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Wind tunnel model of the forest and its Reynolds number sensitivity

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ABSTRACT

A newly designed reduced-scale forest model for Wind Engineering and forest meteorological wind tunnel studies is presented. The Reynolds number dependence of flow at the top of and above the forest canopy was investigated for simulated atmospheric boundary-layer flows with different free stream velocities. For the windward edge region, including a downstream distance of 5.7 tree heights, the flow field of the mean streamwise velocity was identified to be independent of the Reynolds number at $Re_h \geq 31{,}000$ (Re_h based on undisturbed approach flow velocity at canopy top) and at $Re_h \geq 50{,}000$ for further flow quantities (fluctuation velocity, Reynolds stress, vorticity, turbulence kinetic energy, shear production). The dependence for lower Reynolds numbers was attributed to differences in the structure of small-scale wakes arising from flow and separation in and at the top of the forest canopy and to a change in the ratio of bulk momentum of the flow in the forest canopy to that of the flow above in the free air region. The threshold Reynolds number $Re_{h,t}$ depends on the distance from the leading edge as long as the flow still adjusts to the forest canopy before reaching the equilibrium region, rather than being a fixed value.

1. Introduction

Wind tunnel studies of forest flows have gained increasing attention in the fields of Environmental Fluid Mechanics, Forest and Agricultural Meteorology, and Wind Engineering. Objects of investigation comprise general flow and turbulence characteristics in and around forest canopies (e.g. Bai et al., 2015; Chen et al., 1995; Conan et al., 2015; Marshall et al., 2002; Meroney, 1968, 1970; Morse et al., 2002, 2002; Novak et al., 2000; Ruck et al., 2012; Sadeh et al., 1971), wind forces in and storm stability of forest stands (e.g. Gardiner et al., 2005, 1997, Marshall et al., 1999, 2002; Stacey et al., 1994; Tischmacher and Ruck, 2013), exchange and deposition of scalar species and pollutants (e.g. Aubrun et al., 2005; Aubrun and Leitl, 2004; Conan et al., 2015; Coudour et al., 2016; Meroney, 1970; Ruck and Adams, 1991; Wuyts et al., 2008), and, more recently, wind energy-related issues (e.g. Desmond et al., 2017, 2014; Rodrigo et al., 2007). In these studies, the forest canopies were assembled of tree models with some emphasis on reflecting real trees' morphological features and aerodynamic characteristics.

The forest models employed in Meroney (1968, 1970) were built up of single model trees made of plastic simulated-evergreen boughs. Validation of the setup was done by comparing the drag coefficients and typical wake characteristics of the model trees and real trees. Stacey et al. (1994), Gardiner et al. (2005, 1997), Marshall et al. (2002, 1999) and Morse et al. (2002) realized a reduced-scale forest by means of tree models which were aerodynamically and structural-dynamically scaled. The trees were made of injection-molded Nylon stems and low-density polyethylene branch elements attached to match an overall tree shape and to obtain a designated drag coefficient and sway frequency. In the wind tunnel study by Chen et al. (1995), the forest model consisted of flexible tree models. Plastic stripes of defined surface area, modeling the foliage, were mounted radially at two interwound steel wires forming the tree trunk. The approach allowed to simulate a defined leaf area index or density distribution. Aubrun and Leitl (2004), Aubrun et al. (2005), Conan et al. (2015), and Coudour et al. (2016) used an arrangement of opened rings made from metallic meshes to model a forest canopy. The similarity of the tree models was based on reproducing the leaf area density distribution of real trees. Bai et al., (2015) employed a pre-fractal tree model (5 generations) in water flume experiments to mimic a small forest canopy consisting of 12 trees. The pre-fractal morphology was chosen to reflect the multi-scale characteristics of tree elements.

Furthermore, there are numerous studies where forest canopy models with less level of detail in terms of tree morphology were deployed. Rods, stalks, stripes, slender plates or cylindrical elements, either stiff or flexible, arranged in regular patterns or randomly were used to model forest, or more generally, vegetation canopies (e.g. Neff and Meroney, 1998; Poëtte et al., 2017; Poggi et al., 2004; Raupach et al., 1996). In general, these models have a homogeneous structure in wall-normal direction and do not account for variations in vegetation elements/material or

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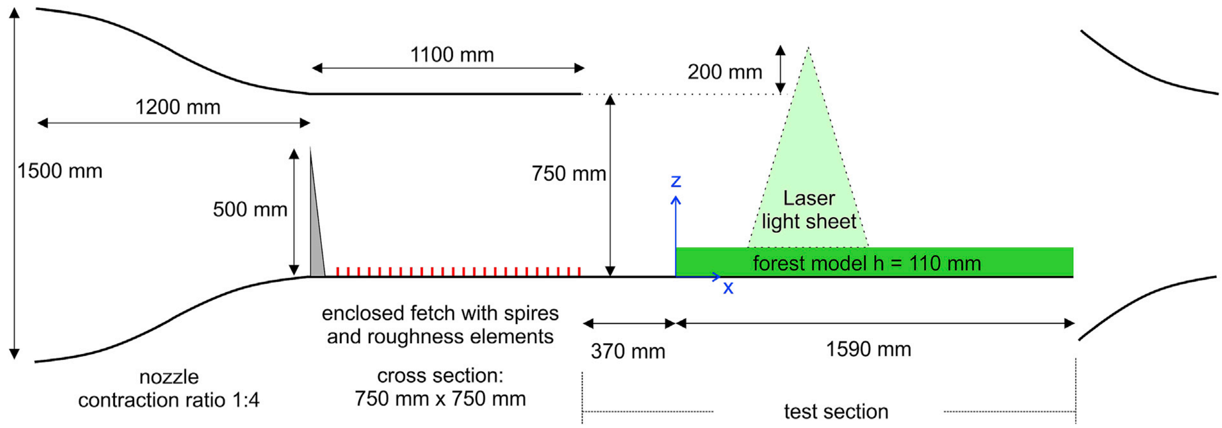

Fig. 1. Dimensions and experiment setup in the Goettingen-type wind tunnel.

morphological differences with height over ground such as the clustering of vegetation elements in the crown. Furthermore, they are no specific forest models but rather considered as vegetation canopy models, mimicking both forest or crop canopies. They are often justified by the authors based on a similarity in frontal and/or surface area index with real forests or crops.

The various forest modeling concepts, including the differences in the manner and level of detail of mimicking morphological features and geometric indices, the different criteria for similitude, partly only referencing to geometric similarity and neglecting kinematic and dynamic similarity, and the various approaches to validation and comparison, indicate that no standardized or widely spread modeling concept exists. This is partly due to the broad scope of questions and topics with regards to forest flows which allow for and even require different modeling concepts. However, this is also partly due to a lack of knowledge and experience concerning the modeling of reduced-scale forest models related to geometric (morphological), kinematic and aerodynamic similarity. Moreover, in comparison to most reduced-scale Wind Engineering studies where flows around bluff and sharp-edged bodies are pivotal, a profound knowledge of the Reynolds number dependence of vegetation flows is missing. For bluff body aerodynamics, the flow field is usually considered to be Reynolds number independent if the obstacle Reynolds number exceeds 15,000, but depending on the topic of interest, higher or lower threshold Reynolds numbers may be applicable. Studies on pollutant dispersion report lower values for selected geometries, see e.g. Snyder (1972) or Meroney (2004) and references therein, whereas for the pressure distribution at the roof of a sharp-edged cube, a Reynolds number sensitivity up to $Re = 50.000$ was found (Költzsch et al., 1997). However, no systematic investigations have yet been performed on the Reynolds number sensitivity with reduced-scale forest or vegetation models and no reference values for threshold Reynolds numbers have been established for reduced-scale modeling of vegetation flows.

In this study, a forest modeling concept for use in reduced-scale wind tunnel investigations is presented. The purpose of the model is to enable the investigation of flow and dispersion processes occurring in the forest crown layer and in the region above. Section 2 introduces the forest modeling concept, detailing aspects of geometric (on a morphological level) and aerodynamic similarity. In Sect. 3, flow field data obtained using the forest model are presented and discussed. Particular emphasis is laid on the kinematic similarity and the Reynolds number sensitivity of flows past the reduced-scale forest model. A summary and conclusions are provided in Sect. 4.

2. Materials and methods

2.1. Experiment setup and measurement technique

The experiments were performed in the open test section of a closed-circuit Goettingen-type wind tunnel. 5 Irwin-type spires (Irwin, 1981) and ground-mounted roughness elements were installed in an enclosed fetch section windward of the open test section to generate a scaled atmospheric boundary layer flow (Fig. 1). The Irwin-type spires had a height of 500 mm, a front face base-width of 50 mm and were spaced 150 mm apart from each other. The array of ground-mounted roughness elements had a frontal area index (roughness element frontal area to total ground area, aka roughness density) of 0.05, a basal area index (roughness element basal area to frontal area) of 0.4 and ended up 370 mm in front of the forest model.

In order to study the Reynolds number sensitivity of the flow past the forest model, atmospheric boundary layer approach flows of various free stream velocities U_δ were realized. The experiment series comprised 9 experiments spanning a Reynolds number range from $Re_h = 3500$ to 71,300 where $Re_h = U_h h/\nu$ with U_h being the approach flow velocity at forest model top $h = 0.115$ m at a distance 1 h in front of the windward forest edge and ν the kinematic viscosity of air, $\nu = 1.5 \cdot 10^{-5}$ m^2/s. Further details on the simulated approach flows are provided in Table 1.

Particle Image Velocimetry (PIV) measurements were performed to determine flow velocities with a planar, two-component (2D/2C) PIV system (Adrian, 1991; Adrian and Westerweel, 2011; Raffel et al., 2007; Westerweel, 1997; Westerweel et al., 2013). The system consisted of a high-speed CMOS sensor of 1280×800 pixel resolution (pixel size $= 20 \times 20$ µm^2) with a Zeiss Planar T*1.4/50-mm ZF lens and a pulsed dual-cavity, frequency-doubled Nd:YAG laser with a nominal energy of 14 mJ per pulse at a frequency of 1000 Hz in Q-switch mode configured by Dantec Dynamics (Dantec Dynamics, 2013). Seeding of the flow was done by vaporization and condensation of a fog fluid (type: Heavy Fog) which produced tracer particles of diameter 1–2 µm.

Measurements were made in the streamwise-oriented spanwise-central vertical plane (x-z) in two fields of view (FoV) covering the forest edge region and a windward part from $-1.1 \le x/h = x^+ \le +5.7$, see e.g.

Table 1
Experiment series and approach flow characteristics.

exp. no.	1	2	3	4	5	6	7	8	9
U_δ [m/s]	1.0	2.0	4.0	6.0	8.0	10.0	12.0	15.0	18.0
U_h [m/s]	0.5	1.0	1.9	2.9	4.0	5.1	6.5	7.9	9.3
Re_h [−]	3500	7700	14,700	22,300	31,000	39,300	50,000	60,600	71,300