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CFD modelling and wind tunnel validation of airflow through plant canopies using 3D canopy architecture

A. Melese Endalew [a,*], M. Hertog [a], M.A. Delele [a], K. Baetens [a], T. Persoons [b], M. Baelmans [b], H. Ramon [a], B.M. Nicolaï [a], P. Verboven [a]

[a] Faculty of Bioscience Engineering, BIOSYST – MeBioS, Katholieke Universiteit Leuven, Willem de Croylaan 42, B-3001 Leuven, Belgium
[b] Applied Mechanics and Energy Conversion Section, Department of Mechanical Engineering, Catholic University of Leuven, Celestijnenlaan 300A, B-3001 Leuven, Belgium

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ABSTRACT

The efficiency of pesticide application to agricultural fields and the resulting environmental contamination highly depend on atmospheric airflow. A computational fluid dynamics (CFD) modelling of airflow within plant canopies using 3D canopy architecture was developed to understand the effect of the canopy to airflow. The model average air velocity was validated using experimental results in a wind tunnel with two artificial model trees of 24 cm height. Mean air velocities and their root mean square (RMS) values were measured on a vertical plane upstream and downstream sides of the trees in the tunnel using 2D hotwire anemometer after imposing a uniform air velocity of 10 m s^{-1} at the inlet. 3D virtual canopy geometries of the artificial trees were modelled and introduced into a computational fluid domain whereby airflow through the trees was simulated using Reynolds-Averaged Navier–Stokes (RANS) equations and k-ε turbulence model. There was good agreement of the average longitudinal velocity, U between the measurements and the simulation results with relative errors less than 2% for upstream and 8% for downstream sides of the trees. The accuracy of the model prediction for turbulence kinetic energy k and turbulence intensity I was acceptable within the tree height when using a roughness length (y_0 = 0.02 mm) for the surface roughness of the tree branches and by applying a source model in a porous sub-domain created around the trees. The approach was applied for full scale orchard trees in the atmospheric boundary layer (ABL) and was compared with previous approaches and works. The simulation in the ABL was made using two groups of full scale orchard trees; short (h = 3 m) with wider branching and long (h = 4 m) with narrow branching. This comparison showed good qualitative agreements on the vertical profiles of U with small local differences as expected due to the spatial disparities in tree architecture. This work was able to show airflow within and above the canopy in 3D in more details.

1. Introduction

The problem of measuring airflow in canopies has been a major issue for experimental analyses (Gross, 1987) because it is difficult and expensive to perform. For the past years several numerical approaches have been developed as a possible solution to address the experimental problem. The most widely used numerical approach to model airflow within and above plant canopies is the averaging procedure adopted by Wilson and Shaw (1977), Raupach and Shaw (1982) and Xu et al. (1997), in which the transport properties of air are averaged over a small lumped volume of the plant to remove flow details associated with individual elements. Even so, the strongly complex three-dimensional, inhomogeneous and turbulent nature of the flow within plant canopy structures and poor understanding of their interactions limited the accuracy of the prediction. Especially the modelling of the interaction between injected spray particles, airflow and the target plant canopy are far more difficult.

In the averaging procedure, there are two methods for considering the effect of the plant canopy on the airflow (Gross, 1987). In the first method the influence of trees on airflow and its turbulence is represented by closure models through additional drag force terms in the momentum and turbulence model equations. This drag force is parameterized using leaf drag area, A (m^{-1}), the dimensionless drag coefficient, C_d and sheltering factor, Sf (e.g. Wilson and Shaw, 1977; Marcolla et al., 2003). In this method A is the important parameter that determines the effects of the canopy on airflow. This parameter must be given as a three-dimensional (3D) function but only a vertical profile is usually known for different types of trees; thus this method is not always applicable (Gross, 1987). In the second method, with knowledge of the volume, V and part of it filled with leaves and branches, V, the volume poros-

* Corresponding author. Tel.: +32 16 32 23 76; fax: +32 16 32 29 55.
E-mail addresses: ayenew.melese@biw.kuleuven.be, ayenewm@yahoo.com (A.M. Endalew).

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Nomenclature

A	plant area density (m^{-1})
C_d	drag coefficient
C_n	effective drag coefficient (m^{-1})
h	height of the trees (m)
I	turbulence intensity (%)
k	turbulence kinetic energy ($m^2\,s^{-2}$)
p	average pressure (Pa)
P	porosity
R_{ij}	Reynolds stress tensor ($m^2\,s^{-2}$)
S_ε	source term for ε ($kg\,m^{-1}\,s^{-4}$)
S_k	source term for k ($kg\,m^{-1}\,s^{-3}$)
S_u	momentum source term ($kg\,m^{-2}\,s^{-2}$)
U	average longitudinal velocity ($m\,s^{-1}$)
u^*	friction velocity in the ABL ($m\,s^{-1}$)
U_{in}	inlet air velocity ($m\,s^{-1}$)
u'_i, u'_j	fluctuating velocity components ($m\,s^{-1}$)
u_i, u_j	component air velocity in x, y and z directions ($m\,s^{-1}$)
V	total volume of a sub-domain (m^3)
V_0	part of the volume filled with leaves and branches (m^3)
x_i, x_j	Cartesian coordinates (m)
y	vertical coordinate axis (m)
y_0	roughness length (m)
y^+	dimensionless wall coordinate
ε	eddy dissipation ($m^2\,s^{-3}$)
κ	Von Karman constant
ρ	density of air ($kg\,m^{-3}$)
μ	dynamic viscosity ($kg\,m^{-1}\,s^{-1}$)
μ_t	turbulent viscosity ($kg\,m^{-1}\,s^{-1}$)
δ_{ij}	the Kronecker delta
α	an attenuation coefficient

Subscripts

i, j	Cartesian coordinate index
ε, k, u	index for the source terms

ity is defined as $P = (V - V_0)/V$ whereby a weighted drag based on tree foliage density is used. However, this method also needs 3D information of the parameter P, which usually is available as single term, which limits its applicability.

In nearly all of these models horizontal homogeneity, neutral stratification and steady state conditions of the canopy structures are assumed (Wilson and Shaw, 1977; Meyers and Paw, 1986; Gross, 1987; Wilson, 1988; Ayotte et al., 1999). Even in some cases plant canopy on the ground surface is considered as a horizontally uniform bottom boundary and the influence can be imposed through the boundary roughness in which the role of the complex canopy structure on turbulent airflow around it was oversimplified (Ni, 1997). However, a natural vegetation canopy consists of an assortment of element types (branches, leaves, fruits or seeds, etc.) exhibiting a range of shapes and sizes. Furthermore, such elements are not homogeneously distributed throughout the stand but tend to be clustered and show varying density. Many of these characteristics are not treated in these models because of the complexity and the need for economy in the numerical computations. In addition to the lower accuracies (Zeng and Takahashi, 2000) due to the assumptions, the independent estimation of the three canopy parameters (A, C_d and Sf), specifically lack of any available experimental method to estimate the last two parameters is a major problem in the applications of turbulence closure models (Marcolla et al., 2003) in canopy flow. A compact tractor-mounted light detection and range (LIDAR) system used for calculating tree area density has been reported to be less suitable to crops with much smaller gap dimensions (e.g. high-density citrus trees and cereal crops) without improving the transmitter/receiver beam profile (Walklate et al., 2002).

Katul et al. (2004) indicated that second and higher order closure models are still computationally expensive and require complex numerical algorithms for three-dimensional transport problems, especially if multiple scalar species must be treated. The drawbacks and limitations of first and higher order closure models (Kaimal and Finnigan, 1994; Shaw, 1977; Wilson, 1989; Ayotte et al., 1999) and that of conventional gradient-diffusion theory (K-theory) and the transilient turbulence theory (T-theory) that have been used to study the turbulent airflow within and above plant canopy have been shown by Ni (1997), Katul and Albertson (1998) and Zeng and Takahashi (2000).

With the recent rapid advances in the speed and capacity of computers it is possible to handle complex computational models involving complex geometries, in relative ease, with reasonably short time and at fairly low computational cost. In recent years, several approaches have been developed to describe the geometric structure of plants in 3D. Some of them include structural models (Godin, 2000), functional structural models (e.g. L-systems) (Prusinkiewicz and Lindenmayer, 1996; Sievänena et al., 2000) and visualization and digitization methods (Sinoquet et al., 1997; Costes et al., 1999). No matter how much accurate methods of simulating the 3D architecture of plants are available, little or no efforts were made to link the 3D architectures of the trees with CFD to simulate air and particle or pollutant transport through the canopies.

The objective of this work was to model airflow through plant canopies by introducing a detailed 3D architecture of the canopy into CFD software and to validate the model using wind tunnel experimental results and compare with previous works and approaches. The validation was mainly based on average velocity before and after the canopies. The numerical part has two parts; (1) simulation for the wind tunnel experiment using scaled model trees, and (2) simulation in ABL using full scale trees. In its present stage this modelling is based on the numerical integration of airflow through two leafless canopies (worst case scenario for drift prediction). The model is intended to represent row planted orchard field through the use of cyclic and periodic simulations considering symmetry along the row of row planted orchard field.

2. Wind tunnel experiment

2.1. Wind tunnel

Wind tunnel experiments were carried out at the Applied Mechanics and Energy Conversion Section, Department of Mechanical Engineering of the Catholic University of Leuven. An open circuit blower type wind tunnel, which is designed to generate a uniform inlet air velocity, was used (Fig. 1). Upstream of the test section is a centrifugal blower (1), a diffuser (2), honey comb screens (3) to reduce turbulence or mean velocity variations, a settling chamber (4) and a contractor (5). Its test chamber (6) has internal dimensions of 40 cm height, 50 cm width and 200 cm length (Fig. 2). The four long sides of the test chamber were made from transparent Plexiglas. One side of the chamber was the air inlet and its opposite side was an outlet. Two scale model trees were placed at the centre of the wind tunnel test chamber as shown in Fig. 2. The trees were placed 15 cm apart from each other.