INVESTIGATION OF INCLINED NEGATIVELY BUOYANT JETS WITH IMAGE ANALYSIS TECHNIQUES

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Abstract Negatively buoyant jets (NBJs) are investigated in a laboratory model by means of two image analysis techniques: Light Induced Visualization (LIV) for the measurement of concentration fields, and Feature Tracking Velocimetry (FTV) for the measurement of velocity fields. The aim of the study is to understand the behavior of the turbulent structures developing in NBJs, and the influence of the non-dimensional parameters in the mixing processes.

INTRODUCTION

A Negatively buoyant jet is generated, typically, when a flow is ejected upwards, with a source of buoyancy and momentum, into a less dense surrounding fluid. Near to the diffuser, where the momentum prevails, the NBJ trajectory is aligned to the momentum and its behavior is basically like the one of a simple jet; farther from the outlet the buoyancy becomes more and more important, it progressively bends the jet axis, and when it prevails, the jet reaches its maximum height and turns, falling down in a plume-like manner. The misalignment between the buoyancy and the momentum causes the lack of axial-symmetry in the NBJs, and the different behaviour of the upper and lower parts of the jet. Nonetheless an in-depth theoretical comprehension of the phenomenon is missing, and in practical application (ranging from brine release into the sea from desalination plants, to oil or gas drilling facilities, discharge of dense effluents from wastewater treatment plants etc), integral model, which are based on the hypothesis of axial-symmetry, are often applied.
The vast majority of the previous experimental studies on NBJs are focused on concentration fields, while only few works are devoted to the analysis of velocity fields. In this work, we analyze the velocity fields, employing an original technique named Feature Tracking Velocimetry (FTV), and the concentration fields, using a Light Induced Visualization (LIV) technique.

EXPERIMENTS

The experimental set-up simulates a typical discharge configuration: a portion of a pipe, laid down into the sea bottom, that discharges the effluent through holes along the wall. The model consists in a long flume, 21 meters long and 30 cm wide, filled with water to simulate the stagnant receiving body. The discharge comes through a pipe, from a constant head tank, by means of a vessel with a sharp-edge circular orifice, 4 mm in diameter. The release, discharged with an angle θ with respect to the horizontal, is a solution of water, sodium sulphate, to increase the density, and pollen particles or titanium dioxide, to perform the FTV, or the LIV, respectively. A pumped diode laser illuminates the mean vertical section containing the , and the images are recorded by means of a high speed camera, 400 fps at full spatial resolution (1728×2240 pixel). In figure 1, two snapshots of a NBJ are shown, one is acquired to perform the LIV (a) and the other one for the FTV (b).
Concentration fields are computed by means of LIV, assuming concentration proportional to the luminosity intensity in images. The FTV is a novel algorithm suitable for velocity measurements from a wide range of seeding density: from the high level typical of PIV down to the low seeding which is characteristic of PTV. Moreover, it is applicable for non-homogeneous density, atypical condition in our analysis, which presents different seeding level between the jet and the environment. The main idea is to compute particle displacements between successive images (and hence velocities) only in presence of high luminosity gradients, so where there are particles, instead of determining velocities using a regular grid, as in traditional PIV.
Under the hypothesis of ergodicity, temporal mean was applied in order to compute ensemble mean and second order statistics from instantaneous fields, for both velocity and concentration. Experiments were performed varying the angle θ, as well as the non-dimensional parameters governing the phenomenon: the densimetric Froude number, Fr, and the Reynolds number, Re.

RESULTS

We present some results concerning the velocity and concentration fields employed to determine the geometrical features of the NBJs. figure 2a, shows the mean velocity field U (normalized by the maximum velocity at the outlet U_{MAX}) for a jet with Fr = 15, Re = 1000 and $\theta = 75°$. The NBJ covers a very short initial distance, where it maintains a width similar to the diameter of the outlet and, afterwards, its width grows due to the onset of the Kelvin-Helmholtz billows. The mean velocity field is symmetrical in the first part of the jet, where the flow is driven essentially by the initial momentum but, as the buoyancy becomes relevant, the span-wise sections become asymmetrical. This behavior is apparent from velocity profiles, orthogonal to the jet axis, computed at different non-dimensional distances along the axis, s/D, and normalized by their maximum axial velocity, U_c, that are plotted in the figure 2b. The profiles are wider in the lower part of the jet (represented by positive values of r/D) with respect to the upper part (represented by negative values of r/D), and this features increases for higher values of s/D. Figure 3a displays the mean concentration field C (normalized by the maximum concentration C_{MAX}) for a NBJ with Fr = 11, Re = 1000 and θ = 75°, while figure 3b shows the corresponding concentration profiles normalized by maximum axial concentration, C_C. As already observed for velocity, also concentration field displays a marked lack of axial-symmetry. This behaviour, which is even strengthen from the analysis of second order structures, mines the feasibility to use integral equations to analyze the phenomenon.

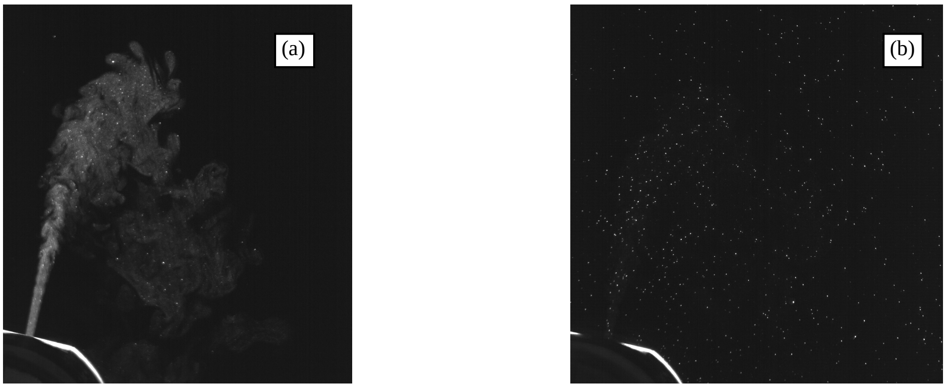

Figure 1. Snapshot of a negatively buoyant jet, with Fr = 8, Re = 1000, θ =75°, the flow is visualized by means of titanium dioxide to perform the LIF analysis (a) and seeded with pollen particles for the FTV analysis (b).

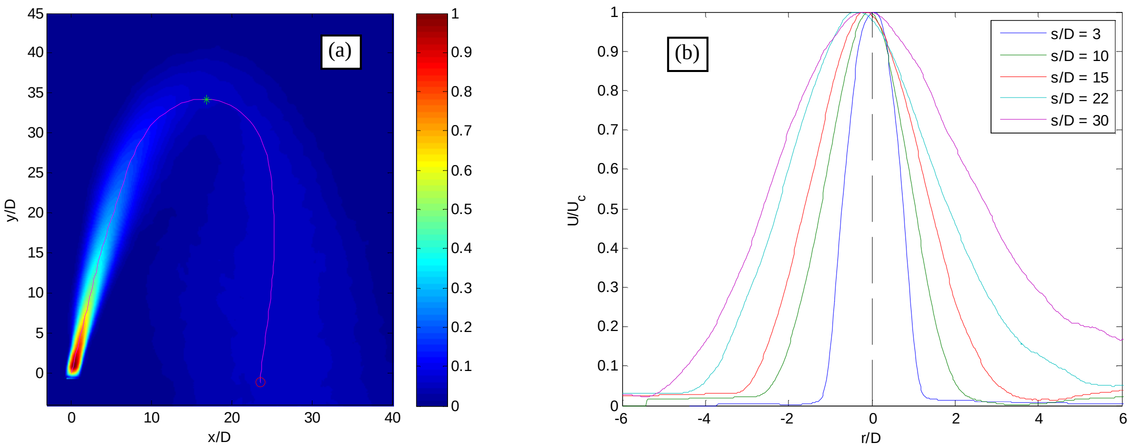

Figure 2. (a) Mean velocity field for a jet with Fr = 15, Re = 1000, and θ = 75°, the green asterisk is the maximum height reached by the jet axist (defined as the locus of the maximum axial velocity), and the red circle is the impact distance. (b) Velocity profiles orthogonal to the jet axis normalized by the maximum axial velocity U_C, (non dimensional axis coordinates s/D are shown in the legend).

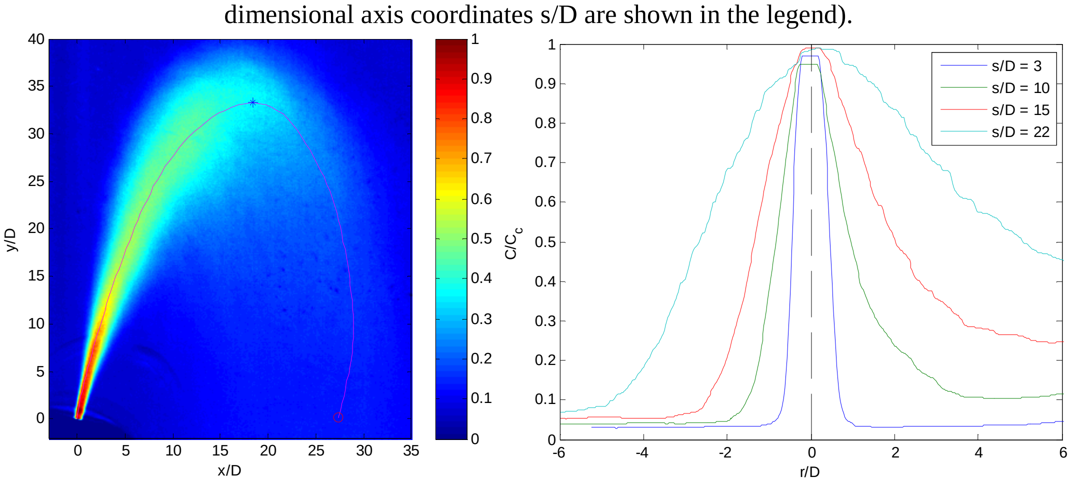

Figure 3. (a) Mean concentration field for a jet with Fr = 11, Re = 1000 and θ = 75°, the blue asterisk is the maximum height reached by the jet axis (defined as the locus of the maximum axial concentration), and the red circle is the impact distance. (b) Concentration profiles orthogonal to the jet axis normalized by the maximum axial concentration C_C, (non dimensional axis coordinates s/D are shown in the legend).