VEGETATED CHANNEL EFFECTS ON ROUND, VERTICAL, TURBULENT, MOMENTUM JET BEHAVIOR

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ABSTRACT

In subsequent years up to now a large number of experimental studies and models on turbulent jets discharged into a crossflow have appeared in the literature. These studies have taken into consideration the 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.). As regards these studies, a lack of data concerning the ambient boundary effect on the jet behavior was observed. The present study was directed toward obtaining a more thorough understanding of the effects of a vegetated bed channel on a round momentum (non-buoyant) jet discharged vertically into a crossflow. To achieve this, several experimental runs 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 have been studied with details via turbulence statistical analyses. It was found that the background turbulence generated by the vegetation strongly affects the jet behavior, i.e. the jet turbulence structures become more complex and the jet penetration height, dilution, and spreading increase significantly.

1 INTRODUCTION

Because of their numerous practical applications, ranging from environmental disposal of effluents into the atmosphere and water to combustion and thrust control, turbulent jets have been widely studied for several decades (e.g. *Rajaratnam,* 1976; *Jirka & Harleman,* 1979; *Petrillo*, 1985; *Morton & Ibbetson*, 1996; *Kuang & Lee*, 2001; *Quinn, 2006*). This interest is motivated in part by the important role that turbulent jets play as the initial mixing phase for pollutants discharged into air and in the water quality modeling.

It is interesting to note that discharging of wastewaters in cross-flow field, via single jet or multiport diffuser, buoyant or non buoyant jets, reflects many complex phenomena. These include deflection and oscillation of jet trajectories, some actions such as mixing of the jet, vortex pair formation within the jet, secondary reverse flow behind the jet, and inhibition of jet buoyancy caused by stratified constriction (*Yang & Hwang,* 2001). The complexity of phenomena depends upon the initial jet characteristics (nozzle shape, dimensions, submerged port height, flow rate), the boundary conditions, and the hydrodynamic features of the cross current (depth, flow rate, stratification, etc). Therefore, an understanding of basic mechanisms related to the outfall process could have significant importance in both engineering control design and environmental management.

The background turbulence is an ambient factor such as currents (*Smith & Mungal,* 1998), density stratification (*Fischer et al.,* 1979) or wave motion (*Mossa,* 2004a; *Mossa,* 2004b), which usually act to influence jet behaviors.

The presence of vegetation in main channels strongly affects the flow turbulence structures. The vegetation effects vary with the flow depth, the degree of submergence, the nature, the density and the distribution of the vegetation (e.g. *Nepf,* 1999; *Bennett et al.,* 2002; *Nepf,* 2004). Therefore, the main question is what happens to a turbulent jet discharge into a vegetated channel flow? Since we noted a lack of data concerning the effects of vegetation on turbulent jet behavior, the present study was directed in order to obtain further understanding of the effects of vegetation on a round momentum (non-buoyant) jet discharged vertically into a crossflow.

2 EXPERIMENTAL 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 was 25.0 m long, 0.40 m wide and 0.50 m deep. The lateral walls and the bottom surface of the channel were constructed of Plexiglas. 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 was 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 was 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 was intercepted by a rectangular reservoir which was 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, were 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 was 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 sides 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.

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 0.003 m. The jet axis was perpendicular to the horizontal channel bottom and discharged toward the channel water surface. The jet nozzle was positioned at 0.03 m from the channel bottom. 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 1 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 components, through the channel cross-sections, were 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.

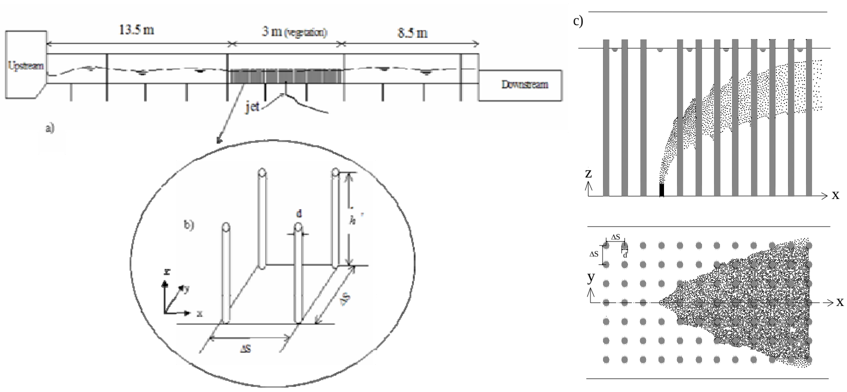

Figure 1. Definition sketch of: a) Channel with the vegetation canopy; b) Vegetation distribution; c) Jet diffusion within the vegetation canopies.

In order to further understand the vegetation effects on the jet behavior, three sets of runs were investigated; the first one concerned the jet discharge into a smooth channel flow and refers to the runs CJ1 to CJ4, the second one concerned the vegetated channel without jet and refers to the runs CV1 and CV2, while the third one concerned the jet discharge into a vegetated channel flow and refers to the runs CJV1 to CJV4. The initial experimental conditions and parameters of these runs 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, $r_{ja} = U_o/U_a$ is the initial jet to ambient velocity ratio (effective velocity ratio), Fr_a is the channel Froude number, Fr_0 is the initial jet Froude number, Re_a is the channel Reynolds number and Re_0 is the initial jet Reynolds number. For the same configurations the difference between Reynolds numbers is due to the difference of ambient water temperature.

	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	0.16	5.90	11.3	37.36	0.083	34.38	16036	13845
	CJ2	30	0.19	5.90	14.9	30.29	0.113	34.38	20383	15437
	CJ3	37	0.16	3.93	16.7	24.91	0.083	22.92	18802	10822
	CJ4	30	0.19	3.93	15.5	20.20	0.113	22.92	20733	10468
Ch + Veg	CV1	37	0.16	#	22.0	#	0.083	#	21517	#
	CV2	30	0.19	#	24.0	#	0.113	#	25698	#
Channel + Jet + Vegetation	CJV1	37	0.16	5.90	25.0	37.36	0.083	34.38	23054	19904
	CJV2	30	0.19	5.90	25.0	30.29	0.113	34.38	26282	19904
	CJV3	37	0.16	3.93	28.0	24.91	0.083	22.92	24591	14154
	CJV4	30	0.19	3.93	25.0	20.20	0.113	22.92	26282	13270

Table 1. Initial conditions and parameters of the experiments.

3 RESULTS

Before starting the experimental runs with the turbulent jet, an initial evaluation of the vegetated channel flow structures was investigated. Figure 2 shows a vector map of the spatial flow velocity distribution of run CV1, at the horizontal plane of z/H = 0.45. The velocity vectors showed in Figure 2 are the resultants of the longitudinal, U, and transversal, V, time averaged velocity components. It can be noted that, around stems, the velocity vectors are strongly deviated from the longitudinal towards the transversal direction, which means an increase of the secondary currents velocity. In addition, a random fashion and highly heterogeneous flow velocity distribution was observed behind the vegetation stems. This can be explained by the development of eddy vorticity structures (*Williamson*, 1985; *Kang*, 2003).

Figure 3 illustrates the relative turbulence intensity distribution of the longitudinal flow velocity component, $rms(u')/|U|$, at the same horizontal plane mentioned above. Here, u' is the fluctuation of the instantaneous longitudinal flow velocity component at a given point. Around stems and specially downstream them, it can be noted that the turbulence intensity appeared very elevated (it reaches nearly 2 as a maximum value). This result well confirms the strong stem-effects on the flow structures. Outside these regions, the turbulence intensities decrease strongly and reach a value less than 0.1. This range of values is comparable to that found with smooth open-channel flows (*Nezu & Nakagawa*, 1993). As a result, the production of turbulence within the stem wakes strongly exceeds the bed shear production through a smooth channel (*Nepf et al.* 1997; *Nepf*, 1999).

Velocity measurements in the plane of flow symmetry are useful in determining the jet penetration within the crossflow which has been one of the primary objective of many experimental and theoretical studies of a jet discharged into a crossflow. It is well-known that, the velocity through the jet decays rapidly, with the increase of the distance downstream the jet source, to values comparable with the crossflow velocity. Therefore, the detection of the decay and deflection of the axial velocity in the jet needs a suitable placement of the measuring probe along the plane of flow symmetry (*x*-*z*) of $y = 0$. For the present study, extensive measurements of the flow velocity in the plane of flow symmetry were taken for all the runs CJ1 to CJ4 of the case of the jet discharged in a smooth channel. As an example, the results of the test CJ1 is presented in Figure 4. The velocity vectors showed in Figure 4 are the resultants of the longitudinal, *U*, and vertical, *W*, time averaged velocity components. It can be noted that the flow field is well described by the measured vectors and the jet penetration within the ambient flow is clearly individualized, as shown by the contours of the vector magnitudes. Close to the jet source, unfortunately, the ADV showed difficulties to take accurate measurements of the flow field. This may be due to the jet small dimensions compared to the sampling volume of the ADV-measuring probe.

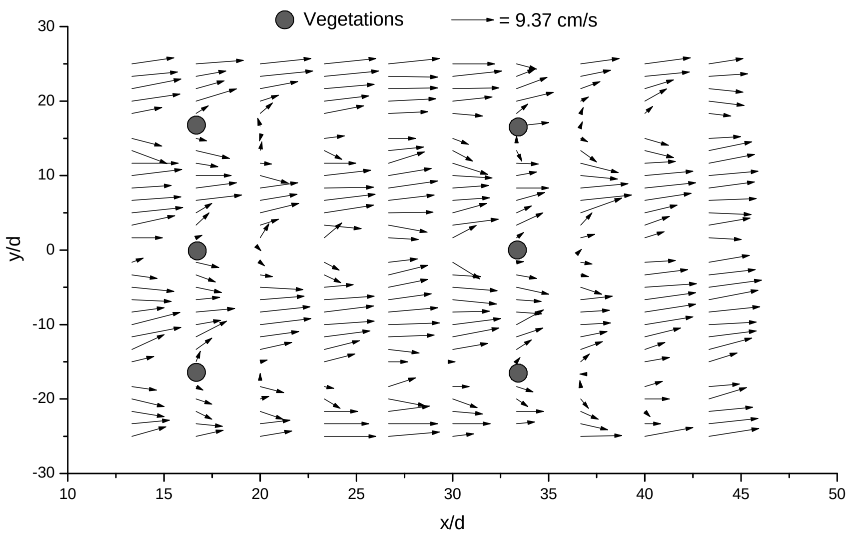

Figure 2. Vegetation effects on the flow velocity distribution in the horizontal plane (*x*-*y*), CV1.

To show the vegetation effects on the jet behaviour, extensive measurements of the field velocity in several cross sections, for all runs, were investigated. Although most measurement were taken in the one-half channel cross section of $y \geq 0$, due to flow symmetry. With the intention of more clearly show the vegetation effects on the jet behavior, a comparison between the jet-runs obtained with the smooth and vegetated channel is suitable. For both cases, Figure 5 shows a contour map of the average vorticity, ω_x, non-dimensionalized by ω_{xm}, where ω_{xm} is the maximum of ω_x in each analyzed section. All sections presented in Figure 5 refer to $x/D = 26.67$. The average constant vorticity contours show an excellent representation of jet spreading within the ambient flow. In the cross-sectional plane (*y*-*z*), vorticity means strength of the longitudinal vortex and it has been evaluated as:

$$\omega x = \frac{\partial V}{\partial z} - \frac{\partial W}{\partial y} \tag{1}$$

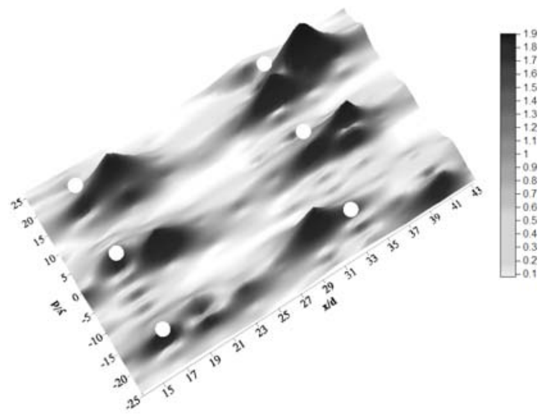

Figure 3. Turbulence intensity, *rms(u')/|U|*, distribution in the horizontal plane, CV1, white discs represent the vegetation stems.

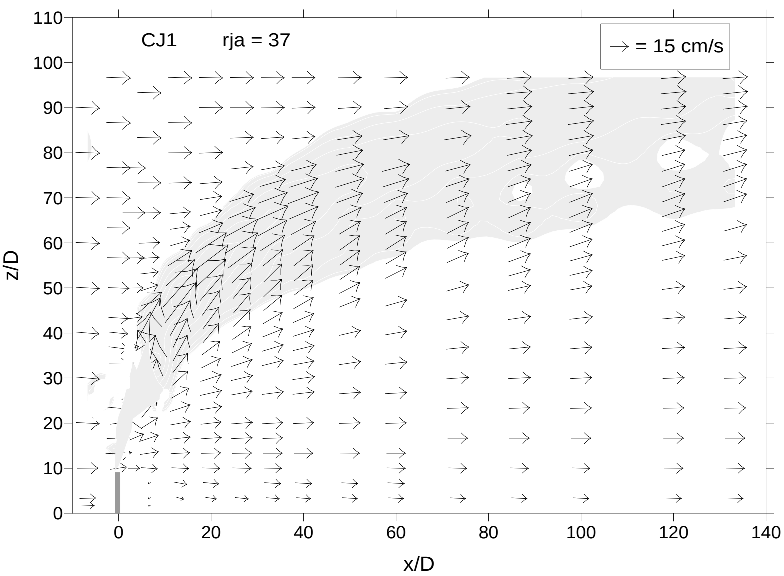

Figure 4. Velocity distribution in the plane of flow symmetry (*x-z*), CJ1.

The contour scales used in Figure 5 were maintained with all runs in order to better highlight the difference between them. In addition, for each run taken with the jet discharged into the smooth channel, we plot its corresponding experiment taken with the jet discharged into the vegetated channel. For the first set of runs CJ1 to CJ4, the prominent feature of the flow-field is that the jet is deflected in the direction of the crossflow as its cross-section quickly assumes a kidney shape dominated by a pair of counter-rotating vortices (CRVP) (*Rajaratnam,* 1976; *Cortelezzi & Karagozian,* 2001). Here, only a single vortex is observed because we plot only one-half of the channel cross-section as mentioned before, while the other one can be determined by symmetry relative to the plane of flow symmetry (y = 0).

Examining Figure 5, the effect of the vegetation stems on the jet behavior is obviously observed in runs CJV1 to CJV4. The effect is translated by the disappearance of both the familiar kidney-shape and the dominated counter-rotating vortices of the jet cross-section. A complex-shape of the jet cross-section and an alternation of positive and negative vorticity contours were observed. This alternation of contours means the formation of several clockwise and anticlockwise vortices through the jet cross-section. Furthermore, it can been seen that vortices occupy almost all the figure areas and reach vertical positions slightly larger than those obtained with runs CJ1 to CJ4. This result may be explained by the fact that with the vegetated channel, the jet spreading and its penetration height increase within the ambient flow. Since the jet and channel Reynolds numbers are sufficiently large, they do not reveal differences on the flow structures for analogous configurations in the present study.

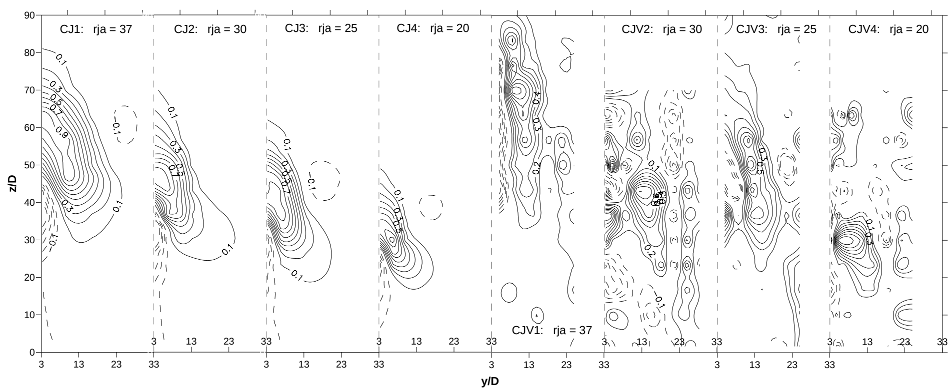

Figure 5. Normalized vorticity (ω_x/ω_{xm}) contours in the cross-sectional planes of x/D = 26.67 for the jet discharged in both the smooth and vegetated channel.

4 CONCLUSION

The present study was conducted in order to obtain a more thorough understanding of vegetated channel effects on a round, vertical, turbulent, momentum jet discharged into an unstratified crossflow. Turbulence statistics were studied in further detail leading to the following first results; (i) with the vegetation canopy, the well-known CRVP (observed with the jet discharged in smooth channel) disappears and several clockwise and anticlockwise vortices take place. Moreover, the familiar kidney-shape of the jet cross-section is less pronounced and a complex shape was observed; (ii) the interaction between the vortices produced by the jet cross-section and those created by the vegetation stems increases the jet spreading within the ambient flow; (iii) with the vegetation canopy the jet penetration height increases.

There are several phenomena associated with turbulent jets in a vegetated crossflow which have not been resolved by this investigation, also for the sake of brevity. In nature, the aquatic vegetations are rigid and flexible, leafed or leafless, have branches or rods, submerged or emerged, etc. The added drag provided by the vegetation greatly affect the flow structures. Because the vegetation drag and its effects depends on the vegetation nature and its density, it may be desirable to perform additional experiments taking into account all these parameters.

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