TURBULENT MIXING PROCESS OF VERTICAL DENSE JET IN CROSSFLOW

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KEY POINTS

- *Turbulence measurement of a dense jet perpendicularly issued into a crossflow.*
- *Analysis of the jet-flow velocity was carried out.*
- *A new empirical closed-form expression to predict the jet trajectory is proposed.*
- *The jet-vortical structures were investigated.*
- *Analysis of the jet-flow turbulence and mixing were examined.*

1 INTRODUCTION

The quantity of wastewater discharge into receiving environment continuously increases with the population growth, urbanization, and industrial expansion. Many nations, such as the Mediterranean countries, which have very scarce water resources or suffer water shortages, are being forced to develop alternative sources derived from seawater desalination to meet the demand for freshwater. In these countries, as an example, the brine is usually discharged in coastal environments as a turbulent jet flow, producing complex hydrodynamic phenomena within the surrounding ambient and affecting the ecosystem services. Mixing of turbulent jets within surrounding environment was the topic of numerous experimental, analytical and numerical studies (e.g., *McDougall*, 1981; *Rathgeber & Becker*, 1983; *Andreopoulos & Rodi*, 1984; *Broadwell & Breidenthal*, 1984, *Gu & Stefan*, 1995; *Huq & Dhanak*, 1996; *Cotel & Breidenthal*, 1997; *Jirka*, 2008, *Marugán-Cruz et al.*, 2009; *Roberts et al.*, 2010; *Bashitialshaaer*, 2013; *Ben Meftah et al.*, 2015; *Dai et al.*, 2016; *Nada et al.*, 2016; *Mossa et al.*, 2017; *Ben Meftah et al.* 2018). Discharge systems need to be well designed to reduce environmental impacts. Therefore, a good knowledge of the interaction between effluent discharge and surrounding flow-field is required to promote best environmental management practice.

Diffusion/mixing processes strongly depend on the strain rates and/or scalar dissipation rates. *Danckwerts* (1952) indicated that the mixing process is a breaking-up of a clump of fluid from large scales to smaller scales, changing the clump size and the molecular interdiffusion, which leads to differences in scalar concentration values. The author pointed out that the mixing degree in flow fields can be mainly expressed by two statistically-defined quantities, a scale and an intensity of segregation. In the case of turbulent flows, the scale and intensity of segregation are analogous to the turbulent length/time scale and the turbulence intensity, respectively. The determination of such scales requires adequate measurements/simulations of the flow turbulence. Recently, *Galeazzo et al.* (2011) have focused on the study of turbulent mixing within a jet in crossflow, comparing experimental results with those of numerical simulations. A combination of planar particle image velocimetry and laser induced fluorescence was used to measure the turbulent velocity and concentration fields. The simulated results, using RANS and LES, showed that the mean jet velocity field was well described, however, the turbulent quantities, such as the Reynolds stresses and the predicted turbulent mixing, were not in good agreement with the experiments.

This manuscript focuses on the analysis of flow turbulence structures that develop when a dense round jet, consisted of a saltwater solution, is injected perpendicularly into a flowing current of fresh water (Figure 1). Figure 1 shows a definition sketch of the dense jet discharged in a main shallow flow of depth H. The jet consists of a vertical (θ=90°) round nozzle, of a diameter D and a port height z_0, which releases effluent of an initial density ρ_0 into a channel crossflow of fluid density ρ_a, with $\rho_a<\rho_0$. The jet discharges at an initial velocity U_0 in a uniform channel/ambient flow of mean velocity U_a. The effluent consists of saltwater solution of initial conductivity c_0 while that of the ambient flow is c_a, $c_a<c_0$. Figure 1 also shows the jet

trajectory, where z_t indicates the maximum rise height of the jet trajectory at the downstream distance x_t and x_i is the downstream distance at which the trajectory impacts the channel bottom.

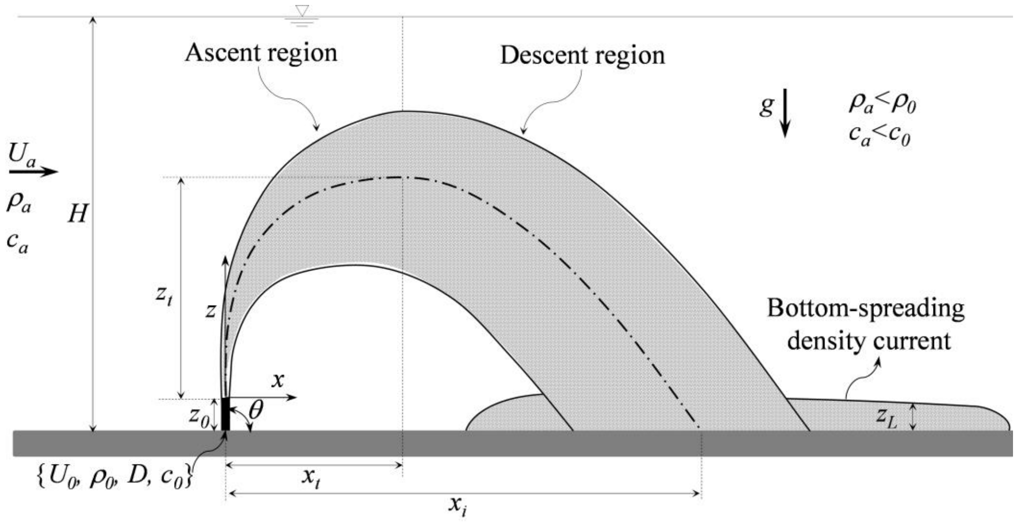

Figure 1. Definition sketch of the vertical dense jet in shallow water, where g is the gravity acceleration, (x, y) are the longitudinal and vertical coordinates, respectively, and z_L is the thickness of the bottom-spreading layer of the density current.

2 EXPERIMENTAL METHOD

Experiments were carried out in a closed circuit flume, specifically designed for the study of buoyant jets, at the Coastal Engineering Laboratory (LIC) of the Department of Civil, Environmental, Land, Building Engineering, and Chemistry of the Polytechnic University of Bari (Italy). The system consists of a rectangular channel made of glass, 15m long, 4m wide and 0.4m deep. The fresh water at ambient temperature is supplied from a downstream big metallic tank, by means a Flygt centrifugal electro-pump, to an upstream steel tank. The upstream tank is equipped with a side-channel spillway with adjustable height in order to maintain constant flow head condition. The overflowing water reaches again the downstream tank. The pumped and overflowed flow rates are measured by means two electromagnetic flow meters, mounted on the channel system. To create a smooth flow transition from the upstream tank to the flume, a set of stilling grids were installed in the outlet of the upstream tank.

The second part of the laboratory model consists of a dense jet hydraulic system. To mix tap/fresh water with salt (NaCl), a large cylindrical storage tank made by fiberglass, of maximum volume $6m^3$, is used. The tank is equipped with four compressed air jets, installed on two levels at opposite positions, to mix the salt with the fresh water. The saltwater is pumped through a pipeline to the jet nozzle. This pipeline is equipped with a regulating valve and a magnetic flow meter to have a well-determined flow discharge. The jet nozzle is of diameter D=10mm, mounted vertically at the center of the flume at a port height z_0=10mm above the flume bottom.

In order to elucidate the three-dimensional characteristics of the vertical dense jet, both the velocity and the salinity flow fields were measured at several sampling locations along the plane of flow symmetry (y=0) and at different cross-sections downstream the jet source (x=0). Since the grid spacing of samples is O(1cm), the measuring instruments are attached to a semi-automatic cross-beam to accurately move and align the different probes at each sampling location. The salinity field was measured by means of a Micro Scale Conductivity Temperature Instrument (MSCTI) by Precision Measurement Engineering (PME), designed to measure the temperature and electrical conductivity of water solutions and moving fluids containing conductive ions. Before starting acquiring data, the probe has been calibrated using a salt solution, of known salinity, prepared in laboratory. At each measurement location, 1000 acquisitions of the water conductivity were carried out at 20Hz. The velocity data were collected using a 3-D Acoustic Doppler Velocimeter

(ADV)-Vectrino system, developed by Nortek, for 60sec at a sampling rate of 150Hz. The sampling volume of the ADV was located 5cm below the transmitter probe. The Vectrino was used with a velocity range equal to ±0.30m/s, a measured velocity accuracy of ±0.5%, a sampling volume of vertical extent of 7mm. For high-resolution measurements, the manufacturer recommends a 15db signal-to-noise ratio (SNR) and a correlation coefficient larger than 70%.

3 RESULTS AND DISCUSSION

The flow velocity-fields, the jet trajectory, the jet-vortical structures, the turbulence intensities, the turbulent kinetic energy, the turbulent length scales, and the dispersion coefficients have been analyzed. The flow velocity-fields show that the dense jet is characterized by an ascending region, of jet-like mixing, and a descending region, of plume-like mixing. The results of the flow-velocity measurements (Figure 2) definitely confirm the formation of the counter-rotating vortex pair (CRVP) through both the ascending and the descending jet regions, a topic of conjecture in previous studies without experimental demonstration. In this study, a new empirical closed-form expression to predict the jet trajectory is proposed. The experimental results indicate a significant increase of turbulence intensities in jet flow-field and a large kinetic energy production. The turbulent length scales show a notable spatial-variation in the jet flow-field, indicating an anisotropic process of the jet flow mixing. The trends of the dispersion coefficients follow those of the turbulent length scales. In comparison with the ambient flow, the jet flow-field shows a decrease of the longitudinal dispersion coefficient and an increase of the vertical one, leading to the increase of the jet width.

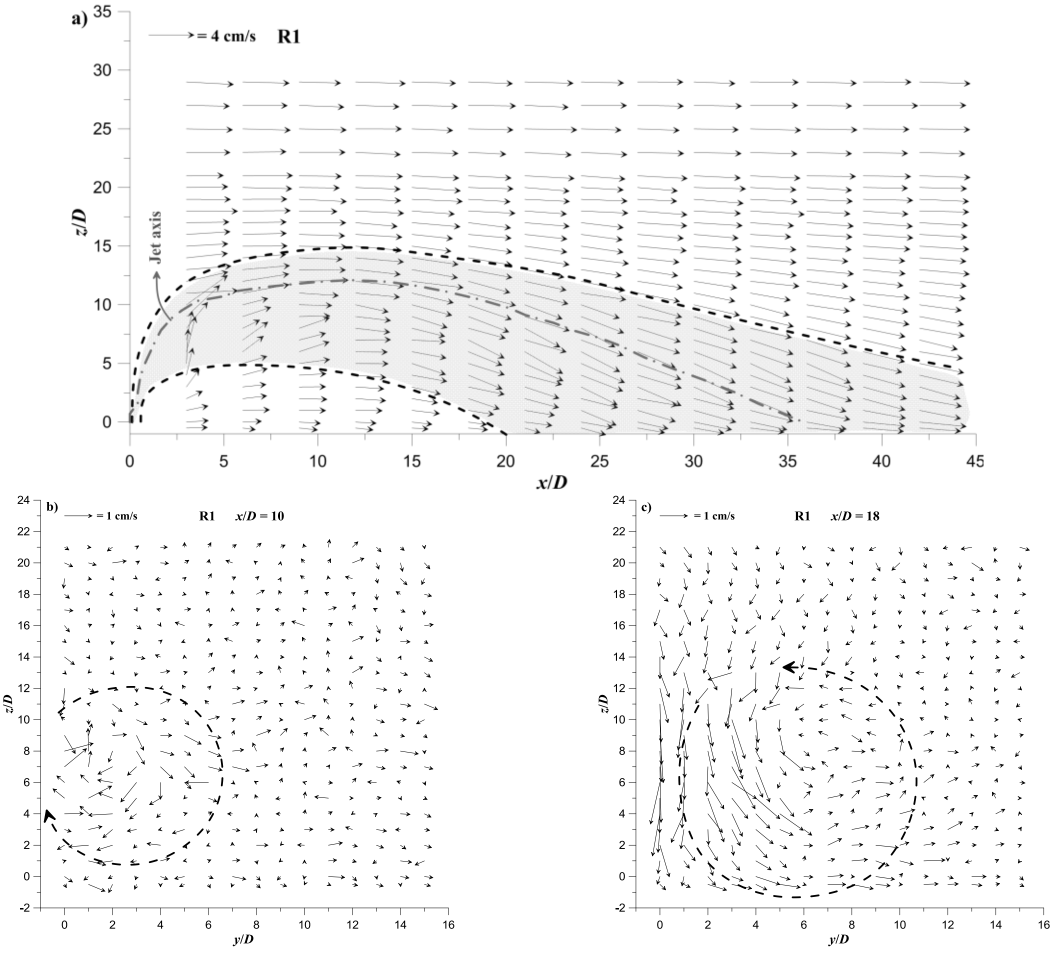

Figure 2. Velocity flow-field of run R1, as an example: a) jet penetration in the (*x*, *z*)-plane of flow symmetry (*y*=0), where *y* is the transversal direction, b) CRVP in the cross-section at *x*/*D*=10, ascending region, c) CRVP in the cross-section at x/D=18, descending region.

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