SIMULATED GROUND DEPOSITION OF FINE AIRBORNE PARTICLES IN AN ARRAY OF IDEALIZED TREE CROWNS

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Abstract. Wind-tunnel experiments were used to investigate the ground deposition of fine airborne particles in an array of idealized tree crowns. The particle ground deposition was modelled with a gaseous tracer instead of solid particles, which is an approach for very fine particles. A chemical method based on the reaction of ammonia and manganese chloride was used to quantify the mass transfer from the simulated atmospheric boundary-layer flow to the surface. Using a tracer gas instead of solid particles can be considered only if turbulent diffusion is the decisive deposition mechanism and effects of sedimentation, impaction, interception or molecular diffusion can be approximately ignored. These constraints are necessary due to scaling problems concerning particle modelling in the small-scale experiment. The intention was to determine the obstacle arrangement density in which the mean ground deposition is maximized for a defined crown form. A deposition amplification factor $\alpha$ was defined as the quotient of deposition efficiencies for an area with tree crowns and an open ground with identical similarity parameters. Based on this calculation an increase of the ground deposition by up to 60% should be realistic through a favourable arrangement of tree crowns and tree number density. An increase in turbulence intensity in the flow leads to a significant amplification of the mean ground deposition.

Keywords: Wind-tunnel modelling, Particle-laden flow, Ground deposition, Tree crown, Ammonia tracer gas.

1. Introduction

The emission of natural or anthropogenic particles into the atmospheric boundary layer often leads to irritation of the inhabitants of surrounding residential areas. Dust emissions from industrial areas and bulk piles can be reduced, for example, through barriers or sprinkler systems but are unavoidable in many situations. Landscape and town planners design specific vegetation areas with the intention of filtering airborne particles out of the atmospheric flow (see Figure 1).

Filtering of particles through dense vegetation is well investigated. Field or laboratory experiments of the dry deposition of particles and gases on homogeneous surfaces have been carried out quite extensively (see reviews of Sehmel, 1980; Hosker and Lindberg, 1982; Nicholson, 1988). The investigations have shown that deposition processes depend in a complex way on numerous parameters as, e.g., the particle density, the particle diameter, the roughness length and the shear velocity. The ground deposition of particles is relatively small within a dense vegetation. For less dense obstacle structures or vegetation arrays there is less information
available concerning ground deposition distributions. However, ground deposition can contribute in no small way to the particle removal.

Experiments with single trees have indicated that beside the filtering effect of the porous tree crown the geometrical shape of the tree hull has a remarkable influence on the ground deposition distribution of particles around the tree (Ruck and Schmitt, 1986; Ruck and Adams, 1991). It was supposed that the planting of less dense tree arrays or the breaking up of a dense vegetation could achieve an increase in overall deposition rate. The latter is believed to be due to the fact that the increase in ground deposition rate can significantly exceed the loss of porous filtering material due to a greater spacing of the trees. To contribute to this fluid mechanical problem, wind-tunnel experiments were performed in this study to determine an optimum particle ground deposition as a function of geometrical tree shape (hull) and tree spacing.

To quantify the mass transfer from the simulated atmospheric boundary-layer flow to the ground, a chemical method based on the ammonia – manganese chloride reaction was used (Kottek et al., 1977). Using a tracer gas instead of solid particles can be considered only if turbulent diffusion is the decisive deposition mechanism and effects of sedimentation, impaction, interception or molecular diffusion can be ignored approximately. Due to scaling difficulties concerning particle modelling these limitations are necessary in the small-scale experiment.

Molecular diffusion, turbulent diffusion, sedimentation, impaction and interception are mechanisms that influence the dispersion of particulate and gaseous pollutants on the ground and the vegetation. The uptake is often controlled by biological, plant physiological and configurational factors that vary with plant architecture. Consequently the pollutant uptake depends strongly on the properties of the deposited substance – gaseous, liquid, solid – on meteorological conditions, and on the surface structure as well as on the particle sizes involved. In the past the
flow properties and the mass exchange between the atmosphere and the biologically active canopy have been intensively investigated. Many of these investigations have been carried out in the field and have provided interesting local information on mean wind and turbulent characteristics, see, e.g., Reifsnyder (1955), Baynton et al. (1965), Smith and Carson (1972), Högström et al. (1989), Bergström and Högström (1989), and Amiro (1990). Deposition models have been based on different assumptions for the turbulent transport of the depositing material (see Raupach and Thom, 1981; Lewellen, 1985). Many of these models used detailed fluid mechanical equations simplified and adapted to the specific problem. Other approaches have described mass transfer at the air-surface interface with multibox resistance models in order to simplify the difficult transfer processes (see Calder, 1961). Over the years experimental evidence has shown that flux-gradient models, which have been used for decades to describe the turbulent transport in plant canopies, are difficult to apply to flow over less dense tree arrays due to the fact that the scale of the transporting turbulent mechanism described with these models is of the same order of magnitude as the gradients involved (see Finnigan, 1985).

The turbulent diffusion plays an important and often dominant role for gaseous deposition and particle deposition in the most relevant size range of particle diameter $d < 10 \times 10^{-6}$ m (see Chamberlain, 1967; Ruck and Schmitt, 1986). The strong correlation between pollutant deposition and turbulent diffusion gives qualitative information about the local deposition potential from flow field investigations. The importance of turbulent diffusion when compared with other deposition mechanisms can be seen if the size range of relevant pollutants is considered. Sulphate and nitrate particles, for example, have a maximum in their particle size distribution between 0.1 and $1.0 \times 10^{-6}$ m (Chamberlain, 1975). Fine water droplets such as fog, which are especially efficient absorbers of pollutants due to their long residence time as well as their surface-to-volume ratio, also fall in the same size range. Some measurements of pollutant deposition levels in dense forests were carried out (see, e.g., Belot, 1976; Garland and Branson, 1977; Lorenz and Murphy, 1985), but these studies usually only give single values and the investigators have not systematically studied the flow field and the pattern of deposition in tree arrays.

In summary, it can be seen that detailed investigations are lacking on the interactions between the atmospheric boundary layer and tree array structure. In fact, the paucity of fluid mechanical knowledge in this field, together with partially unvalidated approaches in the deposition models for complex vegetative surfaces, prevent a prediction of deposition levels around single trees and tree populations. The intention of this study is to provide fluid mechanical background information about basic flow around such structures and, thus, to contribute to a better understanding of flow-induced ground deposition. The conclusions given in this paper were deduced from wind-tunnel studies keeping in mind, however, that a gaseous tracer is used to simulate the flow behaviour of fine particles, which cannot account for all factors involved.
As far as we know, our experiments are the first systematic investigations of this type carried out in a wind tunnel. There are some wind-tunnel experiments on scaled particle behaviour, but made for other purposes than in this study. Braaten (1994) examined the reentrainment-deposition characteristics of large particles from a sparse bed. Goosens (1996) carried out experiments of aeolian dust deposition on topographic scale models of ranges of hills. Hall et al. (1998) made measurements of the deposition of large particles from a small scale model of a chemical warehouse fire plume. Particles were injected into a gas feed line of a source to model the dispersion of buoyant and non-buoyant gas plumes loaded with particles. The deposition of the particles on the ground were monitored by collecting them on sticky microscope slides laid out downstream along the plume centerline. A review of wind-tunnel studies on aeolian processes is given in Pye and Tsoar (1990). There are also full-scale wind-tunnel experiments regarding to particle-laden flows. Visser (1992), for example, made experiments of the dust emissions from a continuous dumping of coal.

2. Similarity Analysis

Certain similarity requirements must be fulfilled in order to transfer results from small-scale wind-tunnel experiments to prototype scale. These similarity laws are usually obtained by dimensional analysis, a method which makes use of the fact that physical equations must be dimensionally homogeneous and hence the parameters occurring therein can only appear in certain combinations (Donat and Schatzmann, 1997).

The geometric lengths related to the axially symmetric trees are the crown height \( z_b \) and the maximum crown diameter \( d_b \). Additionally, the parameter \( \lambda_i \) describes the shape of the crown. The trees in this study are non-porous and have no trunks. \( \Delta x_b \) and \( \Delta y_b \) are the distances between vertical tree axes in longitudinal and lateral directions.

The turbulent, neutrally-stratified atmospheric flow is characterized by a profile power law exponent \( n \), the boundary-layer height \( \delta \), the wind velocity \( U_\delta \) at the height \( \delta \), the density \( \rho_a \) and the viscosity \( \mu_a \) (see Figure 2). Instead of the power law exponent \( n \), the effective roughness length \( z_0 \) can also be used as an independent parameter (see Section 3). The fine airborne particle is characterized by the aerodynamical particle diameter \( d_p \) and the density of the particle \( \rho_p \); \( g \) is the gravitational acceleration.

The deposition efficiency \( D \) defines the probability that a fine particle will be deposited in flat terrain between the tree crowns. With the coordinates in the downstream and lateral directions \( x, y \), respectively, \( D \) depends upon the following variables:

\[
D = f_1(x, y, z_b, d_b, \lambda_i, \Delta x_b, \Delta y_b, n, \delta, U_\delta, \rho_a, \mu_a, d_p, \rho_p, g).
\]  

(1)
Applying dimensional considerations, Equation (1) can be transformed into the following non-dimensionalized form

$$\mathbf{D} = f_2 \left( \frac{x}{d_b}, \frac{y}{d_b}, \frac{z_b}{d_b}, \lambda_i, \frac{\Delta x}{d_b}, \frac{\Delta y}{d_b}, \frac{\delta}{d_b}, \frac{g d_b}{U_\delta}, \frac{\mu_a}{U_\delta \rho_a d_b}, \frac{d_p}{d_b}, \frac{p_p}{\rho_a} \right).$$  \hfill (2)$$

By multiplication of the dimensionless parameters with one another and with constant factors, the definition of the velocity difference $\Delta U = U_a - U_p$, the particle velocity $U_p$ and the ambient velocity at the flying height of the particle $U_a$, which is in a defined relation to $U_a$ due to the power law exponent $n$, and the kinematic viscosity $v_a = \mu_a/\rho_a$, the following modified function can be obtained:

$$\mathbf{D} = f_3 \left( \frac{x}{d_b}, \frac{y}{d_b}, \frac{z_b}{d_b}, \lambda_i, \frac{\Delta x}{d_b}, \frac{\Delta y}{d_b}, \frac{U_\delta \delta}{v_a}, \frac{U_a^2}{gd_p}, \frac{\rho_a}{\rho_p}, \frac{U_\delta d_b}{v_a}, \frac{\Delta U d_p}{v_a}, \frac{2U_a d_p^2 \rho_p}{18 \rho_a \rho_a d_b} \right).$$  \hfill (3)$$

The deposition efficiency $D$ is a function of the dimensionless coordinates $x/d_b$ and $y/d_b$, tree aspect ratio $z_b/d_b$, the shape parameter $\lambda_i$, the dimensionless tree distances $\Delta x/d_b$ and $\Delta y/d_b$, and the power law exponent $n$. The following parameters in the bracket of Equation (3) can be interpreted as

- the boundary-layer Reynolds number $Re_\delta = (U_\delta \delta)/v_a$,
- the particle Froude number $Fr_p = (U_a^2/gd_p)(\rho_a/\rho_p)$,
- the obstacle Reynolds number $Re_b = (U_\delta d_b)/v_a$. 

Figure 2. Sketch of an array of the idealized conical tree crowns.
the particle Reynolds number \( \text{Re}_p = (\Delta U d_p) / v_a \),
and the Stokes number \( \text{Sto} = (2U_a d_p^2 \rho_p) / (18 v_a \rho_s a d_p) \).

Equation (3) indicates that the deposition efficiency \( D \) in both model and full scale takes on identical values if all the dimensionless parameters on the right hand side of this equation can be matched in the wind-tunnel experiments.

In practice, matching of the particle Froude number \( \text{Fr}_p \), the particle Reynolds number \( \text{Re}_p \) and the Stokes number \( \text{Sto} \) is difficult to realize in small-scale experiments because the particle diameter \( d_p \) must be chosen very small. Approximately the effect of these particle parameters can be neglected if it is assumed that the particle can follow exactly the streamlines of the flow. For this case it is allowed to use a tracer gas instead of real fine particles for the deposition experiment in the wind tunnel. If we are not allowed to neglect particle diameter, particle density and gravitational acceleration, \( \text{Fr}_p, \text{Re}_p \) and \( \text{Sto} \) are dimensionless parameters which have to be matched in the wind-tunnel experiments.

In summary the following simplified equation is obtained:

\[
D = f_\lambda \left( \frac{x}{d_b}, \frac{y}{d_b}, \frac{z_b}{d_b}, \lambda_i, \frac{\Delta x}{d_b}, \frac{\Delta y}{d_b}, n, \text{Re}_s, \text{Re}_b \right). \tag{4}
\]

The deposition efficiency \( D \) is a function of the dimensionless coordinates \( x/d_b \) and \( y/d_b \), the tree aspect ratio \( z_b/d_b \), the shape parameter \( \lambda_i \), the dimensionless tree distances \( \Delta x/d_b \) and \( \Delta y/d_b \), the power law exponent \( n \), the obstacle Reynolds number \( \text{Re}_s = (U \delta)/v_a \) and the boundary-layer Reynolds number \( \text{Re}_b = (U \delta)/v_a \).

In case there is homogeneous distribution of fine airborne particles in the cross flow before these particles reach the obstacle array, a mean deposition efficiency can be related to the deposition scenario. Due to experimental reasons in the following a deposition amplification factor \( \alpha \) is defined as the quotient between the deposition efficiencies of an area with tree crowns and an open ground under otherwise identical similarity parameters.

3. Boundary-Layer Modelling in the Wind-Tunnel Experiment

The deposition experiments were carried out in the boundary-layer wind tunnel of the Institute for Hydromechanics of the University of Karlsruhe. The tunnel has a closed flow circulation with an air volume of 420 m\(^3\) and works with a neutral density stratification. The flow establishment section and the test section together have a length of 8 m, a width of 1.5 m and a height of about 1 m. An adjustable ceiling is used to produce a zero-pressure-gradient boundary layer (Figure 3).

Velocity measurements, utilizing a two-component Laser Doppler Anemometer (LDA) system, were made to determine the features of three turbulent boundary layers and their turbulence characteristics. The LDA system includes an argon-ion laser and two double Bragg cells for frequency shifting. The LDA signals
Figure 3. Boundary-layer wind tunnel of the Institute for Hydromechanics of the University of Karlsruhe, Germany.

were detected in forward light scattering. The laser provides coherent light at the wavelengths $\lambda = 514.5 \times 10^{-9}$ m (green light) and $\lambda = 488 \times 10^{-9}$ m (blue light). For the measurements the flow in the wind tunnel was seeded with tracer particles, which had a median diameter of approximately $1.5 \times 10^{-6}$ m. Further details of the LDA measuring techniques are described, e.g., in Durst et al. (1976), Ruck (1987, 1990), Ruck and Adams (1991).

As in dispersion calculation programs, the vertical velocity profile of the wind-tunnel boundary layer is usually approximated by the power law $[U(z)/U(\delta)] = [(z - d_0)/(\delta - d_0)]^n$. Specific power law exponents $n$ can be achieved by use of specific combinations of vortex generators and artificial roughness elements (LEGO) distributed over the bottom of the flow establishment section (Figure 4). In the lower part of the boundary layer, the mean velocity profiles can be approximated by the logarithmic law $[U(z)/U_*] = [1/\kappa] \times \ln[(z - d_0)/z_0]$ with the friction velocity $U_*$, the von Kármán constant $\kappa$, the effective roughness length $z_0$ and the displacement thickness $d_0$. Since processes near the surface are viewed in this study, the logarithmic form is more convenient than the power law form. Therefore the power law exponent $n$ can be replaced by the dimensionless roughness length $z_0/z_b$. In the following both parameters are given in the results of the deposition experiments. If $d_0$ is an important parameter, then $d_0/z_b$ is another dimensionless parameter to consider in the investigation.
In the flow establishment section vertical profiles of velocity and turbulence parameters were measured at distances $x = 3.4$ m and $x = 4.8$ m from the vortex generators. Figure 5a shows the mean velocity profiles $U(z)/U(\delta)$ for all roughness structures. An approximation with the power law leads to a best-fit power law exponent. In detail, the boundary-layer parameters are given in Table I. These parameters are in good agreement with results from empirical relations obtained in experiments with obstacle configuration (Theurer, 1993) and with data obtained in the boundary-layer wind tunnel of the Meteorological Institute of Hamburg University using identical roughness element distributions (Donat and Schatzmann, 1997). Furthermore, vertical profiles of the longitudinal turbulence intensity $\sqrt{u'^2}/U(z)$ (Figure 5b) and the vertical turbulence intensity $\sqrt{w'^2}/U(z)$ (Figure 6a) are shown for the three boundary layers. The vertical momentum flux $\sqrt{-u'w'}/U_*$ is almost constant in the lower boundary layer (Figure 6b).

The results in Figures 5 and 6 show only small differences between the flow patterns measured at $x = 3.4$ m and $x = 4.8$ m for all three roughness types used in this investigation. It can be assumed that at the end of the flow establishment
Figure 5. Vertical profiles measured in the wind tunnel in the flow establishment section at \( x = 3.4 \) m and \( x = 4.8 \) m for three different turbulent boundary layers: (a) Mean wind velocity \( U(z)/U(\delta) \) fitted with the power law; (b) Turbulence intensity \( T_u \) for the \( u \)-component \( \sqrt{u'^2}/U(z) \).

section in \( x = 5 \) m the boundary layer is approximately in equilibrium before the flow reaches the test section. Important changes in the flow characteristics near the surface, which is basically formed through the ground roughness structure, are not expected if the flow establishment section were to be extended. The upper part of the wind-tunnel boundary layer is mainly formed through the vortex generators. Although here the boundary layer is also horizontally homogeneous, for ground deposition the lower boundary layer is more relevant in contrast, for example, to the dispersion of jets or plumes from elevated stacks.

It was the intention to model a limited tree population following the basic idea to design a special vegetation zone between an emission area and a residential area.
Figure 6. Vertical profiles measured in the wind tunnel in the flow establishment section at $x = 3.4$ m and $x = 4.8$ m for three different turbulent boundary layers: (a) Turbulence intensity $T_w$ for the $u$-component $\sqrt{\frac{w'^2}{U(z)}}$; (b) Vertical momentum flux $\sqrt{-u'w' / U_w}$.

Therefore, an equilibrium boundary layer was established that encounters the belt of trees. To model an infinite forest the flow establishment section must be mounted completely with tree crowns to reach an equilibrium boundary layer. But the conclusion cannot be drawn that the ground deposition is constant in flow direction as well, since airborne material is continuously removed from the atmospheric flow.

4. Modelling of the Vegetation Arrays

The shaping of a tree crown depends on numerous parameters as described by many authors (see e.g., Mitscherlich, 1970; Horn, 1971). Geographical location and to-
pographical conditions have a high tree growth. In connection with the location there are different climatic conditions such as temperature, precipitation, sunshine period, including their seasonal variations. The shape of the tree crown can change due to continuous wind forces, or distortions can occur as a result of preferred wind directions.

The condition of the ground and the availability of nutrients are important as well as changes in the growth rate with increasing age of the tree. Furthermore, the tree growth can show remarkable differences between isolated trees and trees in a dense tree population. For single trees the ratio between height growth and width growth is often smaller than for a tree in a stock of trees. In a forest the height of the trunk segment without branches is often higher due to a lack of light near the ground.

Since trees can form extremely diverse crown shapes, a detailed description would require numerous parameters to fulfil all the variations occurring in nature. A differentiation only in various tree species is often not sufficient, as the example of the pine trees indicates (Hecker, 1985). Horn (1971) provides a simple formulation to describe the geometry of tree crowns. It includes the tree parameter, the height, the ratio between height and width, and the convexity, which are comparatively easy to interpret. Zeide (1995) investigated the correlation between crown proportions and the forest stand’s density. To estimate the development of the crown, growth models were made for individual tree types (see, e.g., Cole and Lorimer, 1994; Hynynen, 1995; Biging and Gill, 1997).

In this study four types of idealized tree crowns were investigated, which are adapted from the geometry of typical crowns of natural trees. The following forms were selected: a cylinder, a cone, a sphere and a combination made up of a turned up truncated cone as the lower part and a spherical sector as the upper part. In order, these four crown shapes are similar to a birch tree, a conifer, a plane tree and a pine tree. The conditions for these forms, which cover a wide range of conceivable crown types, are given in Table II. The dimensions of the idealized tree crowns in the wind-tunnel experiments are shown in Figure 7. In the experiments the crown hulls were set up on the ground. Each obstacle arrangement was composed of uniform types. The ratio $\Delta x/\Delta y = 1$ and for each crown form, ground deposition patterns were determined for eight different densities of tree population.

The obstacle Reynolds number $Re_b$ describes the flow around the individual obstacle. In the wind-tunnel experiment a reduction of $Re_b$ in comparison to the full-scale conditions is inevitable. Especially for round obstacles the decrease of $Re_b$ leads to an amplification of the flow in the slipstream behind the obstacle. The crown forms in this study have no sharp edges where the flow can break off in contrast to rectangular solids. To counteract such Reynolds number effects, the obstacles can be covered with sand roughnesses or with stripes – as for small-scale cooling towers – to increase the roughness of the hulls artificially.

In this study the experiments were done without this possibility since the obstacles were arranged in a comparatively dense array and therefore no marked
TABLE II
Idealized tree crowns investigated in the wind-tunnel experiments with the crown height $z_b$, the maximum crown diameter $d_b$, the height of the spherical sector $h_1$, and the height $h_2$ and the ground diameter $d_{kes}$ of the turned up truncated cone.

<table>
<thead>
<tr>
<th>Form parameter</th>
<th>Form of the idealized tree crown</th>
<th>Additional conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_1$</td>
<td>Cylinder</td>
<td>$z_b = 2.0d_b$</td>
</tr>
<tr>
<td>$\lambda_2$</td>
<td>Cone</td>
<td>$z_b = 2.0d_b$</td>
</tr>
<tr>
<td>$\lambda_3$</td>
<td>Sphere</td>
<td>$-$</td>
</tr>
<tr>
<td>$\lambda_4$</td>
<td>Truncated cone/spherical sector</td>
<td>$z_b = 1.5d_b = 6h_1 = 1.2h_2 = 6d_{kes}$</td>
</tr>
</tbody>
</table>

Figure 7. The dimensions of the idealized tree crowns in the wind-tunnel experiments (length in m): (a) Cylinder, (b) Cone, (c) Sphere, (d) Combination made of a turned up truncated cone as the lower part and a spherical sector as the upper part.

flows around isolated obstacles occurred. For this reason non-porous tree crowns were used in the experiments, since here the effect of porosity has less influence than for the flow through thin fences or hedges. Anyway, in the small-scale experiment it is difficult to model the complex flow conditions within a tree crown correctly.

The volume of the four idealized tree crown types was each designed to about $1.44 \times 10^{-4} \text{ m}^3$ to obtain a comparable displacement of the flow for identical wind velocity profiles. In principle in the experiment one must take care that the cross-section in the wind-tunnel test section is not excessively blocked with obstacles to avoid effects through additional pressure gradients in the flow direction. For wind-
tunnel experiments in building aerodynamics a blockage of up to 5% is allowed (Plate, 1995). This limit was not exceeded in the investigations. Otherwise structural measures in the wind tunnel or arithmetical corrections of the flow data are required.

5. Experimental Set-Up for the Deposition Measurements

The ground deposition measuring array with the size of 0.60 m $\times$ 0.48 m was fixed at the end of the flow establishment section in $x = 5$ m. The array was covered with a special blotting paper, which was soaked with a manganese-chloride solution. The ammonia tracer gas injected into the flow was absorbed from the solution resulting in an immediate colour reaction on the paper. Using digital image processing, a grey value distribution of an array can be determined. Calibration experiments have shown that the intensity of the brown/grey colouring can be assumed to be proportional to the time of ammonia contamination and the flow 'activity' (turbulence) above the ground as long as saturation effects on the papers can be avoided.

As an example Figure 9 shows the mean grey values depending on the period of the ammonia contamination for experiments with the release times $t_f = 60$ s, $t_f = 120$ s and $t_f = 180$ s in flat terrain without obstacles. As expected, the grey
Figure 9. Calibration of the ammonia-manganese chloride-method in the wind-tunnel experiment. The brown colouring of an array is shown in mean grey values depending on the period of the ammonia contamination for experiments with the release times \( t_f = 60 \, s, t_f = 120 \, s \) and \( t_f = 180 \, s \). The parameters \( \text{Re}_\delta = 2.0 \times 10^5 \) and \( n = 0.21 \) were kept constant. In aqueous solution the concentration of manganese chloride was \( C_{\text{MnCl}_2} = 50 \, \text{kg m}^{-3} \) and of hydrogen peroxide \( \text{H}_2\text{O}_2 = 2.0 \, \text{Vol.\%} \). The density of the solution on the blotting paper was \( B = 0.295 \, \text{kg m}^{-2} \).

colouring increases with the time of contamination and depends clearly on the ammonia concentration in the wind-tunnel flow. In this case no saturation effects were detected up to the maximum measuring period of \( t_m = 360 \, s \). For experiments with obstacles there is the expectation that the deposition rate could be significantly higher in some sectors of the array in comparison to these calibration experiments. For this reason the release time and the contamination period were fixed to the reduced values \( t_f = 120 \, s \) and \( t_m = 120 \, s \) to avoid a critical level of contamination on the ground between the idealized tree crowns.

Figure 10 shows an isoline plot of the deposition amplification factor \( \alpha \) for a cylinder array \( (\lambda, \eta) \) with \( \Delta x/d_b = 3 \). The experiments were carried out in the boundary layer with the power-law exponent \( n = 0.32 \) and the Reynolds number \( \text{Re}_\delta = 2.0 \times 10^5 \). For evaluation of the data the whole obstacle array is separated into the three partial arrays 1, 2 and 3, which are arranged one behind the other in the flow direction.

From investigations of flows around isolated cylinders it is well known that a horseshoe vortex is formed at the base of the cylinder. In the first partial array
this typical horseshoe vortex can be seen around each cylinder. This is indicated through higher values of the amplification factor immediate near the cylinders with maximum values up to $\alpha = 4.0$ in comparison to lower $\alpha$ values in the middle between the obstacles. These patterns on the ground can also be found in the partial arrays 2 and 3 but there is a tendency that the shaping of the horseshoe vortices are less distinct in the downstream direction.

For all partial arrays the deposition area is integrated including the bases of the obstacles. In this special experiment we obtain mean values of $\alpha = 1.8$ for partial
array 1, $\alpha = 1.6$ for partial array 2 and $\alpha = 1.4$ for partial array 3. For the whole array configuration the mean deposition factor is $\alpha = 1.6$. If the bases of the cylinders are excluded from the calculation, the mean value for the complete array would increase to $\alpha = 1.9$ whereas for the partial arrays $\alpha = 2.1$ (array 1), $\alpha = 1.9$ (array 2) and $\alpha = 1.7$ (array 3) are indicated. The decrease of $\alpha$ with increasing length of the obstacle structure in the flow direction indicates the remarkable influence of the density of the idealized tree crown configuration on the ground deposition. In the following this effect is investigated in more detail.

6. Results of the Deposition Experiments

The experiments were structured into three parts in which the influence of a dimensionless parameter on the ground depositions was investigated separately: these are the dimensionless tree distances $\Delta x/d_b$, the boundary-layer Reynolds number $Re_\delta = (U_\delta \delta)/u_\alpha$ and the power-law exponent $n$ (see Equation (4)).

The four forms of the idealized tree crowns are defined by the tree aspect ratio $z_b/d_b$ and the shape parameter $\lambda_t$ as listed in Table II. For each form the dimensionless tree distances $\Delta x/d_b$ were varied whereas the boundary-layer parameters were kept constant with $n = 0.23$ and $U(\delta) = 6 \text{ m s}^{-1}$. For the array of cylinders ($\lambda_1$) experiments were done for the range between $\Delta x/d_b = 2$ and $\Delta x/d_b = 8$. For the other three forms $\lambda_2$, $\lambda_3$ and $\lambda_u$ the range was set from $\Delta x/d_b = 1.5$ to $\Delta x/d_b = 5$.

Figure 11 shows the deposition amplification factor $\alpha$ for the cylinder array ($\lambda_1$) depending on the dimensionless tree distances $\Delta x/d_b$. The maximum ground deposition is indicated for $\Delta x/d_b = 3.3$ with a value of $\alpha = 1.5$, which means that for this obstacle configuration the ground deposition is 50% higher in comparison to a flat area.

For $\Delta x/d_b \geq 3.5$ there are only slight differences between the values for the three partial arrays. For shorter tree distances there occur remarkable differences until the shortest possible distance $\Delta x/d_b = 2$. For this case the ground deposition in the partial arrays 2 and 3 is even smaller than in the case without obstacles. In general, the ground deposition decreases from the front edge to the back edge of the test array. The flow through the obstacle arrangement and the ground deposition is hindered with increasing density of the obstacle configuration.

In the case of the cone array ($\lambda_2$) the maximum amplification was determined for $\Delta x/d_b = 2.5$ with $\alpha = 1.4$ (Figure 12). For $\Delta x/d_b \leq 3.5$ the differences between the partial arrays are obvious whereas the curve for partial array 1 differs remarkably from both partial array 2 and 3. For the arrangement with the highest density $\Delta x/d_b = 1.5$ the mean deposition attains only 50% of the reference value.

Figure 13 shows the results for the spherical form ($\lambda_3$). It is obvious that the differences in the $\alpha$-values for the whole array are rather similar, but remarkably lower than the values obtained from the experiments with cylinders and cones. The
**Figure 11.** Deposition amplification factor $\alpha$ depending on the tree distance $\Delta x/d_b$ for an array built up with cylinders with $Re_b = 1.8 \times 10^4$, $Re_S = 2.0 \times 10^5$ and $z_0/z_b = 0.008$.

**Figure 12.** Deposition amplification factor $\alpha$ depending on the tree distance $\Delta x/d_b$ for an array built up with cones with $Re_b = 2.6 \times 10^4$, $Re_S = 2.0 \times 10^5$ and $z_0/z_b = 0.005$. 
maximum mean deposition is indicated for the range between $\Delta x/d_b = 2.0$ and $\Delta x/d_b = 3.5$ with $\alpha \approx 1.2$. As for the two previous scenarios, the deposition factors are clearly different between the three partial arrays, here for distances smaller than $\Delta x/d_b = 3.0$.

For the combined form ($\lambda_4$) the maximum deposition with $\alpha = 1.5$ is indicated for the shortest distance $\Delta x/d_b = 1.5$ (Figure 14). The values of $\alpha$ are decreasing slightly and nearly linear with tree distance. Also in this experimental series the ground deposition shows remarkably different patterns for different partial arrays up to $\Delta x/d_b = 4.0$.

In summary the following order concerning the maximum deposition efficiency is obtained: the cylinder form ($\lambda_1$), the combined form ($\lambda_4$) and the cone form ($\lambda_2$) with similar values and the sphere form ($\lambda_3$) with the lowest value. For all experiments it can be indicated that already a few obstacles in the whole array lead to an increase of the ground deposition of about 10% for the whole array.

In the next step the boundary-layer Reynolds number $Re_b = (U_b \delta)/v_a$ was varied to investigate the influence of the mean flow velocity to the ground deposition. For each crown form – except for the combined form – the tree distance was chosen in which the maximum deposition amplification factor $\alpha$ was obtained in the preceding experiments: $\Delta x/d_b = 3.0$ for the cylinders, $\Delta x/d_b = 2.5$ for the cones and $\Delta x/d_b = 2.0$ for both other forms.
Figure 14. Deposition amplification factor $\alpha$ depending on the tree distance $\Delta x/d_b$ for an array built up with $\lambda_4$ forms with $Re_b = 2.6 \times 10^4$, $Re_\delta = 2.0 \times 10^5$ and $z_0/z_b = 0.007$.

Figure 15 shows the mean grey values for wind velocities between $U_\delta = 3$ m s$^{-1}$ and $U_\delta = 12$ m s$^{-1}$ for the four idealized tree crown arrangements and for the surface without obstacles. As expected, the deposition increases (decreasing grey value in the diagram) with increasing velocity of the surrounding flow.

In Figure 16 each curve represents the quotient between the fitted curve for one of the four arrangements and the fitted curve for the surface without obstacles. The dimensionless form indicates that the factor $\alpha$ depends only slightly on the Reynolds number in the range between the values $Re_\delta = 10000$ and $50000$. With the exception of the curve for the conical form, $\alpha$ decreases with increasing $Re_\delta$. For the cylinders and the cones, mean values of $\alpha = 1.5$, for the combined form $\alpha = 1.3$ and for the spheres $\alpha = 1.2$ are obtained for this $Re$-range.

Finally, the influence of the turbulent boundary layer on the ground deposition was investigated, here illustrated for the cylinder array ($\lambda_1$) with $\Delta x/d_b = 3.0$. To compare ground deposition patterns obtained from experiments in different turbulent boundary layers, a height $z$ must be fixed in which the wind velocity $U(z)$ is identical for all experiments. Here the height of the cylinder $z_b$ was chosen to minimize the effects of the different power law exponents $n$ in the effective height interval of the ground dispersion.

Figure 17 shows clearly that an increase of the turbulence intensity of the flow at the beginning of the test section leads to an increase of ground deposition. Between the values $n = 0.17$ and $n = 0.32$ the amplification factor increases from $\alpha = 1.3$ up to $\alpha = 1.6$. The blocking effect on the flow resulting in a decreasing
Figure 15. Mean grey values depending on the wind velocity \( U(\delta) \) for an area without obstacles and for the four obstacle configurations with \( \lambda_1 \) (cylinder), \( \lambda_2 \) (cone), \( \lambda_3 \) (sphere) and \( \lambda_4 \) (turned up truncated cone/spherical sector) with \( n = 0.23 \).

Figure 16. Deposition amplification factor \( \alpha \) depending on the Reynolds number \( Re_\delta \) for the four obstacle configurations with \( \lambda_1 \) (cylinder), \( \lambda_2 \) (cone), \( \lambda_3 \) (sphere) and \( \lambda_4 \) (turned up truncated cone/spherical sector) with \( n = 0.23 \).
of $\alpha$ between the obstacles in downstream direction has similar effects for all investigated boundary layers.

7. Conclusions

Experiments on dry deposition of particles and gases on homogeneous surfaces have been carried out quite extensively, but the results had led to a wide range of behaviour as the reviews from many authors have shown. Moreover there is much less information available for an inhomogeneous surface or for the surface between obstacle arrangements. For these complex structures the determination of mean particle deposition velocities is more difficult than for homogeneous surfaces. In this study it was not the main objective to investigate deposition velocities. It was the intention to determine the obstacle arrangement density in which the mean ground deposition is maximized for a defined crown form. As far as we are aware, there have been no other small-scale or field experiments carried out in the past concerning this question. To close this gap of knowledge these wind-tunnel experiments were designed.

As expected, the results have shown that a dimensionless tree distance $\Delta x/d_b$ can be determined where the ground deposition reaches a maximum value. For a
cylinder array or a cone array the deposition amplification factor reaches a more distinct maximum depending on the tree distance than for an array with spheres or with a combination made of a turned up truncated cone and a spherical sector. For a dense tree crown arrangement in which distances between the edges of the crown are smaller than the crown diameter itself, it is to be expected that the ground deposition is smaller than for a flat terrain.

In general, the effectiveness of the hulls can be taken into the following order: cylinder form, cone form, the combined form and sphere form. This result indicates that an arrangement of crown forms with a wide ground base and a decreasing width with increasing height has the tendency to produce higher ground deposition values, provided that forms with identical volume are compared. A similar effect can be detected if the crown forms are modelled with a trunk. With increasing height of the trunk the influence of the crown form decreases remarkably.

All together, a maximization of the integral ground deposition of between 20% and 60% should be realistic through a favourable choice of the tree crown. Higher values can be found locally in areas around the obstacles. But for dense arrangements the length of the vegetation area must be taken into account, since ground deposition gradients in the flow direction can occur, as the experiments have shown. A downstream extension of the experimental array would shift the maximum amplification factor slightly to higher dimensionless tree distances $\Delta x/d_b$ depending on the configuration density.

As expected, increasing the turbulence intensity in the flow leads to an amplification of the mean ground deposition. The influence of the tree crown porosity was assumed to be negligible in this study. Additional experiments with various porosities should be carried out to examine this fact. With the results of these ground deposition experiments, and the knowledge of the pure filtering effects of the vegetation, for example, landscape and town planners can infer optimum parameters on how to design effective particle-removing vegetation areas.

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**References**


