Turbulent flows interacting with varying density canopies

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Résumé :

Il est maintenant bien connu que les écoulements au travers de couverts végétaux denses et homogènes sont semblables à des écoulements de couche de mélange. C'est ce qu'on appelle l'analogie de couche de mélange. Quand le couvert devient moins dense, une transition se produit : on passe d'un écoulement de couche de mélange à celui d'une couche limite plus ou moins perturbée par l'interaction entre les sillages des éléments du couvert. Un travail expérimental a été développé afin de comprendre et caractériser cette transition dans des couverts de densité variable.

Abstract :

In the case of dense and homogeneous canopies, it is well-known that canopy flows are similar to mixing layer flows (so-called mixing layer analogy). When the canopy becomes sparser, a transition between the mixing layer and the boundary layer perturbed by interactions between element wakes occurs. This transition has still to be fully understood and characterized. An experimental work has been developed in order to study this transition for various density canopies.

Mots-clé : turbulence, écoulement de couvert, densité du couvert, hétérogénéité spatiale

Keywords : turbulence, canopy flow, canopy density, spatial heterogenity

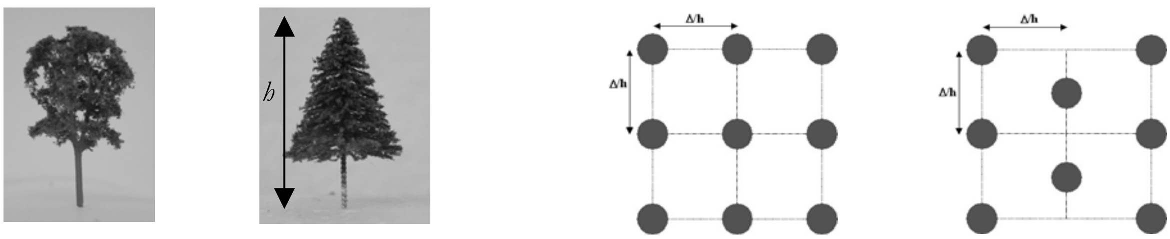
1 Introduction

In the current context of environmental preservation and air quality control, it is important to understand and characterize canopy flows such as those developing over urban areas [1, 2, 3] or natural vegetation [4, 5]. Vegetation canopies and urban canopies can be differentiated by considering the ratio of the shear length scale and the canopy height [6]. Urban canopies are qualified as shallow (ratio~1) whereas vegetative canopies are deep (ratio <<1). While flows through canopies have been extensively studied [5], there are a few works related to flows through sparser canopies. It is very well-known now that canopy flow behavior follows the mixing layer analogy when canopies are relatively dense [7, 4] . This feature has been proved for rigid canopies as well as for flexible ones [8]. But the mixing-layer analogy is only acceptable for relatively dense and homogeneous canopies [5]. When the vegetation density decreases, the canopy flow characteristics evolves from the mixing layer towards a standard boundary layer which is more or less perturbed by isolated canopy elements. A quick overview of literature data underlines the point that turbulent flows through low density canopies have not been studied thoroughly yet. Therefore, the objective of the present study is to identify parameters which govern the transition from the mixing layer flow to the boundary layer flow perturbed by wake interaction in canopies of low density.

2 Experimental facility

The experimental work is developed in a wooden-made open wind tunnel (15 m long). The working section is 5 m long with a square section (0.46×0.56 m^2). The floor slope is adjustable to maintain a zero pressure gradient boundary layer in every configuration (boundary layer or canopy flow). Holes, 0.025 m regularly spaced, were drilled in the last 2 m section of the floor to receive canopy elements. The canopy covers an area of 2×0.56 m^2 and the ratio of the tree height h to the section height is 1:9. Velocity measurements are performed by laser Doppler velocimetry (LDV, one-component and two-component systems) and particle image velocimetry (PIV). These techniques are well-suited for exploring flows through canopies, particularly in the region of the interaction between tree wakes where turbulence intensities can attain values significantly greater than 30%. In order to minimize laser reflection, walls of the working section have been painted black. Seeding is provided by four perfume diffusers feeding a perforated grid placed at the wide angle diffuser inlet of the wind tunnel before the settling chamber. It is performed with olive oil droplets whose mean diameter has been checked by phase Doppler anemometry to be around 1 µm. For LDV measurements, statistical moments are calculated from at least 10000 samples. Convergence of statistical moment calculations is then largely confirmed to within 1% for the two first moments and 6% for cross-moments. For PIV measurements, 3400 images are acquired and 1700 fields are computed. Statistical moments up to the second order, including cross-moments, are calculated. 1000 processed fields are needed to warrant the convergence of the two velocity first moments within 2% while 1400 processed fields are needed for cross-moment convergence within 5%.

The canopy is made of a variable number of artificial coniferous or round trees (Fig. 1a-1b). The tree mean height *h* is 0.05 m. Stems and trunks are metal. Stems are flocked with a fine green foam representing needles or leaves. Trees can be disposed on the wind tunnel floor following two different schemes: an alignement or a staggered scheme (Fig. 1c-1d). The roughness density λ of the canopy is based on the conical form of coniferous trees and it is estimated from image analysis for round trees. λ depends on the type of tree, on the element spacing and on the ground arrangement (Tab. 1). Three spacings Δ have been chosen: 0.05 m, 0.075 m and 0.1 m or, in terms of tree height: *h*, 1.5*h* and 2*h*. In the staggered case, only two spacings are possible: *h* and 2*h*.



(a) Round tree (b) Coniferous tree (c) Alignment (d) Staggered arrangement

FIG. 1 – Canopy element (a,b) and spatial ground arrangement (c,d)

Although spatial averaging is recommended for analysing global turbulence characteristics of canopy flows, local data are generally presented in this paper in order to highlight the variability of the turbulence properties within the canopy and to analyse in detail the similarities and differences between the staggered configuration and the alignment.

	Δ/h	λ		u^* (m.s^{-1})		u^*/U_h	
							
alignment case	1	0.48	0.22	1.14	0.9	0.26	0.12
	1.5	0.2	0.09	0.89	0.8	0.1	0.09
	2	0.13	0.06	0.74	0.65	0.07	0.05
staggered case	1	0.46	0.21		1.05/1.26		0.16/0.19
	2	0.12	0.06	1.08	0.9	0.19	0.11

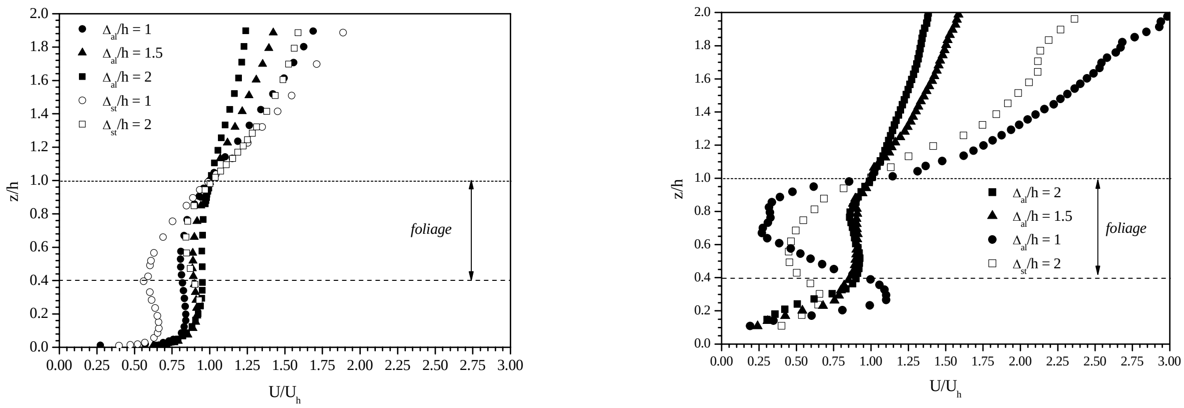
TAB. 1 – Roughness density (λ), friction velocity (u^*), ratio of u^* and the mean velocity taken at $z = h$ (U_h) for each canopy configuration

3 Influence of the canopy density and spatial ground arrangement

3.1 Mean longitudinal velocity profiles

Figure 2 displays the vertical evolution of the mean longitudinal velocity for conifer canopies (Fig. 2a) and round tree canopies (Fig. 2b) for different element spacings and for both ground arrangements. Profiles obtained from PIV measurements (Fig. 2b) are spatially averaged along the longitudinal direction. In the lowest part of the canopy, a mean velocity secondary maximum occurs for all considered cases but it is relatively weak for the sparsest aligned canopies. This secondary maximum is sometimes mentioned [9, 10, 11] and is due here to the empty space under the foliage.

Near the top, the profile gets more and more inflectional as the canopy density increases. The existence of an inflection point at the canopy top, $z = h$, in the mean longitudinal velocity profile is a first clue for the mixing layer analogy. For the aligned canopy, the inflectional region tends to disappear when the canopy becomes sparser, resulting in an increase of the shear length scale associated to the velocity field. Velocity profiles are more inflectional in staggered canopies. The ground arrangement of the roughness elements seems to play a more dominant role with regard to the mean velocity field than the canopy roughness density, the latter not varying from one configuration to the other for the same spacing (see Tab. 1).



(a) Coniferous tree canopies (LDV measurements) (b) Round tree canopies (PIV measurements)

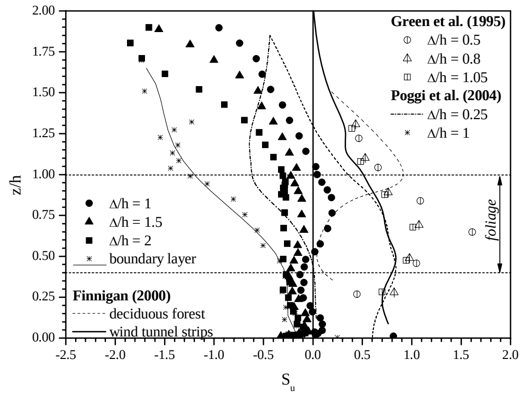
FIG. 2 – Vertical profiles of the mean longitudinal velocity for all canopy densities and both configurations

3.2 Skewness profiles

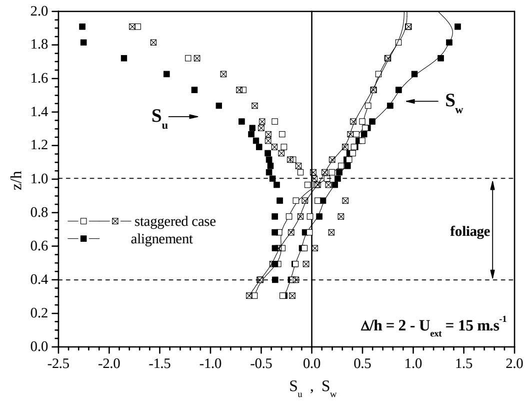
The third moment of velocity fluctuations is an interesting characteristic of canopy flows. The skewness $S_u = \overline{u^3} / \overline{u^2}^{3/2}$ highlights the presence of large extreme fluctuations and the departure from a symmetric Gaussian-like distribution of fluctuations. When Δ/h decreases, the skewness of the velocity longitudinal component S_u inside the aligned canopy evolves from being negative towards being slightly positive (Fig. 3a). The largest positive values remain however smaller than the positive values observed in real canopy flows [5, 11]. The influence of canopy density is more marked than for previous studies [11,12] since the skewness sign changes with spacing. Green's skewness values remain strongly positive, even for the sparsest canopy, while Poggi's tend only towards zero except in the half upper region of the canopy where the values decrease to -0.5. Under every spacing configuration, the skewness recovers, outside the canopy, negative values that are typical of a boundary layer, in agreement with other canopy measurements in wind tunnel (except Finnigan's data [5]) and hydraulic channel [12]. For natural canopies [5, 11], it is likely that measurements have not been performed far enough above the vegetation top to allow the flow to recover its external characteristics.

The ground geometrical arrangement of the canopy appears to play an important role although the canopy density is the same considering a same spacing. For Δ/h = 2 for instance (Fig. 3b), the skewness is negative inside the aligned canopy while it is strictly positive under the staggered configuration inside the foliage region. The skewness value increases with canopy density, reaching value as high as 0.75 inside the staggered canopy (not shown here). The canopy turbulence is thus strongly influenced by the ground arrangement.

The skewness of the velocity vertical component $S_w = \overline{w^3} / \overline{w^2}^{3/2}$ takes negative values inside the canopy foliage (Fig. 3b). S_u and S_w evolve with opposite signs in agreement with literature review [5] indicating an incursion of the fluid from the external layer.



(a)



(b)

FIG. 3 – Vertical profiles of velocity skewness, conifer canopies (a) longitudinal velocity; aligned arrangement (b) velocity longitudinal and vertical components; both spatial arrangements

3.3 Shear length scales

The shear length scale L_s is deduced from the mean longitudinal velocity profile at the vertical position $z = h$:

$$\frac{L_s}{h} = \frac{1}{h} \frac{U_h}{\left(\frac{\partial U}{\partial z} \right)_h} \tag{1}$$

This scale controls turbulence length scales in canopy flows and corresponds to the half vorticity scale in mixing layers [4]. It is a measure of the shear strength: stronger the shear, smaller the shear length scale.

	Δ/h	**L_s/h**		**[11]**		**[13]**	
				λ	L_s/h	λ	L_s/h
alignment case	1	0.34	1.4	1	0.45	1.4	0.44
	1.5		2.2	0.5	0.66	0.54	0.66
	2	1.6	3.9	0.25	0.7	0.24	0.87
staggered case	1		0.9				
	2	0.3	1.9				

TAB. 2 – Shear length scales (L_s/h) calculated at $z = h$ for each canopy configuration

L_s/h decreases when canopies become denser and takes its smallest values for the staggered canopy case (Tab. 2). Moreover, when the canopy density is high as for round tree canopies, the shear is stronger.

The shear length scale for the $\Delta/h = 1$ alignment arrangement is relatively similar to that obtained for the $\Delta/h = 2$ staggered arrangement for both types of canopy. The staggered configuration seems to break more easily large structures than the alignment configuration although the tree spacing of the former configuration is twice the latter. This remark underlines the main influence of the geometrical arrangement of the canopy.

Table 2 provides also some results obtained by Green et al. [11] in natural orchards and Novak et al. [13] in staggered artificial canopies (artificial Christmas tree branches). The scales we calculate from our data are slightly larger than theirs. This is mainly due to larger canopy densities in our experiment.

4 Conclusion

The canopies studied in this paper are characterized by low densities and then can be qualified as sparse canopies. The presented results complete consequently our knowledge of canopy flows since sparse canopies have been a little studied until now.

It seems that the ground arrangement of the canopy plays an important role on the turbulence development of a canopy flow. When its density increases, characteristics for a staggered canopy evolve towards those of a mixing layer more than for an aligned canopy. For a same canopy density, the ground arrangement of the canopy would have to affect the canopy drag coefficient. A more significant parameter to analyse would be then the product $c_d a h$ where c_d is the drag coefficient and a the leaf area density as introduced by Nepf et al. [14]. Indeed, if $c_d a h < 0.04$, the flow could be considered as a boundary layer without inflexion point whereas the inflexion point would be very pronounced if $c_d a h > 0.1$.

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