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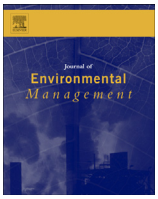

Research article

A laboratory investigation into the influence of a rigid vegetation on the evolution of a round turbulent jet discharged within a cross flow

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A B S T R A C T

The study of buoyant jets, those between pure jets and plumes, has been carried out with ever greater frequency over recent years due to its application in different practical engineering fields, i.e. appropriate design of outfalls for the disposal of municipal and industrial waste waters. The dispersion of waste and the related dilution of pollutants are governed by the mean-flow and turbulence characteristics of the resulting jets, which themselves depend on environmental conditions.

The present study deals with how a uniform cross-stream with a channel bed surface covered by rigid emergent stems affects the behaviour of a circular turbulent buoyant jet. The time-averaged temperature and velocity fields are investigated in order to understand jet diffusion and penetration within the ambient fluid.

The examination and comparison of the measured scalar and vector quantities show that the presence of emergent vegetation in the receiving environment affects both the average flow field and the jet structure, reducing the mean channel velocity, with a notable increase in jet penetration height and dilution compared to the test case without vegetation. This result is confirmed by the several vertical profiles of the mean scalar concentration and the normalized vertical velocity component along the channel centre plane. Moreover, the rigid emergent vegetation and its driven instabilities promote a distortion of the mean concentration and normalized axial velocity component profiles in the trajectory-based coordinate system.

1. Introduction

The use of experimental models for the reproduction of environmental processes, such as the dilution of waste water discharges, is a well-known procedure since the past decades to understand the dynamics occurring in the waters and to design possible interventions for a successful management. When the receiving environment of waste discharges is a natural water body, such as a lake, a river, an estuary or a coastal sea, the physical processes of flow which cause pollutants or natural substances to be transported and mixed, or exchanged, with other media, need. The water quality in regions near an outfall pipeline in the receiving water body and, consequently, the ecosystem services and the environmental use by local populations depend on the effluent quality and its discharge system. Therefore, a good knowledge of the interaction between the effluents, the discharge system and the receiving environments is required to promote best environmental management practices. Several studies and surveys on turbulent jets and plumes, commonly identified as dischargers of pollutant substances such as waste waters, are available in literature (e.g. Morton, 1959; Fischer et al., 1979; List, 1982; Jirka, 2004), and this is no surprise due to their importance in many practical engineering problems and in the application of technological systems that range from environmental to industrial issues.

The dilution and mixing processes in the receiving water body depend on the initial jet parameters (e.g. the velocity distribution and turbulence level, the mass flux and the momentum flux) and the geometrical factors (e.g. the jet shape, its orientation and the attitude of the jet with respect to boundaries or to the vertical direction if the jet has negative or positive buoyancy), as well as on ambient factors with which the jet interacts and from which it is modified, such as cross flow or localised region of turbulence (e.g. Lee, 1984; Kim et al., 2002; Smith and Mungal, 1998; Guo et al., 2005; Cuthbertson et al., 2006), density stratification (e.g. Fisher

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et al., 1979; Boehm et al., 2002), wave motion (e.g. Mossa, 2004a, 2004b) and bottom roughness (e.g. Ben Meftah et al., 2004; Valipour, 2012; Khasraghi et al., 2015; Valipour et al., 2015).

However, the effects of vegetation, one of the most common ambient factors on the dilution processes and thus on jet behaviour in contexts such as discharges in free surface water bodies, remain not deeply investigated. It stands to reason that, to control and reduce the impact of polluting emissions, a study needs (i) to analyse thoroughly the physical mechanisms that underlie turbulent jets, especially buoyant jets, and (ii) to assess the possible environmental factors that interact with the abovementioned issue which must be taken into consideration if a complete and appropriate solution, able to understand and forecast the phenomenon, is to be attained.

The aim of the present study is to develop an understanding of changes in vertical, round buoyant jet behaviour due to the presence in the receiving cross flow of a background turbulence generated by means of artificial emergent vegetation. Even if literature is full of experimental studies on both these environmental topics, i.e. cross flow and vegetation, which are typical conditions in natural river flows, there is a lack of research on the effects of both these factors on jet dilution. This paper is an attempt to remedy these shortcomings in our understanding of buoyant jets. The study adds to recent works by the authors on the dilution of a buoyant jet in a vegetated open channel (Malcangio et al., 2008; Ben Meftah et al., 2014, 2015). To this end, an experimental apparatus is described in the article, composed of a rectangular laboratory flume with a current, into which hot water was discharged through a circular nozzle located vertically at the bottom of the channel. The transversal current was uniform in the rectangular channel, while the rigid emergent vegetation was simulated by equally-distributed metallic cylinders. The survey centred on measuring the time-averaged velocity and temperature in the longitudinal axial plane, as well as in the trajectory based coordinate system.

2. Materials and methods

2.1. Buoyant jet background

A release containing both momentum and buoyancy is designated a “buoyant jet” or “forced plume”. As a result, a buoyant jet has jet-like characteristics depending on its initial volume and momentum fluxes, and plume-like characteristics depending on its initial buoyancy flux. Far away enough from the source the plume-like characteristics always win out, that is, a buoyant jet will always turn into a plume if given enough free distance. To see why, first it should be recalled that if the receiving water is stagnant and homogeneous, the main parameters that can determine the flow in the jet or plume are the initial fluxes of volume, momentum and buoyancy, Q_0, M_0, and B_0, respectively. For a simple turbulent round jet we can define these parameters as

$$Q_0 = \frac{\pi D^2}{4} U_0 \tag{1}$$

$$M_0 = \frac{\pi D^2}{4} U_0^2 \tag{2}$$

$$B_0 = g\frac{(\rho_a - \rho_0)}{\rho_a}\frac{\pi D^2}{4} U_0 = g_0' Q_0 \tag{3}$$

in which D is the jet diameter, U_0 is the mean outflow velocity assumed uniform across the jet and g_o' is the initial apparent gravitational acceleration, depending on the difference between the receiving fluid density ρ_a and the source fluid density ρ_o.

When a fluid is injected upward (downward) into higher (lower) density fluid, the buoyancy is called positive and the related force has the same direction as the jet momentum. When buoyancy forces and the jet momentum oppose one another, such as a fluid injected upward (downward) into a lower (higher) density fluid, the jet is negatively buoyant.

Another important parameter is the well-known jet densimetric Froude number, which relates the inertial forces to buoyancy forces within the plume and assumes zero value for a pure plume, while for a pure jet it approaches infinity. This can be defined as

$$F_{r0} = \sqrt{\frac{M_0 U_0}{B_0 D}} = \frac{U_0}{\sqrt{g' D}}. \tag{4}$$

Since the past, several experimental observations (e.g. Pratte and Baines, 1967; Rajaratnam, 1976; Andreopoulos and Rodi, 1984; Morton and Ibbetson, 1996) have demonstrated that when a buoyant jet interacts with a uniform flow field normal to its axis, it is subject to a deflection in the same direction of the receiving flow field and its cross sections have a classical “kidney” shape, also known as “horseshoe” shape. As discovered by Yuan and Street (1998), the pressure gradient near the trailing edge of the jet-exit increases with an increasing distance from the jet-exit, driving downstream cross flow fluid toward the jet and causing an improved entrainment. If the ambient is confined, as in the present case study with the free surface at the upper boundary, the bent jet gradually reaches the free surface and then spreads rapidly into the receiving water body, following the cross flow direction.

The question now is which path a turbulent buoyant jet will follow because of the cross flow, given the initial fluxes Q_0, M_0, B_0, and the mean cross flow velocity U_a. The solution can best be seen by considering the ratio of the characteristic length scale l_m, which is defined for a momentum jet in a cross flow as follows

$$l_m = M_0^{1/2} \Big/ U_a \tag{5}$$

to the equivalent length scale l_b for a plume in a cross flow,

$$l_b = B_0 \Big/ U_a^3. \tag{6}$$

Both of the length scales represent the vertical distance along the jet trajectory where the vertical velocity of the momentum jet and the plume, respectively, decays to the order of the cross flow velocity. Two asymptotic cases occur, corresponding to l_m greater than and less than l_b. Within each case there are three regimes. For $l_m > l_b$ jet momentum is dominant and the regimes can be loosely described as vertical jet, bent jet, and bent plume. When $l_b > l_m$ jet buoyancy is important, the regimes can be called vertical jet, vertical plume and bent plume. In all cases, buoyancy ultimately controls the trajectory. The relation between the two length scales is useful to describe the buoyant jet trajectory in a uniform cross flow (see Fisher et al., 1979).

The dynamical effect of the ambient current is also determined by the effective velocity ratio

$$r_{eff} = \left[\left(\rho_0 U_0^2\right) \Big/ \left(\rho_a U_a^2\right)\right]^{1/2} = r(\rho_0/\rho_a)^{1/2}. \tag{7}$$

From the experimental results this dimensionless parameter did not show a significant difference from the jet-to-cross flow velocity ratio