ROUND, VERTICAL, TURBULENT, NON-BUOYANT JETS IN VEGETATED CHANNELS

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ABSTRACT

Since a lack of data concerning ambient boundary effect on jet behavior was observed, the present study was conducted in order to obtain further understanding of the effects of a vegetated bed channel on a round non-buoyant jet discharged vertically into a crossflow. To achieve this, several experiments were carried out in the hydraulic laboratory of the Water Engineering and Chemistry Department of the Technical University of Bari (Italy). The hydrodynamic features of the jet were studied with details from turbulence statistical analyses (e.g. velocity field, turbulence intensity, Reynolds stresses, and dissipation rate). It was found that background turbulence, generated by vegetation, strongly affects jet behavior, i.e. the jet turbulence structures become more complex and the jet penetration height, dilution, and spreading increase significantly.

INTRODUCTION

In recent years a large number of experimental studies and models on turbulent jets discharged into a crossflow have appeared in literature. These studies (e.g. Rajaratnam, 1976; Fischer et al., 1979; Davies and Valente Neves, 1994; Papanicolaou and List, 1988) have taken into consideration different jet characteristics (e.g. nozzle shape, dimensions, submerged port height, flow rate, orientation, etc.) and those of the ambient flow (flow regime, depth, density stratification, stagnation, wave motion, etc.). However, these studies (e.g. Mossa, 1998; Mossa, 2004a and 2004b; Ben Meftah et al., 2004a and 2004b; Cuthbertson et al., 2006) have revealed a lack of data concerning the ambient boundary effect on jet behavior, especially in the context of a vegetated bed channel.

Several studies have been conducted to investigate the interaction between currents and vegetation (e.g. Nepf et al., 1997; Nepf, 1999). It was observed that the presence of vegetation, in main channels, strongly affects the flow turbulence structures (Nezu and Nakagawa, 1993). The vegetative effects vary with the flow depth, the degree of submergence, the nature, the density and the distribution of the vegetation.

EXPERIMENT SET-UP

The experimental runs were carried out in a smooth horizontal rectangular channel in the Hydraulic Laboratory of the Water Engineering and Chemistry Department of the Technical University of Bari (Italy). The channel is 25.0 m long, 0.40m wide and 0.50 m deep. The lateral walls and the bottom surface of the channel were constructed of Plexiglas, as shown in Figure 1.

Figure 1. General view of the laboratory channel

The outlet and the inlet structures of the channel were connected to a hydraulic circuit, allowing a continuous re-circulation of stable discharges. The channel is equipped with a series of stilling grids and a side-reservoir spillway with adjustable height in order to maintain a constant and uniform water head. In addition, it is equipped with two movable gates (made of Plexiglas), placed at the inlet and the outlet of the channel, in order to regulate, respectively, the channel flow rate and depth. At the downstream end of the channel, water is intercepted by a rectangular reservoir which is 3.0 m long, 1.0 m wide and 1.0 m deep, equipped with a triangular weir (V-notch sharp crested weir) to measure the channel flow rate.

To simulate vegetation stems, arrays of rigid circular cylinders, made of steel, were used. The lateral surface of the circular cylinder was rough. The stem height, h, and diameter, d, are 0.31 m and 0.003 m, respectively. The stem extremities were inserted into a plywood plaque of 3.00 m long, 0.398 m large and 0.02 m thick, which in turn is fixed along the channel bottom forming the experimental area. In order to reduce the effect of the plywood plaque thick on the experimental area, two other plywood plaques, without vegetation stems of 3.00 x 0.398 x 0.02 m dimensions, were attached to the channel bottom at both the upstream and the downstream side of this area. Stems were spaced longitudinally and transversally, with the same distance ΔS of 5 cm, so that the stem density, n, is 400 stem/m^2 (Figure 2).

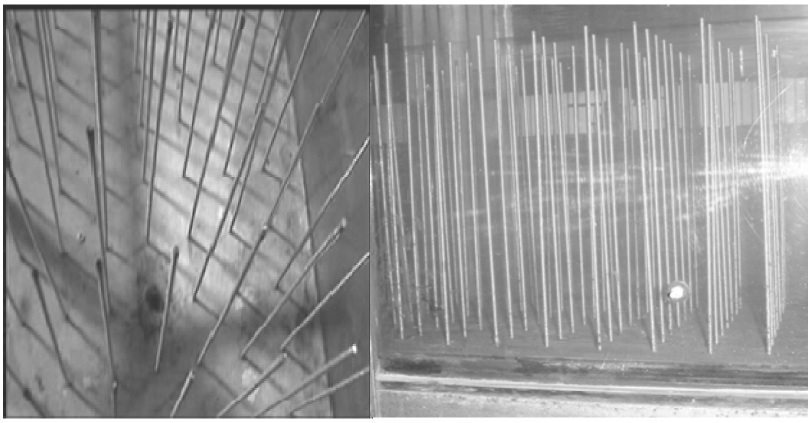

Figure 2. Laboratory channel with artificial vegetation canopy

The jet source was placed at the center of the experimental area, 15.0 m and 0.20 m far from the inlet and the side-walls of the channel, respectively. It consisted of a circular metallic pipe with a diameter, D, of 0.002 m. The jet axis was perpendicular to the horizontal channel bottom and discharged toward the channel water surface. The jet port height, from to the channel bottom surface, was 0.03 m. Therefore, we considered x = 0, y = 0 and z = 0.03 m as the cartesian coordinates at the jet nozzle center, with x-, y- and z-coordinates denoting the longitudinal, lateral and vertical directions, respectively. The jet was connected to a rectangular fiberglass tank by means of a plastic pipe. The tank was 1.0 m long, 0.50 m wide and 0.50 m deep and was positioned at a height of 3.60 m over the channel bottom surface (for further details see Mossa, 2004a; b). In order to maintain the jet discharge constant, water was pumped continuously into the fiberglass tank by an electro-pump with a discharge larger than that of the jet. The water excess, distributed by the side-tank spillway, was driven via a pipeline to re-reach the reservoir from where the electro-pump absorbs the water. The jet flow rate was measured using two flow meters; one measured a flow rate ranging between 0 and 100 l/h, while the other one measured a flow rate ranging between 100 and 500 l/h. Figure 3 illustrates a definition sketch of the laboratory flume with the vegetation canopy. Details of the measurement reach, the channel dimensions, the stem distribution and the jet emplacement in addition to its diffusion within the ambient flow are well presented. Because water is forced to move around the stems, the flow within the canopy is both three-dimensional and highly heterogeneous at the scale of the individual stems. Therefore, the instantaneous three-dimensional flow velocity component, through the channel cross-sections, was measured accurately using a three-dimensional (3D) Acoustic Doppler Velocimeter (ADV) system, together with CollectV software for data acquisition and ExploreV software for the data analysis, all of them products by Nortek. The ADV was used with a velocity range equal to ±0.30 m/s, a velocity accuracy of ±1%, a sampling rate of 25 Hz and a sampling volume 27 mm^3.

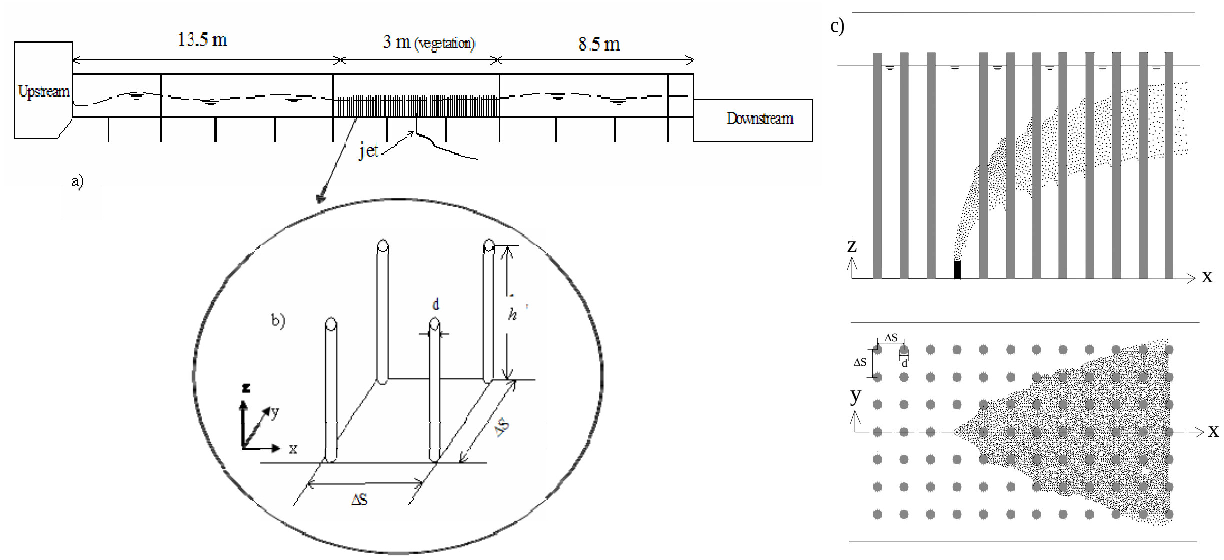

Figure 3. Definition sketch of: a) Channel with the vegetation canopy; b) Vegetation distribution; c) Jet diffusion within the vegetation canopies

In order to further understand the vegetation effects on the jet behavior, three sets of experiments were investigated; the first one concerned the jet discharge into a smooth channel flow and refers to the experiments CJ1 to CJ4, the second one concerned the vegetated channel without jet and refers to experiments CV1 and CV2, while the third one concerned the jet discharge into a vegetated channel flow and refers to the experiments CJV1 to CJV4. The initial experimental conditions and parameters of these experiments are illustrated in Table 1. Herein, H is the ambient flow depth, U_a is the ambient velocity, U_0 is the initial jet velocity, T is the water temperature, r_{ja} (= U_0/U_a) is the initial jet to ambient velocity ratio (effective velocity ratio), F_{ra} is the channel Froude number, $Fr_0 = U_0/(gD)^{0.5}$ is the initial jet Froude number, where g is the gravity acceleration, $Re_a = Q/((B+2H)\nu)$ is the channel Reynolds number, where ν is the water kinematic viscosity, and Re_0 is the initial jet Reynolds number.

Table 1. Initial conditions and parameters of the experiments

	Runs	**H** (cm)	**U_a** (ms^{-1})	**U_0** (ms^{-1})	**T** (°C)	**r_{ja}** (-)	**Fr_a** (-)	**Fr_0** (-)	**Re_a** (-)	**Re_0** (-)
Channel + Jet	**CJ1**	37	0.15	13.27	11.3	85.83	0.08	94.73	15705	20767
	CJ2	30	0.19	13.27	14.9	69.59	0.11	94.73	19963	23156
	CJ3	37	0.15	8.85	16.7	57.22	0.08	63.16	18415	16233
	CJ4	30	0.19	8.85	15.5	46.40	0.11	63.16	20306	15702
Ch + Veg	**CV1**	37	0.15	#	22.0	#	0.08	#	21074	#
	CV2	30	0.19	#	24.0	#	0.11	#	25168	#
Channel Jet + Vegetation	**CJV1**	37	0.15	13.27	25.0	85.83	0.08	94.73	22579	29857
	CJV2	30	0.19	13.27	25.0	69.59	0.11	94.73	25741	29857
	CJV3	37	0.15	8.85	28.0	57.22	0.08	63.16	24085	21231
	CJV4	30	0.19	8.85	25.0	46.40	0.11	63.16	25741	19904

means without the jet

RESULTS

Measurements of the flow velocity components at several horizontal longitudinal and transversal planes were taken for all the experiments. Figure 4 shows an example of the mean velocity vectors (V-W) through the smooth channel cross-section at x/D = 40 for CJ3. The velocity vectors show an excellent representation of the jet spreading within the ambient flow as its cross-section quickly assumes a kidney shape dominated by a pair of counter-rotating vortices (CRVP).

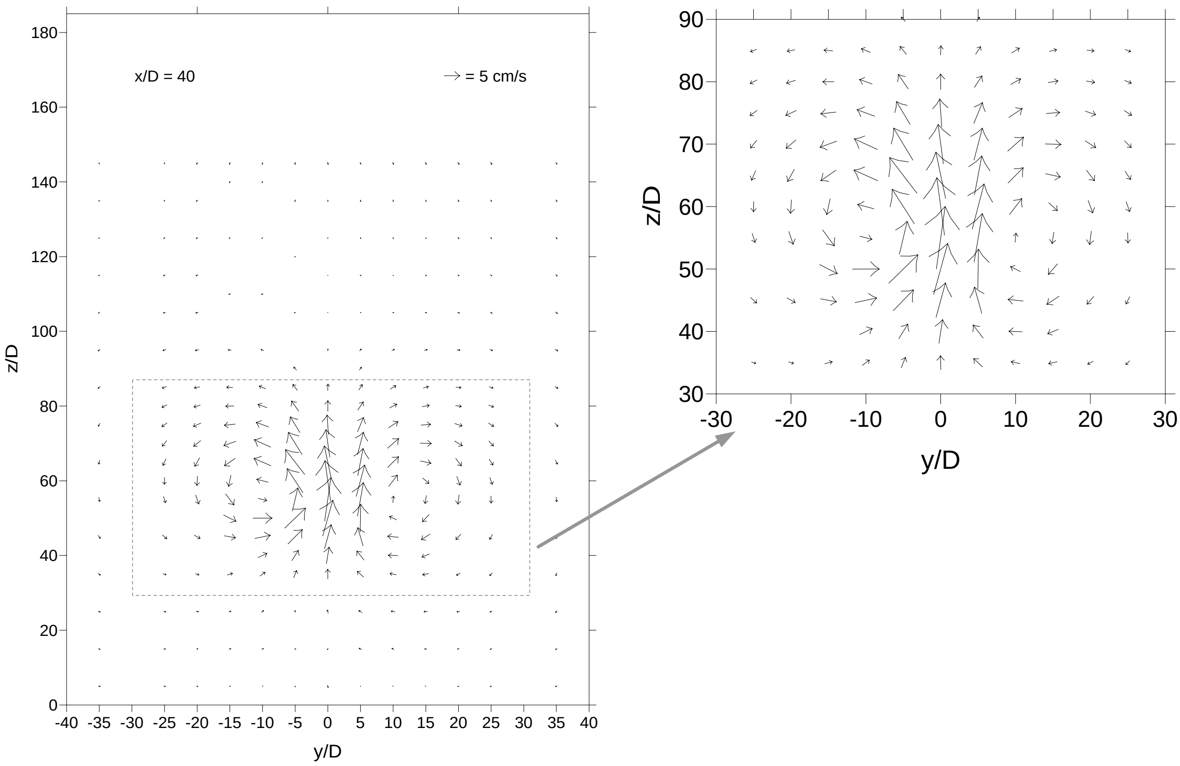

Figure 4. Velocity distribution through the jet cross-section at the smooth channel section (CJ3).

In order to evaluate the effect of vegetation on the channel flow turbulent structures without a jet, we plot in Figures 5a and 5b respectively the vertical profiles of the dissipation rate, ε, and the normalized macroscale, L_x/H, against the normalized vertical coordinate, z/H, for the vegetated and smooth channel flows. The profiles corresponding to (x/d=16.67 and y/d=1.67) and (x/d=33.34 and y/d=8.33) were obtained with the vegetated channel (both of them correspond to CV1) at two vegetation stem locations, while the profiles denoted by SC were obtained at two different positions in the smooth channel (without vegetation and jet). The figures clearly show that the vegetation stems play the role of trapping the large eddy scales, especially eddies >> ΔS, damping them to small scales with a dramatic increase in the dissipation rate.

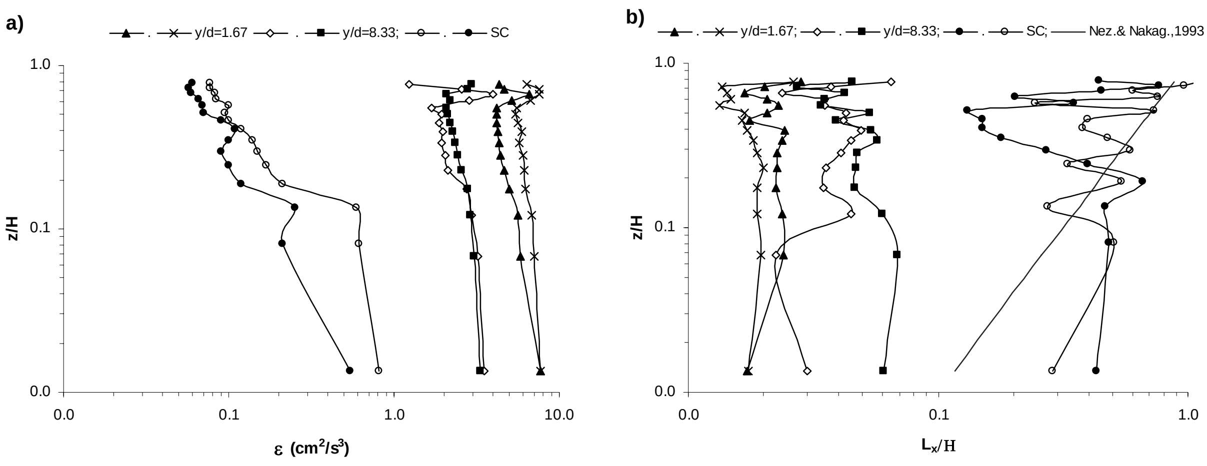

Figure 5. Turbulent flow structures; a) dissipation rate, b) eddies macroscales.

Figures 6a and 6b display the relative turbulence intensity contours of the longitudinal flow velocity component, rms(u')/|U|, through the cross-sectional plane, at x/D = 40, of CJ1 to CJ4 and CJV1 to CJV4 sets of experiments. Because the jet is symmetrical with respect to the x-z plane, y = 0, we only plot the data in the one-half channel cross-section (along positive y). Here, u’ and U are the fluctuation and time average of the instantaneous longitudinal flow velocity component, respectively, at a given point. The figures clearly highlight the significant vegetation effects on the jet structures, where the familiar kidney shape dominated by the pair of counter-rotating vortices (see CJ1 to CJ4) is less pronounced and a complex shape takes place characterized by the occurrence of several vortices (see CJV1 to CJV4). In addition, with vegetated channel the turbulence intensity, jet spreading and jet penetration height increase significantly.

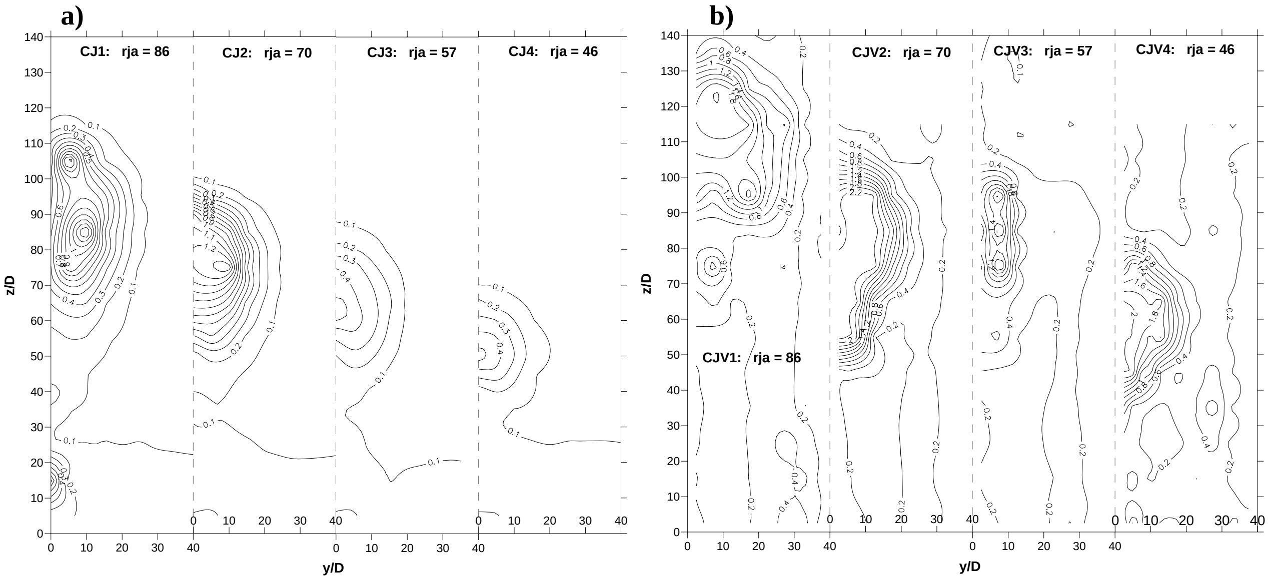

Figure 6. Relative turbulence intensity of the jet (x/D = 40); a) smooth channel, b) vegetated channel.

Figures 7a and 7b show the contours of the normalized shear stress, $-\overline{v'w'}/U^{*2}$, of both the CJ1 to CJ4 and CJV1 to CJV4 sets of experiments, at the same cross-section defined in Figure 6.

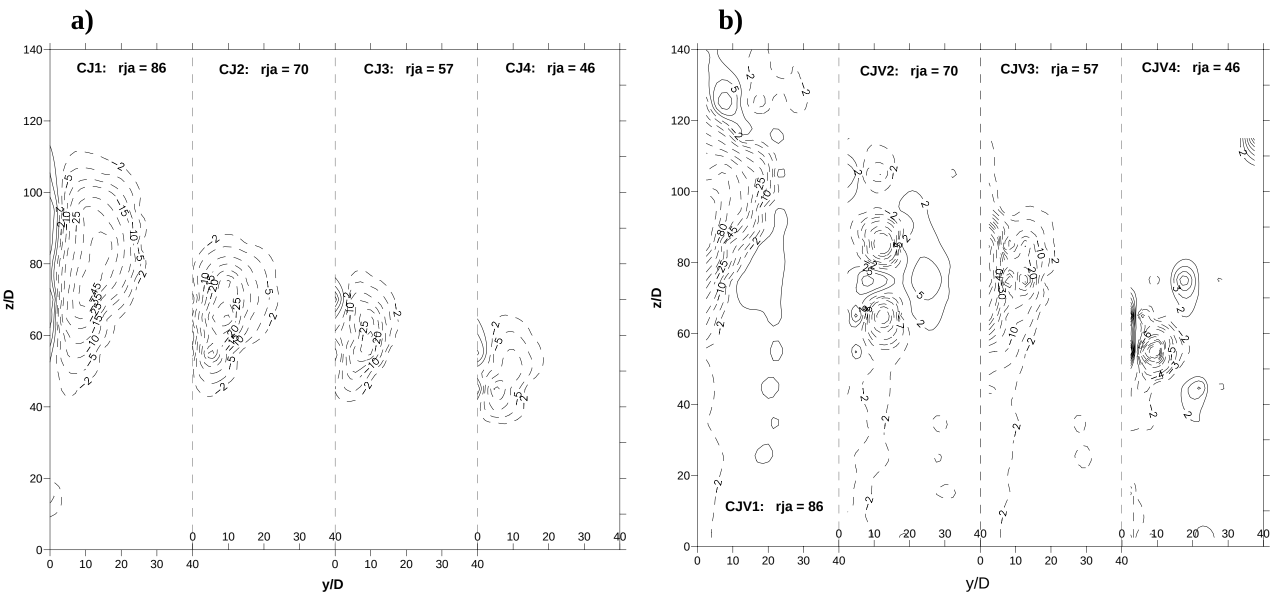

Figure 7. Reynolds stress $-\overline{v'w'}/U^{*2}$ contours (x/D = 40); a) smooth channel, b) vegetated channel.

Here, U^* is the channel-averaged friction velocity calculated at the regions of rms(u’)/|U| ≤ 0.1 and over z/H < 0.2 (Nezu and Nakagawa, 1993), v’ and w’ are the fluctuation of the instantaneous lateral and vertical flow velocity component at a given point, respectively. The positive values of $-\overline{v'w'}/U^{*2}$ are shown by solid lines while the negative values are shown by dashed lines. The same scale on the contours was maintained for all the experiments. In the smooth channel, the dominant CRVP is well pronounced and an “ear-shape” is clearly distinguishable in the four experiments. However, in the vegetated channel the CRVP is transformed into several clockwise and counter-clockwise vortices and the “ear shape” disappears revealing a complex shape. Moreover, the increase of the jet spreading and its penetration height within the ambient flow, observed in Figure 4, is confirmed. Examining Figures 6 and 7, it can be clearly seen that the jet evolution depends also on the effective velocity ratio, r_{ja}.

CONCLUSIONS

The present study was carried out in order to obtain further understanding of the effects of a vegetated channel on a round, vertical, turbulent, momentum jet discharged into an unstratified crossflow. Turbulence statistics were studied in further detail leading to the following results: (i) with the vegetation canopy, the well-known CRVP (observed with the jet discharged in a smooth channel) disappears and several clockwise and counter clockwise vortices take place giving rise to a complex shape of the jet cross-section; (ii) the interaction between the vortices produced by the jet cross-section and those created by the vegetation stems increases the jet spreading and its penetration height within the ambient flow; (iii) with the vegetation canopy the dissipation rate increases through the jet cross-section and iv) the jet evolution depends also on the effective velocity ratio, r_{ja}.

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