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Research article

Experimental study of a vertical jet in a vegetated crossflow

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A B S T R A C T

Aquatic ecosystems have long been used as receiving environments of wastewater discharges. Effluent discharge in a receiving water body via single jet or multiport diffuser, reflects a number of complex phenomena, affecting the ecosystem services. Discharge systems need to be designed to minimize environmental impacts. Therefore, a good knowledge of the interaction between effluents, discharge systems and receiving environments is required to promote best environmental management practice.

This paper reports innovative 3D flow velocity measurements of a jet discharged into an obstructed crossflow, simulating natural vegetated channel flows for which correct environmental management still lacks in literature. In recent years, numerous experimental and numerical studies have been conducted on vegetated channels, on the one hand, and on turbulent jets discharged into unvegetated crossflows, on the other hand. Despite these studies, however, there is a lack of information regarding jets discharged into vegetated crossflow. The present study aims at obtaining a more thorough understanding of the interaction between a turbulent jet and an obstructed crossflow. In order to achieve such an objective, a series of laboratory experiments was carried out in the Department of Civil, Environmental, Building Engineering and Chemistry of the Technical University of Bari – Italy. The physical model consists of a vertical jet discharged into a crossflow, obstructed by an array of vertical, rigid, circular and threaded steel cylinders. Analysis of the measured flow velocities shows that the array of emergent rigid vegetation significantly affects the jet and the ambient flow structures. It reduces the mean channel velocity, allowing the jet to penetrate higher into the crossflow. It significantly increases the transversal flow motion, promoting a major lateral spreading of the jet within the crossflow. Due to the vegetation array effects, the jet undergoes notable variations in its vortical structure. The variation of the flow patterns affects the mixing process and consequently the dilution of pollutants discharged in receiving water bodies.

1. Introduction

Environmental management and sustainable development actually become a common activity of more efficient use of natural resources, forming a key driver of innovation and growth. As an example, Daly (1990) proposed some fundamental principles of sustainable development, one of them, which is in line with the present study, is: "the emissions released by production and consumption processes should not exceed the absorption and regeneration capacities of the ecosystems". In order to achieve such an objective, with wastewater discharges in receiving water bodies, a good knowledge of the interaction between the effluents, the discharge system and the receiving environments is required. For example, aquatic vegetation in natural receiving water bodies strongly affects the ambient flow structures as well as of a discharged wastewater flow, affecting, in turn, the rate of nutrient/contaminant transport and diffusion.

Because of their numerous practical applications, ranging from the discharge of effluents into the atmosphere and water bodies to combustion and thrust control, turbulent jets have been widely analytically, computationally and experimentally studied for several decades (e.g., Ben Meftah et al., 2004; Eroglu and Breidenthal, 1998; Jirka and Harleman, 1979; Morton and Ibbetson, 1996; Muppidi and Mahesh, 2007; Quinn, 2006; Rajaratnam, 1976; Richard and Weston, 1978; Toffolon and

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Serafini, 2013). In fact, it is fundamental the role that turbulent jets play as the initial mixing phase for pollutants discharged into an environmental receiving body (e.g., river, stream, lake, sea, and atmosphere). It is worth mentioning that the discharge of wastewaters into a crossflow, via single jet or multiport diffuser, buoyant or non-buoyant jets, reflects a number of complex phenomena. These include visual deflection and oscillation of jet trajectories, some visualized 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 and Hwang, 2001). The initial jet characteristics (e.g., nozzle shape, dimensions, submerged port height and flow rate), the boundary conditions (e.g., topography, bathymetry, physical properties) and the hydrodynamic features of the cross current (e.g., depth, flow rate, stratification, wave motion), as mentioned in previous studies (e.g., Fischer et al., 1979; Mossa, 2004a,b; Smith and Mungal, 1998), strongly affect the jet mixing processes. Turbulent jets have been widely studied because of their mixing properties. Therefore, an understanding of the jet basic mixing mechanisms could have significant importance for both the engineering control design and the environmental management/monitoring sectors.

A jet in a crossflow is defined as the flow field where a jet of fluid enters and interacts with a crossflowing fluid. The most obvious feature of a jet in a crossflow, as observed by Andreopoulos and Rodi (1984), is the mutual deflection of both the jet and the crossflow. The jet is bent over by the cross-stream, while the latter (crossflow) is deflected as it encounters a rigid obstacle. Consequently, the jet interacts with the deflected flow and entrains fluid from it. With a large ratio of jet to ambient velocities, the jet is only weakly affected near the exit and vertically penetrates into the cross-stream before bending over.

Pathak et al. (2006) indicated that the whole flow field of a jet in a crossflow is characterized by four main vortical structures: (i) shear layer vortices which form at the interface between the jet and the crossflow and have been attributed to Kelvin–Helmholtz type instabilities; (ii) horseshoe vortices due to the adverse pressure gradient upstream of the jet; (iii) wake vortices form at the inner part of the jet; and (iv) counter-rotating vortex pairs (CRVP) form at the cross plane just after the jet hole, becoming as dominant structures downstream in the flow field (Fig. 1).

Sherif and Pletcher (1989), conducting laboratory measurements on a vertical turbulent jet in crossflow, found two mean velocity maxima on each vertical profile. An absolute maximum which is located within the jet field and corresponds to the jet velocity axis and a local maximum appears in the wake-like region. Pratte and Baines (1967), using flow visualization to determine the jet trajectories and its flow widths within the ambient flow, found that the jet length scales are properly normalized by the factor $r_{ja}D$, where $r_{ja} = U_0/U_a$ is defined as the initial jet to ambient velocity ratio, U_0 is the initial jet velocity, U_a is the ambient velocity and D is the jet nozzle diameter.

Vegetation in main channels strongly affects the flow turbulence structures (e.g., Ben Meftah and Mossa, 2013; Ben Meftah et al., 2014). Hydraulic engineers have studied water flow through vegetation to better model sediment and contaminant transport. Field observations demonstrate that submerged and emerged vegetation can baffle local currents and dampen wave energy by providing additional source of drag associated with the plant stems and branches (Nepf et al., 1997). Vegetation also affects the turbulence intensity and then the diffusion process. Because wake turbulence is generated at the stem scale (Nepf, 1999; Poggi et al., 2004; Wilson and Shaw, 1997), the dominant turbulent length scale is shifted downward, relative to unvegetated channel flows (Nepf et al., 1997). Raupach and Thom (1981) and Worcester (1995) indicated that, in vegetated channel, the turbulence production reduces with the reduction of the flow velocity.

In open channel flow with emergent vegetation, Fairbanks (1998) indicated that the vertical profile of the flow velocity consists of two basic regions: a bed-surface boundary layer, in which the flow is dominated by bed generated shear, and an upper region, in which the mean velocity remains fairly constant with the flow depth. Nepf and Vivoni (2000) also showed that only the longitudinal exchange zone is present and the vertical exchange zone vanishes. This implies that the most rate of a passive tracer spreads in the longitudinal and transversal directions. In addition, Zavistoski (1994) observed that as the plant density increases the wake generated turbulence becomes more dominant, which makes the bottom surface boundary layer compressed toward the bed. Since wake turbulence is generated at the stem scale, the use of velocity and turbulence profiles from a single location within the obstructed flow can reveal few information about the flow structure itself (e.g., Tsujimoto et al., 1992). For this reason and for the sake of simplicity, many studies (e.g., Nepf, 1999; Tanino and Nepf, 2008) have used the concept of bulk flow behaviour, averaging the velocity measurements obtained from several locations to create a single profile. Lightbody and Nepf (2006) showed that the dispersion in both directions (transversal and longitudinal) strongly depends on the Reynolds number based on the stem diameter d, $Re_d = Ud/\nu$, and the vegetation density, ad, where U is the velocity upstream of the cylinder, ν is the water kinematic viscosity, and a is the total frontal area (area exposed to the flow) per unit array. The longitudinal dispersion at a moderate Re_d of order 10–1000 is governed by two mechanisms: trapping of tracer in the primary wakes and the advection of tracer through the spatially random velocity field created by cylinder secondary wakes. The vortex-trapping dispersion increases with the increase of vegetation density, and decreases with the increases of Re_d.

In order to contribute to the understanding of the interactions of discharged effluent and obstructed receiving water bodies, the present study aims to analyse the hydrodynamic flow structures of a turbulent momentum jet vertically discharged into a crossflow, obstructed by an array of emergent cylinders.

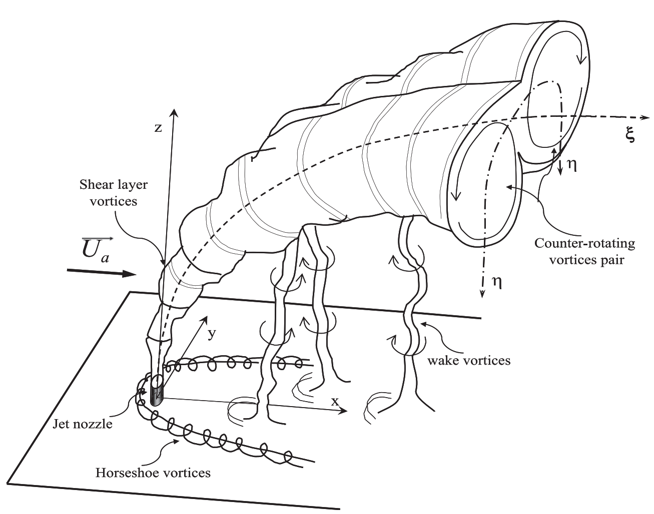

Fig. 1. Sketch of a typical vertical round jet structures in a crossflow. Reproduced from Fric and Roshko, 1994.

2. Experimental set-up

The experimental runs were carried out in a smooth horizontal