FLUID MECHANICAL ASPECTS OF THE POLLUTANT TRANSPORT TO CONIFEROUS TREES

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Abstract. Forest decline in some parts of Europe gave rise to various environmental studies concerning the intake and uptake of pollutants in the ecosphere. As far as fluid mechanics is concerned, the current interest is centered on flow-induced phenomena, e.g., the flow-enhanced deposition of pollutants to trees. In order to understand better the mechanisms of pollutant dispersion and deposition to trees, wind tunnel experiments carried out with small real coniferous trees and model trees are summarized in this paper. The flow around single trees and tree stands, both in flat terrain and on hillsides, has been analysed. The measurements were performed with a two-component laser Doppler anemometer system installed in an atmospheric boundary-layer wind tunnel. A chemical tracer method based on an ammonia-manganese chloride reaction was applied to visualize the deposition patterns around trees and modeled forest stands.

1. Introduction

The cause of the forest die-back in some parts of central Europe has been widely attributed to airborne transport of pollutants. It has often been noted that wind-exposed individual trees or tree stands both in flat terrain and on hillsides have suffered peculiar damage (Schütt, 1981; Rehfuß, 1983; Schöpfer et al., 1984). In addition, Schöpfer et al. (1985) have found that tree stands characterized by factors such as large tree-top roughness and hilly terrain are particularly subject to damage. Thus, it is not surprising that there is considerable interest in fluid mechanical processes, e.g., turbulent transport of pollutants to trees.

The deposition of gaseous and particulate pollutants on vegetation takes place through molecular diffusion, turbulent diffusion, sedimentation, impaction and interception. Furthermore, the uptake is often controlled by biological, plant physiological and configurational factors that vary with plant architecture. Thus, pollutant uptake depends strongly on the properties of the deposited substance (gas, solid particle, droplets), on meteorological conditions, and on the surface structure as well as on the particle sizes involved. The flow properties and the mass exchange between the atmosphere and the biologically active canopy have been intensively investigated in the past. Many of these investigations have been carried out in the field, see, e.g., Reifsnyder et al. (1955), Baynton et al. (1965),

Smith et al. (1972), Högström et al. (1989), Bergström et al. (1989) and Amiro (1990), who provided interesting local information on mean wind and turbulent characteristics. Parallel to field measurements, model investigations have been performed mainly in atmospheric boundary-layer wind tunnels, see, e.g., Meroney (1968), Seginer et al. (1976) and Ruck et al. (1986), measuring time-averaged flow properties in and above the canopy. Theoretically, deposition models have been based on different assumptions for the turbulent transport of the depositing material, as can be inferred from Raupach et al. (1981) or from a review given by 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). Today, experimental evidence shows that flux-gradient models which have been used for decades to describe the turbulent transport in plant canopies, are difficult to apply to canopy flow, 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). Nevertheless, existing literature supports the idea that turbulent diffusion, which comprises all kinds of 'air flow events', sometimes referred to as sweeps, bursts, gusts, etc., contributes most of the deposition of pollutants to canopies.

Limiting consideration to gaseous and/or particle deposition and to the most relevant size range of particle diameter \( d < 10 \, \mu m \), turbulent diffusion plays an important and often a dominant role (see Chamberlain, 1967; Ruck et al., 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. Chamberlain (1975) showed that sulphate and nitrate particles have a maximum in their particle size distribution between 0.1 and 1.0 \( \mu m \). Little et al. (1977) found that most automobile emissions also occur in the same size range. 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.

Measurements of pollutant deposition levels in coniferous forests exist; see, e.g., Garland et al. (1977), Lorenz et al. (1985), Belot (1976). However, these studies usually only give single values and the investigators have not studied systematically the flow field and the pattern of deposition around a wind-exposed single tree or forest stand. For the assessment of deposition levels to forests, it is not only the geometry of an individual tree or forest which is of interest, but also the fluid mechanical interaction between tree height and the form of the surrounding countryside as shown by Shreffler (1978), Sehmel (1980) and Ruck (1987). This mutual influence has not been seriously examined in the literature. Concerning the interaction between the atmosphere and topographical forms, there are also
theoretical studies (e.g., Jackson et al., 1975), laboratory studies (e.g., Baines, 1984; Snyder et al., 1985; Thompson et al., 1985; Pearse et al., 1981), numerical studies (e.g., Emeis, 1987) and field data (e.g., Haufl et al., 1982). These papers provide very complete information on mean velocity and turbulence levels, but the validity of the results is restricted to relatively small surface roughness. The flow over forested hills, however, represents a case of relatively large surface roughness when compared with hill height.

In summary, it can be seen that detailed investigations are lacking on the interactions among the atmospheric boundary layer, forest structure and orography. 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 forest stands. The intention of this paper is to provide fluid mechanical background information about basic flow around such structures and, thus, to contribute to a better understanding of flow-induced pollutant deposition. The conclusions given in this paper were deduced from wind tunnel studies keeping in mind, however, that such experiments are not capable of addressing all factors involved in the uptake of particulate or gaseous pollutants.

2. Theoretical Background

2.1. Deposition Velocities

Mass transport from the atmosphere to surfaces is referred to as deposition. Deposition can be classified as dry and wet. The following discussion relates to dry deposition, i.e., the mass transfer not associated with precipitation.

To describe the deposition of an airborne substance to an air-surface interface, Chamberlain et al. (1953) defined a deposition velocity $v_d$ as the ratio of the deposition flux $\dot{m}$ divided by the pollutant concentration $C$ at a reference height $y$, above that surface. (Note that in this paper, $y$ denotes the vertical axis following the wind-tunnel modelling literature.)

$$v_d = \frac{\dot{m}}{C(y)}$$  \hspace{1cm} (1)

with $\dot{m}$ in g/(m$^2$ s) and $C$ in g/m$^3$.

Deposition velocities for different substances and boundary conditions can be found in published tables; see, e.g., Chamberlain (1975), McMahon et al. (1979), Sehmel (1980). These deposition velocities were mainly inferred from field and laboratory experiments carried out with flat test surfaces. Although many deposition velocity data exist, they are not sufficiently representative to allow a generalized prediction of the pollutant removal process from the atmosphere.
2.2. Deposition and Turbulence

To understand more about the physical phenomena involved in deposition, it is worthwhile to consider existing diffusion and deposition models developed to describe the particle transport near walls; see, e.g., Friedlander et al. (1957), Rouhani et al. (1970), Trelo et al. (1982). These models do not account for vegetative surfaces and canopy flow; however, they document the strong coupling between flow quantities and particulate deposition. It is widely assumed in theoretical modeling of deposition that the particle diffusivity is equal to the eddy diffusivity of the carrier gas (which does not hold for particles in the upper micrometer size range).

Most mathematical diffusion treatments begin with the equation of conservation of mass of the suspended material. In the case of an incompressible turbulent fluid, this leads to the standard diffusion equation:

$$\frac{\partial \bar{C}}{\partial t} + \frac{\partial \bar{u} \bar{C}}{\partial x} + \frac{\partial \bar{v} \bar{C}}{\partial y} + \frac{\partial \bar{w} \bar{C}}{\partial z} = - \left[ \frac{\partial (\bar{u}' \bar{C})}{\partial x} + \frac{\partial (\bar{v}' \bar{C})}{\partial y} + \frac{\partial (\bar{w}' \bar{C})}{\partial z} \right],$$

(2)

where $\bar{C}$ is concentration of the transported material; $\bar{u}, \bar{v}, \bar{w}$ are mean velocity components; $u', v', w'$ are fluctuation quantities; and $\delta$ is the partial derivative. The overbars denote the time mean of the quantities considered. The right-hand terms (eddy flux terms) represent the correlations between the velocity fluctuations and the concentration fluctuations of the suspended material. Introducing the gradient transfer forms and omitting overbars yields:

$$\frac{d \bar{C}}{d t} = \frac{\delta}{\delta x} \left[ K_x \frac{\delta \bar{C}}{\delta x} \right] + \frac{\delta}{\delta y} \left[ K_y \frac{\delta \bar{C}}{\delta y} \right] + \frac{\delta}{\delta z} \left[ K_z \frac{\delta \bar{C}}{\delta z} \right]$$

(3)

with $K_x, K_y, K_z$ as eddy diffusivities in the $x, y, z$ directions ($y$ perpendicular to the deposition surface). For the two-dimensional steady-state boundary-layer case, Equation (3) reduces to

$$u \frac{\delta \bar{C}}{\delta x} = \frac{\delta}{\delta y} \left[ K_y \frac{\delta \bar{C}}{\delta y} \right].$$

(4)

If the flow approaches a wall (surface of deposition), $u$ becomes zero and the deposition flux $\dot{m}$ can be written:

$$\dot{m} = \left[ (D + K_y) \frac{\delta \bar{C}}{\delta y} \right]_{y=0}.$$  

(5)

In Equation (5), the molecular diffusion constant $D$ was added as, e.g., in the model of Lin et al. (1953). However, adding of molecular and turbulent diffusivities is questionable. Anyway, comparing the orders of magnitude shows that the
molecular diffusion can be neglected in most cases. Equation (5) must be expanded, if the suspended material consists of particles which are additionally transported by sedimentation. In this case, a convective term which describes the settling (settling velocity \( u_s \)) has to be introduced:

\[
\dot{m} = \left[ K_r \frac{\delta C}{\delta y} + \nu_r C \right] y \rightarrow 0 = \nu \dot{C}_{(y \rightarrow 0)}.
\] (6)

As can be seen from Equation (6), determination of the deposited mass flux can be performed by either measuring the eddy diffusivity \( K_r \) (and the settling velocity if relevant) of the suspended material or measuring the deposition velocity \( \nu \). In both cases, the local concentration must be known. As an approximation, the eddy diffusivity \( K_r \) of the suspended material is, as mentioned above, often set equal to the eddy diffusivity of the continuous phase flow \( K_r \).

\[
K_r \approx K_r = -\frac{\overline{u'v'}}{\overline{du/dy}}.
\] (7)

Thus, provided Equation (7) holds for the specific suspended material, the deposition flux can be estimated from flow field measurements near the deposition surface. Although the above considerations are limited and do not account for, e.g., differently orientated and porous vegetative surfaces or the resuspension of deposited material, Equations (6) and (7) indicate the strong coupling between flow quantities and deposition characteristics. Qualitatively, a change in surface roughness reflects a change of measured turbulent flow quantities, which is equivalent to a change in deposition flux. Therefore, it is not surprising that field and experimental model investigations have shown good agreement between the qualitative behaviour of measured deposition and local flow quantities.

2.3. Canopy flow

The flow within and over a vegetative surface can be separated into an outer region comprising the flow above the canopy and an inner region of flow through the canopy. In theoretical modeling, the flow in the inner region is usually referred to as uniform canopy flow, because most of the models neglect transition zone effects, e.g., effects associated with the leading and trailing edges of a forest. These regions are often treated separately in the literature; however, models exist which combine both in order to provide a more comprehensive description of the flow field, see e.g., Barr (1971).

If a continuous phase flow field has to be treated, the considerations usually begin with the momentum conservation equations which for an incompressible, quasi-steady, two-dimensional turbulent form are:

\[
\frac{\partial \overline{u}}{\partial x} + \frac{\partial \overline{u}}{\partial y} = -\frac{\delta \rho}{\rho \partial x} - \frac{\delta \overline{u^2}}{\partial x} - \frac{\delta \overline{u'v'}}{\partial y} + \nu \left[ \frac{\delta^2 \overline{u}}{\partial x^2} + \frac{\delta^2 \overline{u}}{\partial y^2} \right].
\] (8)
\[
\frac{\partial \bar{u}}{\partial x} + \frac{\partial \bar{v}}{\partial y} = -\frac{1}{\rho} \frac{\partial \bar{p}}{\partial y} + \frac{\partial \bar{u}'u'}{\partial y} - \frac{\partial u^*}{\partial x} + \nu \left[ \frac{\partial^2 \bar{u}}{\partial x^2} + \frac{\partial^2 \bar{u}}{\partial y^2} \right] - g.
\] (9)

If a homogeneous structure of the canopy can be assumed, which is expressed by setting \( \bar{v} = 0 \) and \( \partial \bar{u}/\partial x = 0 \), Equations (8) and (9) reduce to:

\[
0 = -\frac{1}{\rho} \frac{\partial \bar{p}}{\partial x} + \frac{\partial \bar{u}'u'}{\partial y} + \nu \frac{\partial^2 \bar{u}}{\partial y^2},
\] (10)

\[
0 = -\frac{1}{\rho} \frac{\partial \bar{p}}{\partial y} + \frac{\partial \bar{u}^2}{\partial x} - g.
\] (11)

In Equation (10), the pressure gradient in the longitudinal direction is of interest. Neglecting \( \partial \bar{p}/\partial x \) and integrating Equation (10) yields \( \tau = \text{const} \). Introducing the Prandtl momentum mixing-length concept yields a logarithmic wind law. However, the mixing length \( l(y) \) has to be chosen according to the differing flow conditions in the inner and outer flow regime. In the outer flow, the mixing length is linearly proportional to height above ground. The flow outside the plant cover can thus be described by the well-known logarithmic law, see, e.g., Plate et al. (1965)

\[
\frac{u(y)}{u_\tau} = \frac{1}{k} \ln \left( \frac{y - d}{y_0} \right),
\] (12)

where \( u_\tau \) is the shear velocity, \( d \) the zero plane displacement, \( y_0 \) the roughness height and \( k \) the Karman constant.

The mixing length in the inner flow regime is modeled differently. Inoue (1963) and Cionco (1965) based their models on a constant mixing length in the canopy volume. This leads to a windspeed \( u(y) \) in the idealized canopy which can be described by an exponential expression

\[
u(y) = u_H \exp \left[ -\alpha \left( \frac{y}{H} - 1 \right) \right],
\] (13)

where \( H \) denotes the canopy height and \( \alpha \) the attenuation coefficient, which reflects the airflow response to the canopy roughness.

Uchijima (1962) modified the constant mixing-length approach by including the zero plane displacement and the physical height of the canopy while a trigonometrical relation between mixing length and height was formulated by Cowan (1968). Barr (1971) treated the flow in the inner regime as a turbulent Couette flow type between two parallel moving plates; see Reichardt (1956), yielding a parabolic distribution of mixing length with height. The different behavior of mixing length in the outer and inner regimes could sometimes be combined into a mixing-length relation in uniform canopy flow modeling. Nevertheless, the experimental evidence for these mixing-length approaches is relatively poor, so that other investigators,
e.g., Saito et al. (1970) replaced the mixing length by a length scale derived from the autocorrelation of the vertical velocity fluctuations.

To apply uniform canopy flow models to finite canopy flow conditions (e.g., flow into a finite and topographically varying forest stand with edges) is however, an incorrect simplification. This is due to the fact that in reality, \( \partial \delta / \partial x \), \( \partial \beta / \partial x \), \( \partial \gamma / \partial y \) and the gradients of the derivable moments are at least locally non-zero. Therefore, for the most relevant cases, the flow field within and above a real forest stand can, at best, be roughly approximated by Equations (10) and (11) or by logarithmic or exponential wind laws. Higher order models, which incorporate edge effects of a canopy are rare and do not account sufficiently for the vertical variation of turbulence in the edge regions. A comprehensive overview of numerical approaches to describe canopy flows is given by Cionco (1985). The flow over and through a forest edge is becoming more and more the subject of numerical studies, see e.g., Li et al. (1990). However, consideration of existing models for canopy flow suggests that there is a substantial need for experimental data to define the flow field characteristics in transition zones, e.g., the leading and trailing edges of a forest canopy.

3. Experimental Details

All experiments were performed in the 1.5 m octagonal cross-section, closed circuit wind tunnel of the Institute of Hydromechanics/University of Karlsruhe. An atmospheric boundary layer was simulated within the test section, using vortex generators (triangular drag element – ‘spires’ – 60 cm high) and roughness elements in the 3.5–6 m long flow-development section; see Figure 1. The combination of the spires and roughness elements allowed the realisation of different boundary-layer conditions. For the model investigation, a profile exponent of \( \alpha = 0.23–0.26 \) in \( u^+ = y^+ \) was chosen; the effect of atmospheric stratification was ignored. The experiments were conducted with flow velocities of 2.0–2.5 m/s. Model trees with simulated porosities as well as young coniferous trees were located in a specifically adapted atmospheric boundary layer (for boundary-layer simulation, see, e.g., Counihan, 1969; Meroney, 1968). The model trees consisted of simulated
evergreen boughs formed according to the shape of the original conifers. The volume porosity of the material used for the crown simulation was 93.4%.

For the model tree investigations, the boundary-layer thickness was 0.6 m, the shear stress velocity typically 0.05–0.07 m/s and the ratio of displacement thickness to momentum thickness $H_t$ = 1.29. The flow velocity measurements were performed by a two-component laser Doppler anemometer (LDA) system including an argon-ion laser (3 W) and two double Bragg cells for frequency shifting; see Figure 2. The LDA-signals were detected in forward light scattering and the data were evaluated by counter-based electronics. For the flow measurements, the air was seeded with micrometer-sized tracer particles (median diameter $\approx$ 1.5 $\mu$m). With this particle size and within the given fluid velocity range, the flow characteristics of the continuous phase flow could be inferred from the measured particle velocities. For further details of the LDA measuring techniques, see, e.g., Durst et al. (1976), Drain (1980) and Ruck (1987, 1990).

The similarity rules for simulation of boundary-layer flows in wind tunnels are known; see, e.g., Armitt et al. (1968), Counihan (1969) and Cermak (1971). To achieve similarity in turbulent flow, it is sufficient in many cases to ensure flow separation at the edges of the model. If separation occurs, there will be no significant change in the flow field and in transport phenomena with a further
increase in flow velocity. This allows investigations with lower Reynolds numbers than those given by the exact Reynolds similarity rules. Indeed, most model investigations in boundary-layer wind tunnels are carried out with a relatively low flow velocity. If the model is porous and has no sharp edges, this approach can fail. Therefore, it is necessary to verify the flow field Reynolds number independence for porous obstacles by pre-investigations in the wind tunnel yielding a 'critical' Reynolds number which must be exceeded for the experiments. It should be noted that similarity between model and nature can only be provided for transport phenomena caused by larger scale eddies which carry the main turbulent energy.

For qualitative information about flow and deposition patterns, laser light sheet flow visualization was used (Beiser, 1974; Schmitt et al., 1986). Photographs were taken using a CCD video camera. These could be directly reproduced or processed by a digital image-processing system to enhance or filter the digitized image; see, e.g., Ekstrom (1984), Haberäcker (1985) and Ruck (1990).

The deposition measurements were made with a remission photometric method following Kottke et al. (1977). In this method, ammonia is used as a tracer gas, which upon reaching a coated substrate causes a chemical reaction which turns the substrate brown. The intensity of the coloration is a function of deposition rate. The coating consists of a solution of manganese chloride. As substrates, either the obstacles (trees) themselves or additionally mounted white filter paper was used. For the investigation of trees with high aerodynamic blockage, i.e., with almost no porosity, small cone-shaped jackets made of filter paper were attached to the tree surface. Quantitative evaluation of the deposition patterns on the filter paper were performed using digital image-processing technique. The grey levels on the filter paper could be digitized, stored and processed into histograms. Through calibration, these histograms could be converted into colour density. Thus for each tree, an average deposition level as well as its distribution could be measured, depending on the prevailing wind direction.

The primary geometric variables of interest are tree height $K$, tree spacing $a$, stem height (branch free bole) $s$, hill height $H$, hill length $L$ and boundary-layer thickness $\delta$; see Figure 3.
4. Flow around Single Trees

Figure 4 shows the mean velocity profile around a young coniferous tree in the center plane (plane perpendicular to the ground, containing the tree stem, parallel to the main wind direction). In Figure 5, the corresponding turbulent shear stress is plotted. Successive LDA measurements in different planes yielded a picture of the time-averaged flow field. Figure 6 sketches for a single tree, the flow field obtained by local LDA measurements, which allows one to distinguish flow structures.

Local LDA-measurements showed that as tree porosity decreased, the vortex structure associated with each tree moved closer to the tree; see Figure 6. Further-
more, the height of the exposed section of tree trunk was also important. While a tree without a branch-free trunk had a larger separation region behind it, a tree with an exposed trunk showed evidence of flow acceleration under the tree and damping of the turbulence in this region. Correspondingly, there was higher ground deposition measured for the case without an exposed trunk. In Figure 7, the local deposition distribution of an isolated real conifer with and without a branch-free trunk is given. The areas of different deposition levels were visualized.
Fig. 7. Ground deposition distribution of an isolated conifer with and without a branch-free trunk, obtained by a chemical tracer method and visualized as grey-leveled areas by digital image processing; see also Ruck and Schmitt (1986).
by the aforementioned chemical tracer method and digital image processing (the darker the area, the higher the deposition). In front of the trees, an enhancement of deposition to the ground was observed, due to horseshoe-type vortices. It was found that the closer the branches to the ground, the more material was removed by deposition. The experiments have shown that an ‘efficient cross-section’ of a tree for the pollutant removal process is greater than can be deduced from its geometrical leaf area and can only be assessed by including fluid mechanical aspects. This means however, that the interaction of tree shape, topography and atmospheric boundary-layer condition have to be considered in order to validate the tree’s efficiency in pollutant removal. The results suggest that cone-shaped conifers without branch-free trunks (especially young and middle-aged conifers) act much more efficiently with respect to pollutant deposition to the ground than other tree shapes, e.g., most deciduous trees. LDA measurements and the application of flow visualization techniques on a variety of differently shaped model trees in the wind tunnel support these findings.

For the intake of deposited material into needles, leaves and soil, the flow field and the deposition pattern around a wind-exposed single tree are of importance. Samples from the windward side can significantly differ in deposition from those taken on the leeward side. This holds not only for isolated trees exposed to a predominant wind direction but also for groups of trees as we shall see in the next section.

5. Flow around Forest Stands

5.1. Flow and Deposition onto Plane Forests

To model a forest on a flat landscape, several different real and model trees were tested in the wind tunnel. Table I summarizes the tree geometries and the planting patterns. The forests differed in their tree spacings, expressed here as $a/K$, the tree spacing compared with the height of the tree, as well as the average tree height compared with the incoming boundary-layer height, $K/δ$.

In case I–IV, the average cone-shaped model tree consisted of plastic simulated evergreen boughs and had no branch-free trunk. The model trees of case V were
shaped in detail including crown and exposed trunk heights to ensure maximum similarity between rebuilt and original forest canopies. Volume porosities in all cases were between 92–94%. Figure 8 is a sketch of the model trees used.

In case I-IV, the simulation was performed with identical trees. The model forest of case V was built up from photographs and terrestrial analyses of a real forest near the village of Besenfeld in the Black Forest of southwest Germany. The forest chosen faces southwest, the direction of the prevailing wind, and is situated in a region where tree die-off within the Black Forest is especially severe. The forest was modeled tree by tree including stem and crown height and location. To build the forest, individual trees were attached to separate “Lego” blocks and these were fixed to the pegboard mounted flush with the upstream section. Finally, the forest designated “stand using real trees” was built using live spruce trees (Picea glauca conica) to examine the flow field within the trees. As indicated, model and live trees (saplings) with different heights were investigated. In general, the larger trees were used to examine the flow field within the forest, while the smaller trees were used to examine the flow and turbulence levels above the forests.

In Figure 9, the LDA-measured velocity profiles of the case I forest are plotted. The general retarding effect of the forest on the wind profile is easily observed, occurring in all cases investigated. This effect is, of course, due to the increased drag of the trees when compared with the roughness elements upstream of the forest. In Figure 9 for $x/K > 4$, an inflection point can be seen in most of the velocity profiles near $y/K = 1.5$. This phenomenon has also been observed by Meroney (1968) in a model deciduous forest. Thom (1975) associates these inflection points with tree top level ($y/K = 1$). In theory (Thom, 1971), the inflection point occurs at the juncture above which the turbulent length scale grows linearly, and below which the length scale is constant. Obviously, this location must not be at $y/K = 1$. The velocity measurements for the other forest cases gave clear evidence that the inflection point lies between $1 \leq y/K \leq 1.5$, depending strongly
Fig. 9. Mean velocity as a function of streamwise distance for the plane forest case I; \( a/K = 0.5 \).

Fig. 10. Development of the mean streamwise velocity (normalized with the equilibrium velocity downstream from the edge) behind the forest edge at average treetop level \( y/K = 1.0 \).

on the streamwise location \( x/K \), the tree density \( a/K \) and the ratio of forest height to boundary-layer thickness \( K/\delta \).

Figure 10 gives the streamwise development of the mean velocity measured at treetop level \( y/K = 1 \). The absolute level of velocity is a strong function of boundary-layer thickness and stand density. All the profiles show a similar trend. The
velocity undergoes a slight initial acceleration in the region $0 \leq x/K \leq 4$ followed by deceleration.

From Figure 10, it can be inferred that the mean streamwise velocity at treetop level decreases into the canopy. At some distance behind the forest edge and after reaching uniform pressure conditions, an equilibrium velocity profile is observed. Normalizing the measured mean velocity at treetop level with the corresponding equilibrium velocity allows one to compare the velocity decrease into the canopy for different roughness and boundary-layer conditions. It can be seen that the velocity at treetop level decreases much more into the forest with smaller heights of the forest stand ($K/\delta$).

Figure 11 shows the LDA-measured streamwise velocity profiles for cases I, II, III and V. The profiles also include points below treetop level in so far as an interference between the trees and the laser beams of the applied LDA-method could be avoided. From the slope of the profiles near the forest, it can be seen that the velocity gradient $du/dy$ first increases sharply and then relaxes somewhat. When roughness changes, as it does at the forest edge, profiles usually show two logarithmic regions, one in the outer part of the boundary layer corresponding to the old roughness, and a second in the inner part of the layer corresponding to the new roughness value. The same trend was noted in the rough-wall boundary-layer study of Antonia \textit{et al.} (1971). As will be seen later, the behaviour of $du/dy$ is reflected in the shape of the turbulence profiles.

The profiles of Figure 11 can be used to define the edge of the internal boundary layer. The easiest definition is the intersection point of the two log-law regions which are plotted in Figure 11. The growth of the internal boundary layer is similar for all cases; see Figure 12. For comparison, the growth law due to Wood (1982)
has been included, but offset at $x/K = 0$ by 1.5 K. With this large offset, the growth rate is correctly predicted by the power 0.79, used in the expression of Wood. The large offset required is further evidence of the extreme perturbation occurring at the forest edge. Antonia et al. (1971) had a much smaller internal layer.

In Figure 13, the streamwise development of the profiles of turbulent kinetic energy are plotted for cases I and IV. The value of the turbulent kinetic energy
Fig. 11. Development of streamwise velocity profiles in logarithmic coordinates.

Fig. 12. Internal boundary-layer height as a function of streamwise distance for several cases.

$q^2/2$ is calculated as $0.75(u'^2 + v'^2)$, following the normal convention, since $w'^2$ measurements were not possible. In all cases, the turbulence values displayed large gradients in the streamwise and vertical directions. As can be seen, an overshoot in turbulence values is noticed, which is not unusual when a boundary layer is subject to perturbations (Tani, 1968). The overshoot has also been observed for the change in roughness by Antonia et al. (1971) and for forest flow by Pendergrass et al. (1984). In all cases, and also for the data noted here, the turbulence values fall continuously after reaching a peak, when normalized by the free stream velocity.

To understand more about the physics of turbulent correlations, it is helpful to examine the transport equations for the Reynolds shear stress and for the turbulent
kinetic energy; see e.g., Rotta (1972). The term $\bar{u}'\bar{v}' \cdot \delta \bar{u}/\delta y$ is primarily responsible for the production of turbulent kinetic energy in two-dimensional flow. The term $\bar{u}'^2 \cdot \delta \bar{u}/\delta y$ represents the production term in the transport equation of the Reynolds stress in two-dimensional flow. The magnitude of both terms is also important for computational models of boundary-layer flow. For cases I and IV, the production terms are strongly peaked at $x/K \approx 2$. This location, of course, corresponds with the peak values of $\bar{u}'\bar{v}'$ and $q^2/2$, which can be inferred from Figure 14.

It is remarkable that the measurements yield higher production values at treetop level near the leading edge of a forest, whereas downstream from the forest edge, higher production occurs significantly above treetop level. For boundary-layer flow, the diffusion of $q^2/2$ is determined by the vertical gradient of $(\bar{u}'^2 + \bar{u}'^2 \bar{v}')$, where a positive gradient denotes a loss of turbulence energy within a region. For shear stress, the diffusional term is $\delta (\bar{u}'\bar{v}')/\delta y$ and here, a negative gradient denotes a loss of $(-\bar{u}'\bar{v}')$. The triple products measured for a position far from the forest edge ($x/K = 18$) are given in Figure 15. It can be seen that at a height of $1 < y/K < 3$, turbulence energy is lost by diffusion, which corresponds to the region of high production. At and below tree top, the absolute value of the triple products drops significantly. This suggests that turbulence is diffusing into the canopy. For $y/K > 3$, the diffusion represents a net input of turbulence. This indicates the growth of the inner layer into the outer layer.

As a measure of mixing near the forest, the mixing length $l^2 = \bar{u}'\bar{v}'/(\delta \bar{u}/\delta y)^2$ is shown in Figure 16 for the boundary layer of cases I and IV. After the forest edge, the value of the mixing length at any height $y$ shifts downward in the
streamwise direction to a new equilibrium line, due to the development of the internal boundary layer. Downstream of the forest edge, the mixing length is roughly constant below $y/K = 2$, which confirms the model assumptions of Inoue (1963) and Cionco (1965). Above this level, the mixing length increases almost linearly with height, as one would expect from Prandtl’s theory.

To examine the deposition to a forest, deposition measurements were carried out using the ammonia-manganese chloride reaction. The deposition surfaces were coated with manganese chloride and the wind tunnel air was mixed with ammonia gas. A relative deposition level can then be visualized from the colour intensity of the deposition surface, which turns brown as a function of time and local...
deposition probability. For measurement of the relative deposition to trees, strips and small cone-shaped jackets of filter paper were placed over individual trees. Many experiments with cone jackets at different locations were performed to ensure that this monitoring technique did not change the canopy porosity significantly. On each jacket, the wind direction was noted. Evaluation of the deposition surfaces was performed optically by digital video image processing referring the grey level (8-bit resolution) of the detected brown coloration to the average grey level measured far downstream of the forest edge, i.e., the region of uniform canopy flow.

In Figure 17, the measured relative deposition to trees as a function of streamwise distance from the forest edge is shown for case V. This case is complex because tree height and stand density vary as a function of position within the forest. Consequently, the data scatter is much more pronounced than in the other
Fig. 17. A comparison of the distribution of tree damage within a real forest with the measured deposition level in a model of the same forest in the wind tunnel (case V): damage rate "0" without needle loss, "1" small needle loss, "2" sick, "3" worst condition.

cases investigated. However, case V allowed comparison of the experimental wind tunnel findings with the real streamwise damage behaviour analysed by aircraft-based infrared photography. Additionally in Figure 17, a typical strip of the lecoal crown map and a sketch of the forest site are given, together with the analysed damage behaviour of the real forest stand. It can be inferred from Figure 17 that shortly beyond the forest edge, the deposition level in the model forest, which
was rebuilt in accordance with the original, reaches a high level. Therefore, the deposition declines with streamwise distance from the forest edge. The decline of deposition level downwind of the leading edge was observed for all cases investigated and is supported by field analyses, e.g., Hager et al. (1985), who investigated the content of sulphur in fir needles as a function of streamwise position downwind of the forest edge. For cases I–III, the decrease of deposition with distance occurred earlier; however, in these cases the canopy was more regular, consisting of similar trees. An examination of the stand structure in case V as a function of the streamwise distance indicates that in this particular case, the turbulence and deposition level stay at a higher level longer because of the non-uniformity of the forest canopy. It is remarkable that the location of maximum damage downwind of the forest edge coincides with the location of measured maximum turbulence level and deposition in the wind tunnel experiments. Although the number of comparisons between real forest damages and model forest findings is small, the results indicate that the turbulence pattern in and above the forest canopy is linked with the patterns of deposition and tree damage.

5.2. Flow and Deposition over Two-Dimensional Forested Hills

Flows over topographical features have been studied theoretically, e.g., by Jackson et al. (1975), in the laboratory, e.g., by Baines (1984), Thompson et al. (1985), Pearse et al. (1981), and in the field, e.g., by Haut et al. (1981). Thus, a wide range of turbulence and mean flow information is available. Neal et al. (1981) reported that the effect of adding roughness to a model hill was significant in the lower 20% of the boundary layer. Britter et al. (1981) found that a separation zone on the lee side of a hill could be induced by adding roughness elements. In these studies, the roughness elements were quite small in comparison with the size of the topographic features. However, studies which describe the interaction of the atmosphere, forest structure and topography are quite rare.

For atmospheric flow over hills, at least six length scales are important but by limiting the study to low hills and neutral density flow, four non-dimensionalized variables remain: $H$, $L/H$, $K/H$ and $a/K$ with $\delta$, the boundary-layer thickness, $H$, the hill height, $L$, the hill length, $K$, the tree height and $a$, the tree spacing. Of these variables, the present study examined hill steepness $L/H$ (5, 10 and 20), tree density $a/K$ (1.0 and 0.5) and $K/H$ (by comparing the flow over hills with different surface structures). Other important non-dimensional groups in the study of atmospheric flow over forested hills are the Reynolds number, the Rossby number and the Richardson number. Of these, only the Reynolds number was considered. The Rossby number is usually considered unimportant in micrometeorological studies, and by assuming neutral conditions, stratification effects as parameterized by the Richardson number could be ignored. Reynolds numbers of meteorological flows, even at low wind speeds, are much larger than could be achieved in the wind tunnel used. Using a free-stream velocity of 1.5 m/s, the Reynolds number based on boundary-layer momentum thickness was $Re_\delta = 8,000$. 
and the Reynolds number based on hill height was 20,000. While these values are not comparable to those in the environment, they are high enough to ensure fully turbulent flow and the correct modeling of the most important turbulent scales. With the size of the boundary layer (60 cm) fixed, the hill height was chosen to be $H = 20$ cm, and the tree height $K = 5$ cm (see Figure 8). If a scale of 400:1 is chosen, the experiment models 20 m trees on an 80 m hill embedded in a 240 m thick boundary layer. Since both separated and non-separated flow cases were of interest, different hill slopes were used (maximum $9^\circ$, $18^\circ$ and $36^\circ$).

The first series of tests undertaken was to examine the flow over a rather steep hill ($L/H = 5$) for two different tree densities ($a/K = 0.5$, $a/K = 1.0$, staggered) compared with the flow over the same hill without trees but with small ($\approx 1$ cm) roughness elements. In Figure 18, the mean velocity data. Reynolds shear stress and the turbulent kinetic energy are plotted for the hill $L/H = 5$. The figure shows that below 2.0 tree heights, the flow is strongly decelerated by the effect of the trees. On the windward side, the deceleration is apparent but smaller in magnitude. Here, the strong deceleration is confined to a thin layer within the trees. Basically, the effects of tree cover on a hill are an increased roughness level and displacement of the flow. The roughness effect dominates on the windward side because the acceleration of the outer flow hinders build-up of the displacement. Examination of velocity profiles for $a/K = 1.0$ in log-form indicated that the displacement effect was almost absent in the strongly accelerated windward side. On the lee side, the displacement effect of tree cover can easily be seen when the line of zero velocity $u = 0$ is examined in the separated flow regime; see Figure 19. In this figure, it is clearly seen that increasing tree density leads to increasing displacement of the profiles upward. On the leeward side, both the displacement effect and the increased roughness are responsible for the earlier separation noted for the forested cases. The profiles on the hill top for the non-forested case have a much thinner boundary layer than the forested cases, leaving more energy available to overcome the adverse pressure gradient. Consequently, in the forested cases, the flow is most likely to separate earlier. Aerodynamically, the latter corresponds to a steeper effective hill shape. In Table II, the shift in separation and reattachment point for the three cases is given.

The turbulence profiles in Figure 18 indicate that on the windward side of the hill, the turbulence levels above the canopy (not at tree top level) decrease, corresponding to the well-known damping effect caused by the acceleration of the outer flow. This decrease was small and hardly noticeable on the scale of Figure 18. Downwind of the hill top, the turbulence levels in the outer flow increase strongly due to the development of a free shear layer. The differences in the turbulence profiles for the three ground-cover cases are rather small on the windward side, whereas downwind of the hill top the differences become more pronounced. The peak $q^2$ and $\overline{u'v'}$ values for the non-forested case are larger and closer to the hill.

The larger values result from the larger velocity gradients in the non-forested
Fig. 18. Comparison of the profiles of mean velocity, Reynolds stress and turbulent kinetic energy over a hill of \( L/H = 5 \) for three different ground-cover cases.
Fig. 19. Comparison of the $\delta = 0$ line downstream of a hill of $L/H = 5$ for three different ground-cover cases.

### TABLE II

<table>
<thead>
<tr>
<th>Case</th>
<th>Separation $x/H$</th>
<th>Reattachment $x/H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No trees</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>$a/K = 1.0$</td>
<td>0.75</td>
<td>7</td>
</tr>
<tr>
<td>$a/K = 0.5$</td>
<td>0.5</td>
<td>7.5</td>
</tr>
</tbody>
</table>

As expected, the position of the maximum values follows the separation streamline. If the profiles of the forested cases are shifted vertically so that the location of the peak values corresponds to the non-forested case, it is obvious that the width of the region of high turbulence for the forested cases is much larger than for the non-forested cases. This is confirmed by close examination of the velocity profiles which shows that the shear layer is substantially thicker for the forested cases. Limiting the considerations to treetop level, in contrast to the outer flow, a substantial increase of turbulence on the windward side of the hill is observed with increasing streamwise distance from the edge. Figure 20 shows the increase of the turbulent kinetic energy at treetop level when compared with data over a flat forest (the data in this figure are partially extrapolated from data near the canopy). Due to the deviation of the flow by the hill shape, the flow penetrates farther into the canopy with increasing streamwise position, leading to increasing turbulence levels in the forest cover. In all cases investigated, the maximum turbulent kinetic energy was measured on the windward side near the hill top.

In meteorological and siting studies, a speed-up or acceleration factor is frequently defined expressing the ratio of the wind velocity at a given height above the hill top to that of the undisturbed flow at the same height above ground: see Figure 21. For the present case, there are two perturbations, the forest (which began at $x/H = -2.5$, the beginning of the hill), and the hill itself. In Figure 21a,
the ratio of the velocity above the hill crest at a height $\Delta y$ above ground is compared to that of the oncoming flow at the same height above the flat surface far upwind of the hill. In this diagram, both forest and hill effects are included. It is obvious that the forest affects the flow up to a height of about $\Delta y/H \approx 0.5$. As a result, the largest acceleration factor for the forested hill is about 1.4 compared to almost 2.2 for the rough hill without trees. Above $\Delta y/H = 0.5$, the flows all show the same acceleration factor, reflecting the shape expected from potential flow theory. In Figure 21b, the velocity over a forested hillcrest is compared with that over a forested plane of the same tree density at the same height above the ground and at the same horizontal streamwise distance from the forest edge. It can be inferred that very large acceleration factors appear. The acceleration factor in-
creases with increasing stand density, indicating that the denser forest leads to a larger displacement effect. Figure 22 gives the acceleration factors for the three hill types investigated. For steeper hills, an increasing penetration of the flow into the forest canopy is registered as evidenced by the lower position of the “knee” in the curves in Figure 22. While for $L/H = 20$, the effect of the trees reaches almost $\Delta y/H = 1.6$, for $L/H = 5$, the effect of the trees is confined below $\Delta y/H = 0.5$. Increasing hill steepness also leads to higher acceleration factors; however, for the hills studied, this increase was not proportional to $H/L$ as predicted by the Jackson and Hunt (1975) theory and by potential theory.

In Figure 23, the deposition of ammonia as a function of streamwise distance is shown for the forested hill case $L/H = 5$. Each point in Figure 23 represents the average relative deposition to a jacket on a tree within the canopy (averaged through the canopy height). Despite some scatter in the mass transfer data, the deposition pattern over a single isolated forested steep hill is clearly seen. At the leading edge of the forest, a rise in deposition is observed according to the findings reported in the section before. After the edge, the deposition level tends to decrease; however, this decrease is compensated with increasing streamwise distance by the influence of the hill slope, yielding a rise in deposition level up to the top. After the separation on the lee side of the hill, deposition levels fall to a value $1/2$ to $1/3$ of those at hill top. The deposition is roughly constant after $x/H = 1$ in the main part of the separation. As can be seen from the streamlines in Figure 24, $x/H = 1$ corresponds to the start of the separation zone.
Fig. 23. Relative deposition levels over the forested hill $L/H = 5$, $a/K = 1.0$, $K = 5\, \text{cm}$, $H/K = 4$.

Fig. 24. Streamlines over the forested hill $L/H = 5$, $a/K = 1.0$, $K = 5\, \text{cm}$, $H/K = 4$.

6. Conclusion

The present study summarizes experimental investigations in a boundary-layer wind tunnel of flow behaviour in and around isolated trees, forest stands in flat
terrain and on hill sides. Despite some simplifications, which have to be made in modeling natural flows in a wind tunnel, basic flow phenomena could be resolved. The quantitative determination of mean velocity and turbulence data as well as the measurement of the correlations of velocity fluctuations in the flow fields investigated, allowed us to assess the deposition potential of single trees and extended flat and hilly forest stands. The results show that the measured turbulence level is strongly linked with the level of deposition. This could be verified both in model investigations and in real forest stands. For the plane forest, measured deposition levels were highest at the windward edge of the forest and fell with increasing streamwise distance. This pattern has been observed in nature and can be explained from velocity and turbulence data. For forest stands on hills, it was found that the hill steepness can compensate for the decrease of deposition with increasing streamwise distance from the edge. Depending on the slope of the hill, the deposition increases uphill, reaching a maximum at hilltop. For forested hills, the mean velocity and turbulence profiles were shifted vertically the order of a tree height by the forest cover. Denser stands led to a larger displacement. At the hilltop, the forest cover reduced the velocity at a given height when compared to the non-forested cases. This led to earlier separation of the flow and a thicker free-shear layer. Also for the forested hills, the deposition levels coincided with the level of turbulence measured at canopy height.

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References

ASPECTS OF THE POLLUTANT TRANSPORT TO CONIFEROUS TREES


