International Symposium
On Turbulence and Shear Flow
Phenomena (TSFP-8)
August 28 - 30, 2013 Poitiers, France

EXPERIMENTAL INVESTIGATION OF INCLINED NEGATIVELY BUOYANT JET

Ferrari Simone
Department of Ingegneria Civile, Ambientale e Architettura
University of Cagliari
Via Marengo 2, 09123 Cagliari - Italy
ferraris@unica.it

Badas Maria G.
Department of Ingegneria Civile, Ambientale e Architettura
University of Cagliari
Via Marengo 2, 09123 Cagliari - Italy
mgbadas@unica.it

Besalduch Luigi A.
Department of Ingegneria Civile, Ambientale e Architettura
University of Cagliari
Via Marengo 2, 09123 Cagliari - Italy
besalduch@unica.it

Querzoli Giorgio
Department of Ingegneria Civile, Ambientale e Architettura
University of Cagliari
Via Marengo 2, 09123 Cagliari - Italy
querzoli@unica.it

ABSTRACT

An inclined negatively buoyant jet (NBJ) is a physical phenomenon that develops when a fluid is discharged upwards into a lighter fluid (or downwards into a heavier fluid) with a release angle to the horizontal different from 90°. As in this phenomenon there are both a source of momentum and a source of buoyancy acting in different directions, its physics turns out to be very complex and not entirely explained. In order to get a deeper insight into the phenomenology of inclined NBJs, we have carried out an experimental measurement campaign in the laboratory, employing a novel non intrusive image analysis technique, namely FTV (Feature Tracking Velocimetry) to measure instantaneous velocity fields. Here we report first and second order velocity statistics, in order to highlight some of the geometrical features of the mixing properties of inclined NBJs.

INTRODUCTION

A negatively buoyant jet (NBJ) is a physical phenomenon that develops when a fluid is discharged, with a non negligible initial momentum, upwards into a lighter fluid or downwards into a heavier fluid. NBJs can be found in a large number of practical applications, ranging from the sea discharge of brine through submerged outfalls from desalination plants (Lai and Lee, 2012) or of dense effluents from wastewater treatment plants (Koh and Brooks, 1975), to improvement of water quality by forced mixing in reservoirs, small lakes or harbours (McClimans and Eidnes, 2000), to two-phase jets as in the exit snow from snow-ploughs (Lindberg and Petersen, 1991), or to sand and slurry jets as dredging and island building operations and pulverized coal combustion (Hall et al, 2010): an extensive list can be found in Ferrari and Querzoli (2010). NBJs are typically released in opposite direction to the buoyancy and with a certain angle to the horizontal, in order to increase the path of the NBJ and, consequently, to maximize the dilution. NBJs are driven from a source of both momentum and buoyancy: close to the outlet, the momentum prevails, so the NBJs behave basically as a simple jet; far from the outlet, otherwise, the buoyancy prevails, bending the NBJ and forcing it to behave in a plume-like manner. As momentum and buoyancy do not act in the same direction, the physics behind NBJs turns out to be very complex, leading to a not fully understood phenomenon.

The vast majority of the previous studies dedicated to NBJs (e.g., Cipollina et al., 2005) were performed via Light Induced Fluorescence (LIF) techniques, so the only measured quantities were the concentration fields, whilst in only few works the velocity fields were measured.

For instance, Querzoli and Cenedese, 2005, used both LIF and Particle Tracking Velocimetry (PTV) techniques, to study velocity and concentration profiles of laminar horizontal NBJs at different Froude numbers. Shao and Law (2010 and 2011) focused on NBJ released horizontally or with small angles to the horizontal (30° and 45°), to investigate the disposal of NBJs in shallow coastal wasters. They used combined Particles Image Velocimetry (PIV) and Planar Laser Induced Fluorescence (PLIF). Another paper based on PIV – LIF measurements on inclined NBJs, released at the end of a pipe, is the one by Lai and Lee (2012): the release angles were between 15° and 60° to the horizontal and the Froude number between 10 and 40.

In this work, we have investigated in the laboratory inclined NBJs employing a novel technique, namely FTV (Feature Tracking Velocimetry), in order to measure and study the velocity fields, and we present some results concerning the velocity fields, which were employed to determine some geometrical features of NBJs, and one of their second order statistics (the Turbulent Kinetic Energy, TKE) to characterize some of the mixing features.

NON-DIMENSIONAL PARAMETERS

As already stated, a negatively buoyant jet is driven by a source of momentum and one of buoyancy. When the receiving fluid is stagnant, the only parameters characterizing the initial conditions are Q (the initial flux of volume), M (the initial flux of momentum) and B (the initial flux of buoyancy per unit mass) (List, 1979).

Two characteristic length scales can be defined:

$$l_Q = \sqrt{\pi/4}D \cong D \tag{1}$$

$$l_M = \frac{M^{3/4}}{\sqrt{B}} \tag{2}$$

l_Q is a measure of the distance over which the volume flux of the entrained ambient fluid becomes approximately equal to the initial volume flux (Q);

l_M is a momentum length scale and represents the distance over which the buoyancy flux becomes approximately equal to the initial momentum flux (M), and the jet behaves like a plume.

This two length scales can be related to Richardson number Ri, representing the relative importance of the buoyancy flux to the momentum flux:

$$Ri = \frac{l_Q}{l_M} \tag{3}$$

The most employed non dimensional parameter for the classification of NBJ in the scientific and technical literature is the densimetric Froude number, Fr:

$$Fr = \frac{U_{MAX}}{\sqrt{g\frac{\rho_{DISC} - \rho_{REC}}{\rho_{REC}}D}} = \sqrt[4]{\frac{\pi}{4}}Ri^{-1} \tag{4}$$

where U_{MAX} is the mean initial jet velocity, g the gravitational acceleration, ρ_{DISC} the discharged fluid density, ρ_{REC} the receiving fluid density and D the outlet diameter. Fr is the ratio of inertial forces to buoyancy ones and it is proportional to the opposite of Ri:

$$Fr = \sqrt[4]{\frac{\pi}{4}}Ri^{-1} \tag{5}$$

The other relevant non-dimensional parameters controlling the behavior of inclined NBJs are the Reynolds number:

$$\mathrm{Re} = \frac{U_{MAX}D}{\upsilon} \tag{6}$$

Where υ is the kinematic viscosity of the discharged fluid, and the angle to the horizontal, θ: as this last parameter controls the misalignment between the flux of buoyancy and the initial flux of momentum, a NBJ is axisymmetric only as far as θ is equal to 90°.

EXPERIMENTAL SET-UP

The experimental set-up simulates a typical configuration of a submarine outfall, a portion of pipe, laid down on the sea bottom, with orifices along the pipe wall: as shown in Mi et al. (2001 and, 2007), this kind of release allows a larger entrainment than the one achievable with a release at the end of a pipe, which is the most investigated configuration in literature. In the model, a stagnant receiving body is simulated by a 21 m long flume, with glass walls, filled with water. The discharge comes through a pipe, which is connected to a constant head tank, by means of a cylindrical vessel, with a sharp-edge orifice on its lateral wall. The released fluid is a solution of water, sodium sulphate (to increase the density) and pollen particles (to visualize the jet). The jet middle vertical section is lighted by a light sheet, generated by a diode pumped green laser with a cylindrical lens. The experiments are recorded by a high speed video camera. In figure 1, a snapshot of a NBJ (with a densimetric Froude number Fr of 15 and a release angle to the horizontal θ of 65°) shot during an experiment for FTV is shown. The experiments were performed varying the densimetric Froude number, the angle to the horizontal and the Reynolds number, to study the influence of these parameters on the behaviour of the turbulent characteristic of NBJs.

FTV ALGORITHM

The algorithm used to perform experiments is an original technique, namely Feature Tracking Velocimetry (FTV). The main idea of this technique (and one of its main differences from classical techniques such as Particle tracking Velocimetry, PIV) is to compare windows only where the motion detection may be successful, so where there are high luminosity gradients, instead of using a regular grid as in traditional PIV. Hence, FTV is suitable for measurements from a wide range of seeding density and/or non-homogeneous one, for example between the jet and the external fluid, where other techniques yield significant errors, due to the non-homogeneous seeding at the boundary.

The procedure of analysis consists of:

- identification of the features using the Harris corner detection (a corner is a region with high luminosity gradients along the x and y direction) (Harris & Stephens, 1988);
- ordering of the features according to their corneress (the value of the Harris formula), and choice of the best features;
- comparison of the windows centered in the image "i^{th}" with windows around the position of the initial feature in the image "$i+1^{th}$";
- measure of the velocity as the displacement minimizing the dissimilarity, computed using the Lorentzian estimator;
- validation of the samples with an algorithm based on a Gaussian filtering of first neighbors (define by the Delaunay triangulation).

The statistics of velocity fields are subsequently obtained, by time averaging, under the hypothesis of ergodicity.

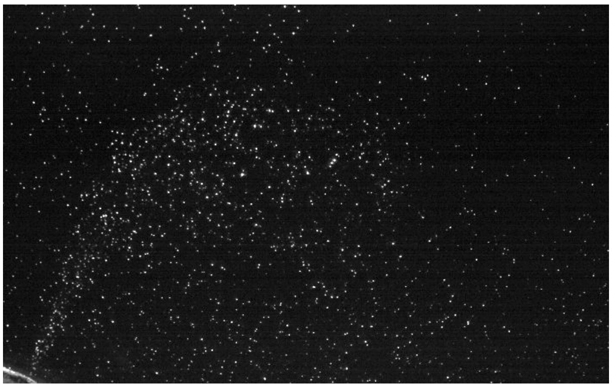

Figure 1. A snapshot of a negatively buoyant jet, with a densimetric Froude number Fr = 15, Re = 1500 and a release angle to the horizontal θ = 65°, seeded with pollen particles for the FTV (Feature Tracking Velocimetry) analysis.

RESULTS

In figure 2a, the mean velocity field U, normalized by the maximum velocity at the outlet U_{MAX}, for a jet with Fr = 15 and θ = 65°, is shown. The NBJ covers a very short initial distance, where it maintains a width similar to the diameter of the outlet and, after this distance, its width grows due to the onset of the Kelvin-Helmholtz billows. This means that near the nozzle, when the momentum prevails, the behavior of a NBJ is similar to the one of a simple jet, whilst, far from the nozzle, the buoyancy prevails, the NBJ reaches the maximum height and it bends down, behaving more in a plume-like manner. The axis of the jet has been defined as the locus of maximum intensity of velocity and plotted in figure 1 as a pink line. It is possible to see that 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 soon as the buoyancy becomes relevant, the span-wise sections become asymmetrical, because in the lower parte of the jet the local unstable stratification tends to transform the growing waves (Kelvin-Helmholtz instabilities) in plumes propagating downwards at the lower boundary.

This behaviour is apparent from velocity profiles, orthogonal to the jet axis, plotted in figure 2b, computed at different non-dimensional distances along the axis, s/D, and normalized by their maximum (axial) velocity, U_C. The upper region of the jet is on the left-hand side (negative values of r/D), the lower one on the right-hand side (positive values of r/D). If the mean velocity profiles near the orifice (e.g. s/D = 3) are symmetrical, in the other profiles, further from the origin of the jet, the lower portion of the jet is wider than the upper one, with this asymmetry that increases with increasing values of s/D.

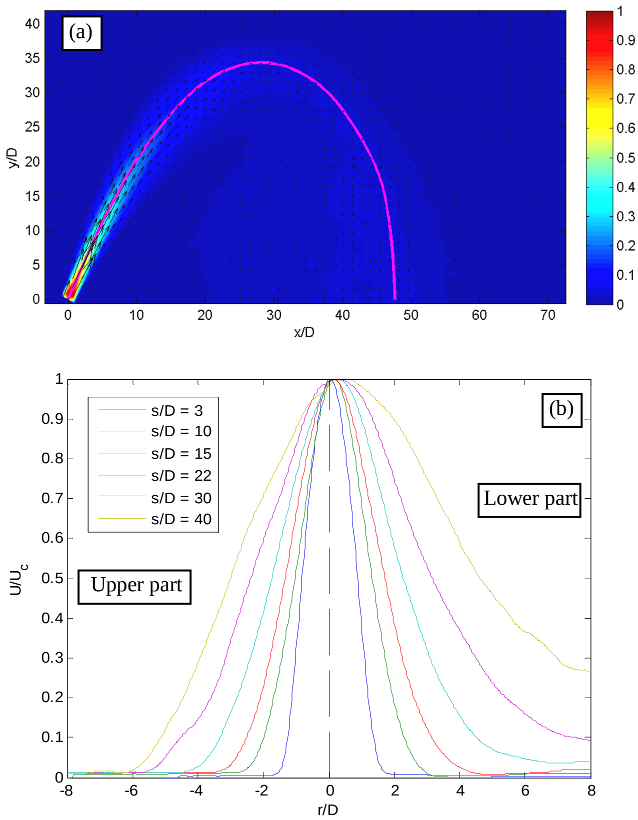

Figure 2. For a the same jet of figure 1: (a) map of the non-dimensional mean velocity U/U_{MAX} (U_{MAX} is the maximum velocity at the outlet), the pink line represents the jet axis (defined as the locus of maximum intensity of velocity); (b) velocity profiles orthogonal to the jet axis normalized by the maximum axial velocity U_C (non-dimensional axis coordinates s/D are shown in the legend; positive values of r/D identify the lower portion of the jet, negative ones identify the upper portion).

This lack in axisymmetry is mainly due to the different conditions of stratifications that can be found in the upper and lower boundaries of negatively buoyant jets: a stable stratification on the upper jet boundary and an unstable one on the lower boundary. This lack in axisymmetry suggests that a great care should be adopted when applying the integral equations for axisymmetric jets to inclined negatively buoyant jets.

In figure 3, the mean streamwise centreline velocity decay is shown, with pink asterisks, for the same NBJ of previous figures and for the data by Quinn (2006), regarding a simple jet issuing from a sharp-edged orifice (black circles) and a simple jet issuing from a contoured orifice (black stars). s/D is the non-dimensional distance measured from the jet origin along the axis. The NBJ values measured in the present work show a similar trend to the sharp-edged orifice ones, starting with values larger than one because of the vena contracta effect. The coefficient of contraction (i.e. the ratio between the area of the orifice to the area of the jet at the vena contracta) seems to have similar values (around 1.25) for the simple jet and the NBJ, showing that, so close to the origin, the buoyancy does not affect the NBJ behaviour. The NBJ decay is slowly faster than the simple jet one only at the beginning (up to 8 diameters from the origin); after 10 diameters from the origin, the behaviour of the centreline velocity decay of these three different kind of jets is very similar.

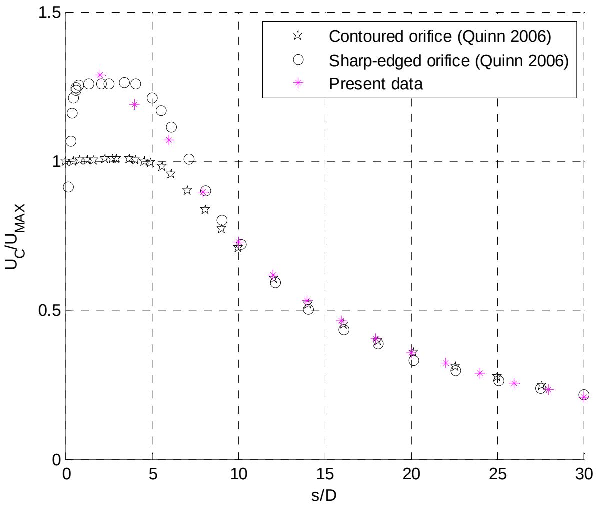

Figure 3. Mean streamwise centreline velocity decay U_C/U_{MAX} for the same NBJ of figure 1, pink asterisks, and a simple jet released from a sharp-edged orifice, black circles, and from a contoured orifice, black stars (Quinn 2006); U_{MAX} is the mean initial jet velocity; s/D is the non-dimensional distance measured from the jet origin along the axis.

In figure 4a, the non-dimensional mean Turbulent Kinetic Energy (TKE) field, normalized with U^2_{MAX}, is shown: the lowest values of TKE are in the central jet region and the maximum values are at the jet boundaries, where the turbulence is originated by the buoyant and the mechanical generated eddies.

Figure 4b shows the TKE profiles normalized by TKE_C (i.e. the maximum axial TKE) measured at different distances from the origin s/D: the lack of symmetry between the lower and the upper parts of the jet is apparent. The highest peak of the TKE value is at the upper boundary (where there is a stable stratification and, consequently, the TKE finds the opposition of the buoyancy, acting in the opposite direction to the momentum, and allows the Kelvin-Helmholtz waves to develop completely), the lower peak at the lower boundary (where there is the mentioned unstable stratification). As s/D increases, the TKE generated at the jet boundaries tends to spread toward the centre of the jet and, consequently, the TKE profiles tend to become more uniform.

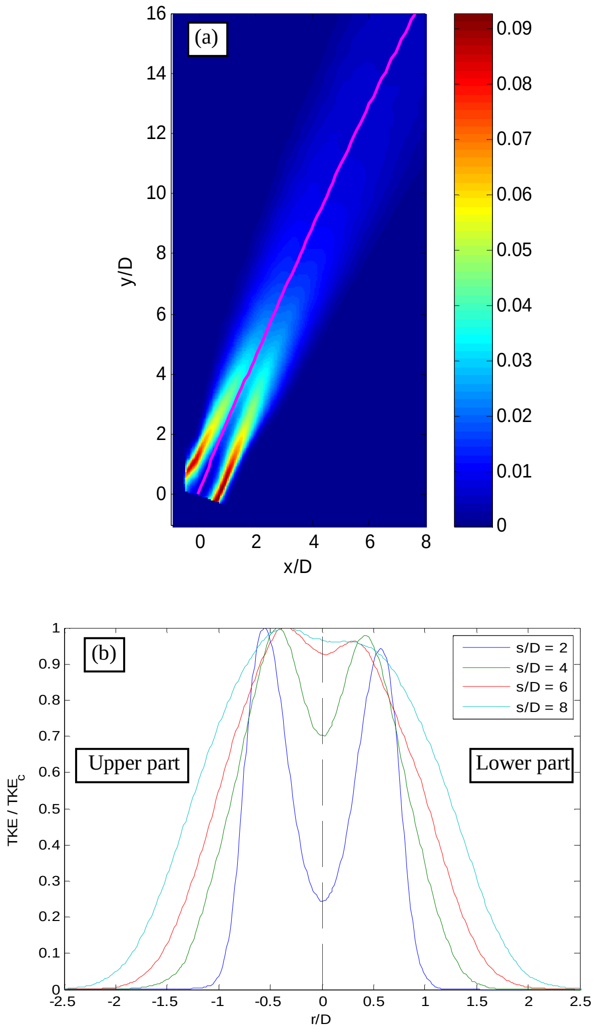

Figure 4. For a the same jet of figure 1: (a) map of the non-dimensional mean Turbulent Kinetic Energy (TKE), normalized with U^2_{MAX}; the pink line represents the jet axis;. (b) TKE profiles orthogonal to the jet axis normalized by TKE_C, i.e. the maximum axial TKE (non-dimensional axis coordinates s/D are shown in the legend; positive values of r/D identify the lower portion of the jet, negative ones identify the upper portion).

CONCLUSION

The behaviour of negatively buoyant jets, released from a sharp-edged orifice, was investigated by means of an original, non-intrusive, image analysis technique to measure the velocity fields, namely Feature Tracking Velocimetry. Some first and second order statistics of the velocity fields (velocity and turbulent kinetic energy , as well as their profiles, orthogonal to the jet axis, and the mean streamwise centreline velocity decay) were computed to better characterize the negatively buoyant jet behaviour.

The velocity fields and the velocity profiles shows that NBJs are symmetrical in their first part, close to the jet origin, where the flow is driven essentially by the initial momentum, but, as soon as the buoyancy becomes relevant, it becomes non axisymmetric, with the lower portion of the jet that is wider than the upper one. This lack in axisymmetry suggests that a great care should be adopted when applying the integral equations for axisymmetric jets to inclined negatively buoyant jets.

The mean streamwise centreline velocity decay shows that NBJ have a similar trend to sharp-edged orifice simple jets, with similar values of the coefficient of contraction, confirming that, close to the origin, the buoyancy doesn't affect the NBJ behaviour, even if the NBJ decay is slowly faster than the simple jet one only at the beginning.

The fields and profiles of Turbulent Kinetic Energy TKE highlight once more the mentioned lack in axisymmetry: the highest peaks of the TKE value are at the upper boundary, the lower peaks at the lower boundaries, with the TKE generated at the jet boundaries that tends to spread toward the centre of the jet (with more uniform profiles) as the distance from the origin increases.

REFERENCES

Cipollina, A., Brucato, A., Grisafi, F., Nicosia, S., 2005, Bench scale investigation of inclined dense jets, *J. Hydraulic Eng.*, 131(11), 1017–1022.

Ferrari, S. and Querzoli, G., 2010, Mixing and re-entrainment in a negatively buoyant jet, *Journal of Hydraulic Research*, 48(5), 632-640.

Hall, N., Elenany, M., Zhu, D., and Rajaratnam, N., 2010, Experimental Study of Sand and Slurry Jets in Water, *J. Hydraul. Eng.*, 136(10), 727–738.

Harris, C. and Stephens, M., 1988, A combined corner and edge detector, in: *Proceedings of the 4th Aivey Vision Conference*, Manchester, 147-151.

Koh, R.C.Y. and Brooks, N.H., 1975, Fluid mechanics of wastewater disposal in the ocean, *Ann. Rev. Fluid Mech.*, 7, 187–211.

Lai, C.C.K. and Lee, J.H.W., 2012, Mixing in inclined dense jets in stationary ambient, *Journal of Hydro-environment Research*, 6, 9-28.

Lindberg,W.R. and Petersen, J.D., 1991, Negatively buoyant jet (or plume) with application to snowplow exit flow behaviour, *Transportation Res. Record.*, 1304, 219–229.

List, E.J., 1979, Turbulent jets and plumes, in: Fisher, H.B., List, E.J., Koh, R.C.Y., Imberger, J. and Brooks, N.H. (Eds), *Mixing in inland and coastal water*, New York, USA, Academic Press, 315-389.

McClimans, T. and Eidnes, G., 2000, Forcing nutrients to the upper layer of a fjord by a buoyant plume, *Proc. 5th Intl. Symp. Stratified Flows*, Vancouver, 199–204.

Mi, J., Nathan, G.J. and Nobes, D.S., 2001, Mixing characteristics of axisymmetric free jets from a contoured nozzle, an orifice plate and a pipe, *J. Fluid Eng. ASME*, 123(4), 878-883.

Mi, J., Kalt, P., Nathan, G.J. and Wong, C.Y., 2007, PIV measurements of a turbulent jet issuing from round sharp-edged plate, *Exp. Fluids*, 42(4), 625-637:

Querzoli, G. and Cenedese, A., 2005, On the structure of a laminar buoyant jet released horizontally, *J. Hydraulic Res.*, 43(1), 71–85.

Quinn, W.R., 2006, Upstream nozzle shaping effects on near field flow in round turbulent free jets, *European Journal of Mechanics B/Fluids*, 25, 279–301.

Shao, D. and Law, A.W.K., 2010, Mixing and boundary interactions of 30° and 45° inclined dense jets, *Environ. Fluid Mech.*, 10, 521-553.

Shao, D. and Law, A.W.K., 2011, Boundary impingement and attachment of horizontal offset dense jets, *Journal of Hydro-environment Research*, 5, 15-24