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Development of an improved physical modelling of a forest area in a wind tunnel

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Abstract

A new concept to model a finite forest area in a boundary layer wind tunnel is proposed. A specific arrangement of rings made from metallic mesh is used in order to reproduce the effect of trees on the atmospheric boundary layer. The comparison between field data and wind tunnel data of wind profiles through the canopy is satisfying and that justifies the use of this model concept to manufacture the model of the finite inhomogeneous forest area surrounding the Research Centre of Jülich (Germany), as guaranteed within the research project ECHO.

Keywords: Forest canopy; Porosity; Wind turtulence; Deciduous forest

1. Introduction

In the framework of the Emission and CHemical transformation of Organic compounds (ECHO) project, the transport of the biogenic volatile organic compounds (BVOC) inside and above a forest canopy is investigated. The aim is to determine the net source of reactive trace compounds supplied by a mixed forest stand. The chosen field site is the finite mixed forest area surrounding the Research Centre of Jülich (Germany). The emission rates of BVOC from a mixed forest stand needs to be quantified, the amount of primary emitted volatile organic compounds (VOC), which are transported directly into the planetary boundary layer and the amount of VOC, which are chemically processed within the canopy needs to be determined. Specialists with different competences, as biologists, chemists and meteorologists, were federated in that project to study these different questions. Methods of investigation use all available tools, to include field campaigns, laboratory experiments, numerical and physical modelling. The contribution to this project of the University of Hamburg is to design a model of the finite forest area and to study it in an atmospheric boundary layer wind tunnel. The flow properties and the transport of emissions inside and above the canopy are studied.

In order to reproduce the resistance to the wind generated by the trees while enabling an easy reproducibility of the model, an arrangement of opened rings made from metallic mesh was chosen. A comparable design was used by Beger (1983) to model a forest area but no further publications related to this set-up are available. In this study, a quadratic arrangement of metallic mesh was used. Hall et al. (1999) used some closed rings of metallic mesh to model high vegetation inside courtyards. Their choice was intuitive and the quality of the physical modelling was not tested.

The set-up chosen in the present study is not designed with respect to shape, drag coefficient or leaf area index (LAI) similarities between field and model. The strategy was to achieve the same aerodynamic properties of the inside and above canopy flow, as measured at the field site.

This paper presents the first test of this concept for homogeneous in height forest areas.

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2. The field site and the field experiments

The deciduous forest stand in Jülich is representative of a typical European forest area. It covers 350 ha and is located in a farmland-type region. The inhomogeneity in the distribution of tree species, of tree age and of tree height is significant. As a consequence, a careful tree inventory was carried out. The meteorological conditions are permanently recorded at the meteorological tower at seven stations located from 10 to 120 m above ground. In the framework of the research project ECHO, three additional measurement towers were built-up inside the forest in order to measure the meteorological conditions as well as the biogenic VOC concentrations inside and immediately above the forest canopy. The main tower is located in an area planted with oak and beech trees, which are 150 years old. The local average tree height is between 25 and 30 m and the local LAI is 3.6, which is considered as representative of a dense canopy.

The 10-min-average horizontal velocity and its standard deviation were measured at the main tower with ultra-sonic anemometers–thermometers during 2 h on the 13th of September 2000 at 5, 10, 17 and 30 m with a mean wind direction of 281° and a mean wind speed of $4.2\,\mathrm{m\,s^{-1}}$ measured at 30 m above ground. At the meteorological tower, the mean temperature gradient was determined between 20 and 120 m as −1.59°C/100 m. According to the terminology of the VDI-guideline 3782/1 (2001), the diffusion class during this experiment was 'C' in terms of Pasquill's classification scheme (Pasquill, 1974), denoted as 'neutral'. The forest fetch of the main tower for a westerly wind direction is 1400 m with the last 370 m covered with 25–30 m trees. These measurements are used to perform the comparison with the wind tunnel data.

3. The wind tunnel experiments

3.1. The forest area model

A specific arrangement of open rings made from metallic mesh was used to simulate the forest stand. The metallic mesh was made out of steel wires of diameter 0.4 mm and a mesh size of 2.8 mm. On the uppermost third of the ring height, the mesh was bent twice in order to decrease the local porosity, thus simulating the influence of the vegetation at the tree crown. The ring diameter was 2/3 H, with H ring height. Rings with five different heights, $H=$ 0.042, 0.058, 0.075, 0.092 and 0.108 m, were manufactured (Fig. 1). The rings were glued on five different plates (Fig. 2) with the arrangement described in Fig. 3. They covered an area of 1 m width and 1.4 m long.

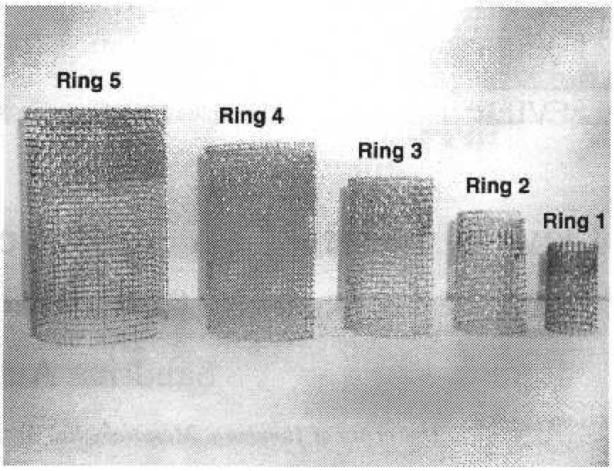

Fig. 1. Open rings made from metallic mesh of (from left to right) 0.108, 0.092, 0.075, 0.058 and 0.042 m high.

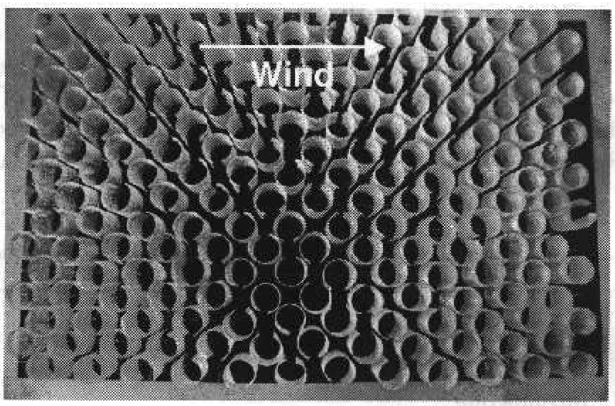

Fig. 2. 1 m × 1.4 m testing plate with rings of 0.108 m high.

3.2. The experimental set-up

Each plate was separately tested in the small boundary layer wind tunnel of the Meteorological Institute of the University of Hamburg, Germany. It is an open-circuit type with a test section of 1.5 m wide, 1 m high and 4 m long. The boundary layer development section that precedes the test section is 7.5 m long. Its floor was covered by roughness elements. The size and distribution of the roughness elements (Lego® pieces) fixed to the floor, as well as the design of the spires (1 m high) fixed at the entrance of the wind tunnel, controlled the properties of the induced boundary layer, approaching the edge of the forest area model. An adjustable ceiling covers the entire tunnel in order to compensate the longitudinal pressure gradient.

Flow measurements were performed with a 2D fibre-optic Laser-Doppler-Anemometer (FVA-LDA, Dantec®) with 500 mm focal distance. The flow was seeded with micro-particles of 2 μm diameter.

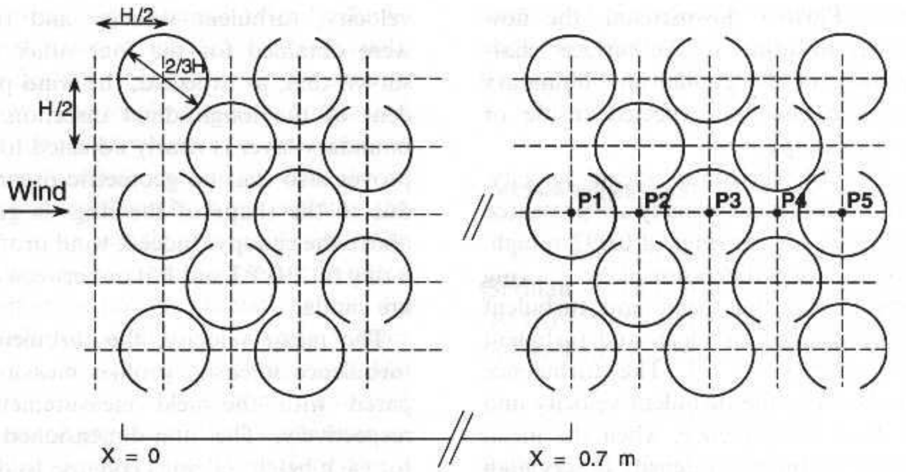

Fig. 3. Aspect ratio and arrangement of the metallic rings on the testing plate.

The coordinate system is such that X-axis is aligned with the wind direction, Y-axis is lateral and Z-axis is vertical ascendant. $X = 0$ is at the edge of the forest area model, $Y = 0$ in the middle of the forest area model and $Z = 0$ at the ground level.

3.3. *The modelled approach flow*

The surroundings of the studied finite forest area are farmlands and grasslands, which belong to *moderately rough* surfaces. Based on a compilation of field data, the German guideline VDI 3783/12 (2000) provides requirements for the proper modelling of the neutral atmospheric boundary layer up to a height of 100 m. The atmospheric boundary layer is replicated in the wind tunnel with a geometric scale of 1:300.

For moderately rough surfaces, the power law exponent should be between $0.12<\alpha<0.18$, the roughness length between $0.005<z_0<0.1$ m full-scale and the displacement height $d_0 \approx 0$. These ranges for α and z_0 subsequently parameterise the range of the turbulence intensity profiles.

The properties of the modelled boundary layer were checked at 0.5 m (150 m in full-scale) upstream of the edge of the forest area. The best fit to the measured wind profile with an exponential function was obtained with a power-law exponent $\alpha = 0.19$. The wind profile fits to a logarithmic function up to $z = 300$ mm (i.e. 90 m full scale). The extrapolation of the logarithmic law towards the zero-value of velocity gives the associated roughness length $z_0 = 0.34$ mm (i.e. 0.102 m full-scale). The ceiling of the wind tunnel section is adjusted in order to obtain a static pressure distribution in agreement with the tolerance threshold criteria recommended by the guideline VDI 3783/12 (2000):

$$\left(\frac{\partial p}{\partial x}\times\delta\right)\Big/\left(\frac{1}{2}\rho\times u_\delta^2\right)\leqslant 0.05, \tag{1}$$

where $\partial p/\partial x$ is the longitudinal pressure gradient, δ is the boundary layer thickness, ρ the density of air and u_δ the flow velocity at the top edge of the modelled boundary layer. As a consequence, the modelled boundary layer should have the properties of a surface layer (constant shear layer). Indeed, the vertical distribution of the shear stresses does not vary more than 10% up to $z = 200$ mm (i.e. 60 m full-scale). The friction velocity is estimated to be $u_* = 0.24$ m/s (i.e. $u_*/U_\delta = 0.048$ with U_δ horizontal velocity at the top of the boundary layer). The turbulence intensity profiles are enclosed within the ranges advised by VDI 3783/12 (2000) for a height up to $z = 300$ mm (i.e. 90 m full-scale).

4. The canopy flow—comparison between field and wind tunnel data

The approach boundary layer is fixed and has the properties of the atmospheric boundary layer replicated with a geometric scale of 1:300 while the testing plates are covered with different ring heights $H = 0.042, 0.058, 0.075, 0.092$ and 0.108 m. As a consequence, the testing plates replicate homogeneous forest areas with trees of 12.5, 17.5, 22.5, 27.5 and 32.5 m high, respectively.

Horizontal mean and turbulent velocity profiles, $U(z)$ and $u'(z)$, respectively, were measured, for each class of rings, at five different $H/2$-spaced longitudinal locations (see points P1–P5 in Fig. 3). The first location P1 is in the middle of the plate: $X = 0.7$ m, $Y = 0$, or $X/H = 16.7, 12.1, 9.3, 7.6$ and 6.5, respectively. These fetches do not ensure that the local flow measurements are representative of an equilibrium boundary layer developing on a very-rough surface (Irvine et al., 1997). On the other hand, Morse et al. (2002) showed that the major adjustments to the new surface take place up to $X/H = 4$ for the streamwise mean and fluctuation velocity, and up to $X/H = 5$ for the vertical fluctuation velocity and the shear stress. Farther downstream, the flow continues progressively to adjust to the surface, characterised by the growth of the equilibrium boundary layer, without dramatic changes expected inside or immediately above the canopy.

The vertical profiles of horizontal mean velocity, turbulent velocity and turbulence intensity are presented in Figs. 4a–c, respectively, for the rings of 0.092 m high. The vertical dimension is non-dimensioned by the ring height (or tree height) and the mean and turbulent velocities are non-dimensioned by mean and turbulent velocities measured at $z/H = 1.3$. The turbulence intensity is the ratio between the turbulent velocity and the mean velocity. As a consequence, when the mean velocity is very low, the turbulence intensity is very high and a small variation of mean velocity will lead to a large variation of turbulence intensity. This feature, visible inside the canopy at heights smaller than $z/H = 0.8$ should not be interpreted as a discrepancy between measurements. Similar profiles of horizontal mean velocity, turbulent velocity and turbulence intensity were obtained for the four other rings heights. It is shown that, as expected, the wind profiles are independent of the longitudinal direction, ensuring that the boundary layer is nearly adjusted to the new surface. It proves also that no geometric organisation of the flow due to the shape of the rings is generated inside and above the canopy. Indeed, wind profiles measured inside a ring (at P1, P3 and P5) or between rings (at P2 and P4) are similar.

The mean velocity, the turbulent velocity and the turbulence intensity profiles measured at P3 are compared with the field measurements in Figs. 5a–c, respectively. The non-dimensioned profiles measured for each height of rings collapse to one curve and are in agreement with the field data. The wind profiles are representative of a dense forest canopy (Gardiner 1994; Raupach et al., 1996), since the velocity is very low and nearly constant within the canopy and has a very strong gradient in the upper part of the canopy. The vertical

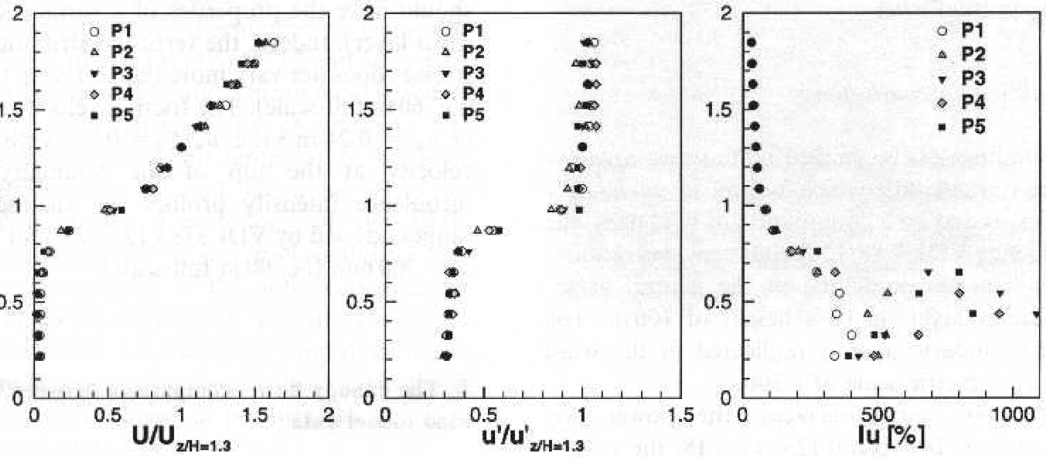

Fig. 4. Vertical profiles of horizontal mean velocity (a), turbulent velocity (b) and turbulence intensity (c) measured at five different locations ($X = 0.7, 0.7+H/2, 0.7+H, 0.7+\ 3H/2$ and $0.7+2H$) for the test plate covered with rings of $H = 0.092$ m high.

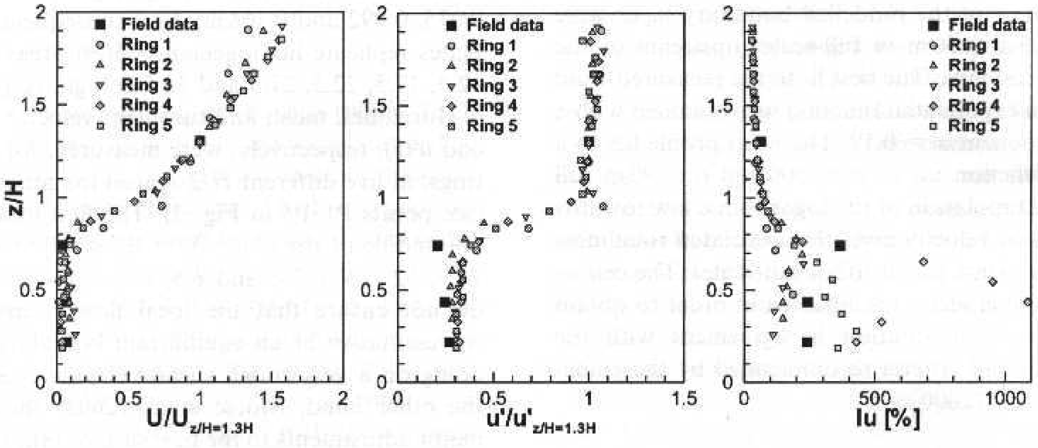

Fig. 5. Vertical profiles of horizontal mean velocity (a), turbulent velocity (b) and turbulence intensity (c) measured in the field and in the wind tunnel at P3 ($X = 0.7+H$), for the five different ring heights.

distribution of the horizontal turbulent velocity shows that the turbulence properties of the flow are completely different in the two distinct regions, inside the canopy and above the canopy. The inside region is dominated by the local effect of the forest whereas the one above is representative of an atmospheric boundary layer developing on a very rough surface. In both regions, the standard deviation stays nearly constant and the transition between these two states takes place between $0.85 < z/H < 1.1$. Despite the previous remarks about the lack of fetch to obtain an equilibrium boundary layer at the measurement locations, the constancy of the turbulent velocity profiles above the canopy up to $z/H = 2$, for all cases, tends to prove that the local boundary layer is already adjusted to the rough surface for a height up to $z/H = 2$.

5. Conclusion

The present study illustrates the possibility to simulate the flow inside and above a forest canopy using a specific arrangement of metallic mesh rings. The modelling concept enables one to reproduce the flow properties of a dense, to very dense, forest canopy without reducing the possibility to measure the flow field inside the canopy, as with tree shape-based modelling concepts. Furthermore, the vertical porosity heterogeneity (as most forests are) can be easily designed and manufactured. This preliminary study confirms that the model of the inhomogeneous and finite forest area of Jülich can be reasonably replicated using this modelling concept. With this complete model, the forest fetch features (length and tree height distribution) upstream of the measurement location will be reproduced, leading to a proper comparison with field data. Furthermore, the distribution of the non-streamwise velocities, the shear stress and the spectral content of the flow inside and above the canopy will be considered in order to enhance the validation of the modelling concept.

Acknowledgements

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