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WIND TUNNEL EXPERIMENTS OF THE GROUND DEPOSITION OF AIRBORNE PARTICLES AMONG AN ARRAY OF IDEALIZED TREE CROWNS

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INTRODUCTION

The emission of natural or anthropogenic particles into the atmospheric boundary layer often leads to irritations of the inhabitants of surrounding residential areas. Dust emissions from industrial areas, bulk piles etc. 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 to filter airborne particles out of the atmospheric flow (see Figure 1).

Figure 1: Principle sketch of the ground deposition after particle erosion from a bulk pile.

Filtering of particles through or above dense vegetation is well investigated. Field or laboratory experiments of the dry deposition of particles and gases on homogenous surfaces were carried out quite extensively (see reviews of Sehmel, 1980; Hosker and Lindberg, 1982; Nicholson 1988 etc.). The investigations have shown that deposition processes depend in a complex way on numerous parameters and that ground deposition of particles is relatively small with dense vegetation. For less dense obstacle structures or vegetation arrays there is less information available concerning ground deposition distributions. However, ground deposition can contribute to no small extent 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 due to the fact that the increase in ground deposition rate can exceed significantly 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 an ammonia - manganese chloride - reaction was used (Kottke, Blenke and Schmidt, 1977). Using a tracer gas instead of solid particles can be considered only if the turbulent diffusion is the decisive deposition mechanism and effects of sedimentation, impaction, interception or molecular diffusion can be ignored approximately.

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 occuring therein can only appear in certain combinations (Donat and Schatzmann, 1997).

The geometric lengths related to the rotationsymmetrically trees are the crown height z_b and the maximum crown diameter d_b. Additionally the parameter λ_i describes the shape of the crown. The trees in this study are non-porous and have no trunks. Δx_b and Δy_b are the distances between vertical tree axis in longitudinal and lateral direction. The turbulent, neutrally stratified atmospheric flow is characterized by a profile power law exponent n, the boundary layer height δ , the velocity U_δ in the height δ , the density ρ_a and the viscosity μ_a (see Figure 2).

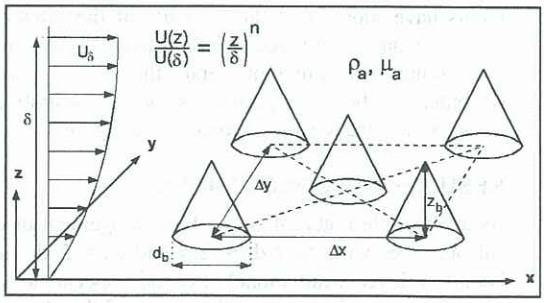

Figure 2: Sketch of an array of the idealized conical tree crowns.

The deposition efficiency D defines the probability that a particle will be deposited in the flat terrain between the tree crowns. D depends upon the following variables:

$$D = f_1\left(z_b, d_b, \lambda_i, \Delta x_b, \Delta y_b, n, \delta, U_\delta, \rho_a, \mu_a\right) \quad (1)$$

Applying dimensional considerations, equation 1 can be transformed into the following non-dimensionalized form

$$D = f_2\left(\frac{z_b}{d_b}, \lambda_i, \frac{\Delta x}{d_b}, \frac{\Delta y}{d_b}, n, \mathrm{Re}_\delta, \mathrm{Re}_b\right) \quad (2)$$

The deposition efficiency D is a function of the tree aspect ratio z_b / d_b, the shape parameter λ_i, the dimensionless tree distances $\Delta x / d_b$ and $\Delta y / d_b$, the power law exponent n, the obstacle Reynolds number $Re_b = (U_\delta d_b) / \nu_a$ and the boundary layer Reynolds number $Re_\delta = (U_\delta \delta) / \nu_a$.

In case it is not allowed to neglect particle diameter, particle density and gravitational acceleration, the particle Froude number Fr_p, the particle Reynolds number Re_p and the Stokes number Sto are additional dimensionless parameters which have to be matched in the wind tunnel experiments. Due to experimental reasons in the following a deposition amplification factor α is defined as the quotient between the deposition efficiencies of an area with tree crowns and an open ground under otherwise identically similarity parameters.

EXPERIMENTAL SETUP

The deposition experiments were carried out in the boundary layer wind tunnel of the Institute for Hydromechanics of the University of Karlsruhe (see Ruck and Adams, 1991). Specific power law exponents n can be achieved by use of specific combinations of vortex generators and artificial roughness elements distributed over the bottom of the flow establishment section. In these experiments n = 0.23 was chosen representing a suburban roughness type (see Donat and Schatzmann, 1997). The ground deposition measuring array with the size of Δx = 60 cm * Δy = 48 cm was fixed at the end of the flow establishment section. 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 color reaction on the paper. Using the 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 as proportional to the time of ammonium contamination and the flow 'activity' (turbulence) above the ground as long as saturation effects on the papers can be avoided (see Figure 3).

RESULTS AND CONCLUSIONS

As an example Figure 4 shows the arrangement of conical obstacles with $\Delta x / d_b = 2.5$ and $z_b = 2\ d_b$ in the boundary layer wind tunnel. For this special arrangement Figure 5 shows an isoline plot of the deposition amplification factor α. The experiments were carried out with the power law exponent n = 0.23 and the Reynolds number $Re_\delta = 2.0 * 10^5$. For the 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 flow direction.

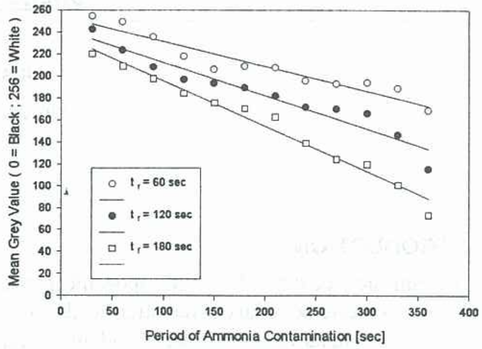

Figure 3: Calibration of the ammonia - manganese chloride - method in the wind tunnel experiment. The brown colouring of an array is shown in mean grey values depending on the period of the ammonia contamination for experiments with U(δ) = 6 m / s.

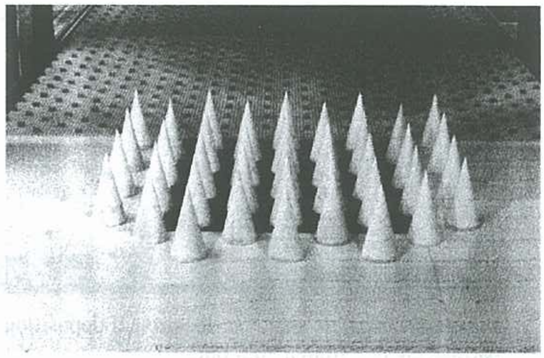

Figure 4: Arrangement of a conical form with $\Delta x / d_b = \Delta y / d_b = 2.5$ and $z_b = 2\ d_b$. The dark area between the cones indicates the investigated deposition zone.

From investigations of flows around isolated round obstacles it is well known that a horseshoe vortex is formed at the base of the obstacle. In the first partial array this typical horseshoe vortex is indicated through higher values of the amplification factor immediate near the cones with maximum values up to α = 3.6 in comparison to lower α values in the middle between the obstacles. These patterns on the ground can be found also in the partial arrays 2 and 3 but there is a tendency that the shaping of the horseshoe vortices are less distinct in downstream direction.

For all partial arrays the deposition area is integrated including the bases of the obstacles. In this special experiment it results in mean values of α = 1.5 for partial array 1, α = 1.3 for partial array 2 and α = 1.2 for partial array 3. For the whole array configuration the mean deposition factor is α = 1.4, which means that for this obstacle configuration the ground deposition is 40 % higher in comparison to a flat area. The decreasing of α with increasing length of the obstacle structure in flow direction indicates the remarkable influence of the density of the idealized tree crown configuration on the ground deposition.

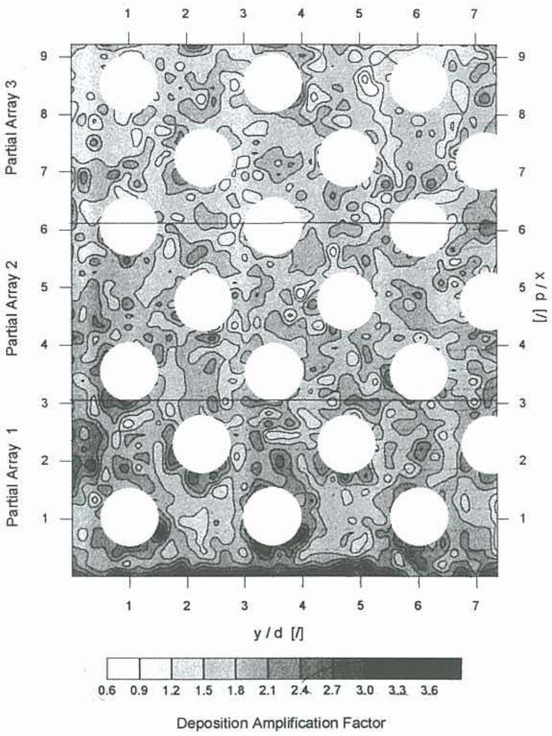

Figure 5: Isoline plot of the deposition amplification factor α for a cone array: $\Delta x / d_b = 2.5$, $z_b = 2\ d_b$, $Re_b = 2.6 * 10^4$, $Re_\delta = 2.0 * 10^5$ and $n = 0.23$.

Figure 6 shows the deposition amplification factor α for a cone array depending on the dimensionless tree distances $\Delta x / d_b$. The maximum ground deposition is indicated for the demonstrated case with $\Delta x / d_b = 2.5$. 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 arrays 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.

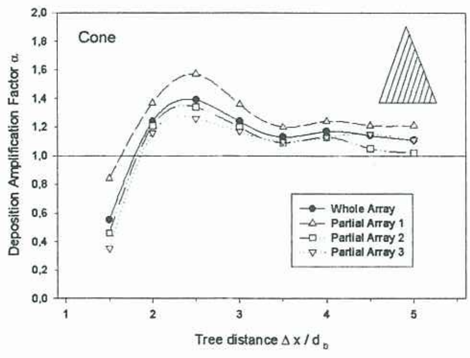

Figure 6: Deposition amplification factor α depending on the tree distance $\Delta x / d_b$ for an array built up with cones with $Re_b = 2.6 * 10^4$ and $Re_\delta = 2.0 * 10^5$.

Further experiments with different idealized tree crowns have shown, that 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 flow direction can occur. 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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