approaches deposition velocities are inferred indirectly from predicted particle fluxes.

Chamberlain’s (1967) experimental data for deposition to real grass shown in Fig. 5 are in marked contrast with those for artificial grass, with the values of $V_{dep}$ being about quarter as large at the higher wind speeds. This difference indicates the importance of the stickiness of the deposition surface in the capture of large particles like Lycopodium spores. Chamberlain (1967) suggested that the role of stickiness is two-fold. Namely, particles striking a sticky surface are more likely to be captured and are less likely to rebound, and once on a sticky surface they are less likely to be blown off again. Indeed, by observing that deposited particles on the real grass or artificial grass were not removed by subsequent exposure in the wind-tunnel at high wind speeds, Chamberlain (1967) demonstrated that rebound and not blow-off was the important effect with Lycopodium spores and ragweed pollen. The ineffectiveness of wind alone in re-suspending particles is most certainly a consequence of particles being imbedded within the viscous sub-layer of the bound-
ary layer of the air flow. Given capture efficiencies less than unity and the importance of rebound in determining the transport of *Lycopodium* spores, it is therefore not surprising that the model is seen in Fig. 5 to over-predict deposition to real grass.

The deposition velocities of the smaller particles (particles of polystyrene with mean diameter 5 µm, droplets of tricresylphosphate with mean diameters of 2 and 1 µm, and Aitken nuclei with mean diameter 0.08 µm) onto artificial grass were under-predicted by two or more orders of magnitude, with Brownian motions predicted to make an insignificant contribution to particle deposition. For these particles, unlike for the spores, gradient-diffusion (turbophoresis) is an important transport mechanism. Indeed, it dominates particle transport in the ‘diffusion’ and ‘diffusion-impaction’ regimes (Young and Leeming, 1997). Gradient diffusion is unlikely to be well described with the adopted parameterization of normal rms fluid velocities. Unfortunately without experimental data, it is difficult to improve upon this parameterization. In the next section, it will be shown that when normal rms fluid velocities are known, the deposition velocities of micron and sub-micron size particles can be accurately predicted.

### 6.2. Experiments of Wells and Chamberlain (1967)

Wells and Chamberlain (1967) measured the deposition velocities of Aitken nuclei, droplets of tricresylphosphate and particles of polystyrene onto a cylindrical rod placed axially within a vertical fully-developed turbulent pipe flow. For the experiments of Wells and Chamberlain (1967), the non-dimensional aerodynamic response times of these particles lie predominantly within the ‘diffusion-deposition’ regime and so Brownian motions dominated the deposition process. Both the cylinder and the pipe were earthed to avoid electrostatic effects. Wells and Chamberlain (1967) considered two deposition surfaces: brass which was hydraulically smooth and filter paper which had fibres of mean length 100 µm (l^+<10) and was, depending on the value of \(u_s\), either hydraulically smooth or close to being hydraulically smooth.

The particles were tagged with a radioactive marker. The radioactivity of the particles in the airstream was determined from the average radioactivity of particles caught in samplers fitted at either end of the pipe. The numbers of particles deposited was measured from the radioactivity on the deposition surface.
Deposition velocities are principally determined by the characteristics of the near-wall turbulent boundary, which are largely insensitive to geometric detail provided of course that there are no recirculation zones and stream-line curvature is negligible. This has been strikingly illustrated by Young and Leeming (1997) who showed that measurements of deposition velocities from a diverse range of experiments collapse onto a narrow band of values when quantities are appropriately non-dimensionalized using the friction velocity and the kinematic viscosity. It is therefore legitimate to compare the experimental data of Wells and Chamberlain (1967) with predictions obtained from LS models for particle deposition from fully developed turbulent pipe flow onto the pipe itself. This is advantageous because unlike for the flow utilized by Wells and Chamberlain (1967), the flow characteristics of fully-developed turbulent pipe flow are accurately known. Moreover, the axial symmetry of the pipe facilities of the use of one-dimensional LS model along with the one-dimensional treatment of deposition are described in Section 5.

Model predictions were obtained using the LS model for Brownian particles, assuming that the deposition surfaces were located at 0 μm and 0.45 μm × 100 μm. This LS model is strictly applicable only for non-dimensional aerodynamic response times, 0.1 < τp*, because then deposition is dominated by Brownian diffusion within a very thin layer directly adjacent to the deposition surface. For larger values of τp*, the effects of particle inertia, which are not accounted for in the model, become important in determining particle deposition. The fluid velocity statistics required for these simulations are taken from Reynolds (1999b) and references therein using cubic spline interpolation, ensures that the velocity gradient is continuous throughout the boundary-layer. The forms for the velocity variance and mean dissipation rate fits to experimental data and data from direct numerical simulations.

Fig. 6 shows a comparison of predicted and measured deposition velocities as functions of the particle

\[ y^+ \leq 5 \]
\[ 5 < y^+ < 30 \]
\[ y^+ \geq 30 \]

The form of the mean velocity in the buffer zone (5 < y^+ < 30), obtained by Kallio and Reeks (1989)
were, however, over predicted. It was suggested that
ments. Deposition velocities of spores onto real grass
and other natural surfaces with micro-roughness ele-
deposition of sub-micron sized particles onto leaves
success of the model for Brownian-particle deposi-
tional tool of practical use which is applicable
The approach offers a simple, fast and reliable com-
have been extended to account for surface roughness.
spores to artificial sticky grass and sticky rough glass
favourably with the measured deposition velocities of
completely rough. Model predictions compared very
putational tool of practical use which is applicable
In contrast with other modelling approaches for
modelling approaches for rough surfaces (e.g. Wood, 1980; Fan and Ahmadi, 1993) but in agreement with the experimental data of Wells and Chamberlain (1967), predicted deposition velocities are seen not to become almost independent of particle aerodynamic response times in the ‘diffusion-deposition’ regime, at least for the roughness under consideration.

7. Conclusions

Lagrangian stochastic models for the dispersion and deposition of ‘heavy’ and ‘Brownian’ particles have been extended to account for surface roughness. The approach offers a simple, fast and reliable computational tool of practical use which is applicable to surfaces, ranging from hydraulically smooth to completely rough. Model predictions compared very favourably with the measured deposition velocities of spores to artificial sticky grass and sticky rough glass and with the deposition of micron and sub-micron sized particles to hydraulically smooth surfaces. The success of the model for Brownian-particle deposition suggests that the model can predict correctly the deposition of sub-micron sized particles onto leaves and other natural surfaces with micro-roughness elements. Deposition velocities of spores onto real grass were, however, over predicted. It was suggested that this was because the capture efficiency of real grass is significantly different from unity, which results in significant differences between the numbers of particles which strike the grass, which in the model are assumed to deposit, and the numbers of particles which actually deposit. Extending the model to surfaces having capture efficiencies less than unity is problematic because rebound is determined in part by the streamwise velocity variance of the air flow and incorporating this quantity into LS models leads to a non-uniqueness problem. This difficulty could be circumvented by simply ignoring any contributions to rebound from streamwise velocity fluctuations and retaining a one-dimensional LS model but without a rigorous means for determining capture efficiencies and bounce back velocities the resulting model will be ad hoc in character.

References


