Study of a co-flowing hot jet: an application of direct 3DBOS technique in research wind tunnel

David Donjat[1,*], Francois Nicolas[1], Aurelien Plyer[2], Francis Micheli[1], Philippe Cornic[2], Guy Le Besnerais[2], Frédéric Champagnat[2], Yves Le Sant[3], Jean-Michel Deluc[4]

[1]ONERA Centre de Toulouse, France
[2]ONERA Centre de Palaiseau, France
[3]ONERA Centre de Meudon, France
[4]ONERA Centre du Fauga-Mauzac, France
*corresponding author: david.donjat@onera.com

Abstract Onera has been working for several years on the measurement of three-dimensional and instantaneous flow fields in order to improve the characterization of various types of complex flows. Background Oriented Schlieren (BOS) is an experimental technique to measure the density field where variations of optical index are indirectly measured by imaging deviations of light rays passing through the flow. Density fields derive directly from optical index estimation through the Gladstone-Dale equation. Due to its relative simplicity, the BOS technique allows to easily multiple the number of points of view in order to achieve a complete 3D flow tomography. Here, the technique is adapted on a large research ONERA wind tunnel. The tested flow is a co-flowing hot jet (with a total temperature of 80 °C) generated at the wingtip of a simplified half-wing fixed on the floor of the test section. The upstream wind tunnel flow has a speed of 20 m/s with total temperature and pressure equals to ambient conditions. The 3DBOD system consists of 12 cameras distributed on a side and the ceiling of the test section, the ground and the other side of the vein is dedicated to screens. Image processing is performed with the complete treatment software developed in the project. Three-dimensional density field of the unsteady jet flow is successfully obtained. In parallel, the hot co-flowing jet is also investigated with stereo PIV technique and thermocouple measurements in order to have a complete description of the flow. In particular, thermal measurements allow a complete comparison with 3DBOD results and confirm the quality of the density reconstructions.

Keywords: background oriented schlieren, 3D tomography reconstruction, inverse problem, hot plume, wind tunnel

1 Introduction

Schlieren optical methods use the information of the change of refractive index induced by a fluctuation of density, generating a deflection of light rays between the different regions of the flow. Among these methods, the BOS technique (or "Background Oriented Schlieren") quantifies the value of the beam deflection angle. It appears as an indirect method of density measurement. Since the first works in the early 2000s, numerous studies have demonstrated the application potential of this method for aerothermal flows [1], wake phenomena [2], supersonic flows [3][4] or flames [5].
The BOS experimental procedure consists in recording a couple of images of a textured background with a specific pattern without any flow (i.e. reference frame) and with the flow in between the camera and the background as described on figure 1. Image correlation algorithms provide the apparent displacement of the texture background through the flow of interest. Knowing the calibration of the camera, we can deduce from the displacements the angles of deviation associated with the visualized flow. If we are able to measure light deviation from a sufficient number of points of view, a reconstruction of the density field can be achieved by numerical inversion of the classical equation:

$$\varepsilon_u = G \int \frac{\partial \rho}{\partial u} ds \qquad (1)$$

where G is the Gladstone-Dale constant and $u = x, y, z$, the three directions.

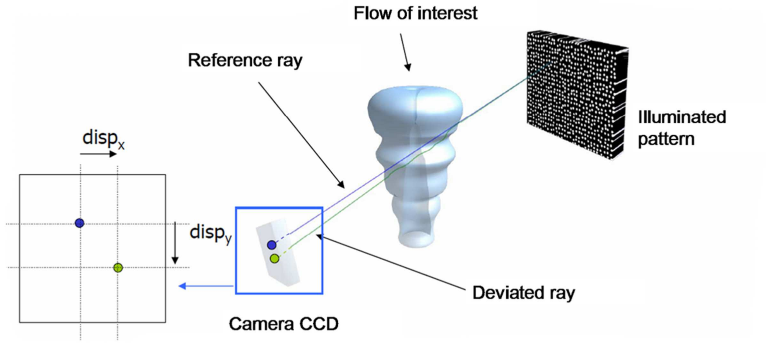


Fig. 1 BOS technique

The reconstruction of a 3D density field without symmetry called 3DBOS requires the acquisition of several projections. The difficulty of the problem is directly linked to the number of projections available. Several recent studies describe three-dimensional reconstructions from BOS data. In our study, we favour the algebraic approach that appears to be the most relevant, since it behavior is more robust for limited and noisy data which is a current situation in the context of the 3DBOS. Ihrke [6][11] is the first to use this approach in a BOS data processing. Subsequently, this approach was used by Ota to rebuild the mean field around an asymmetric body in a flow Mach 2 [3] and a flow of natural convection [5]. In both cases, the proposed strategy is based on a reconstruction of the gradient fields in the three directions with ART approach following by an integration to obtain the density field. Opposite to this sequential approach, the method proposed by ONERA consists in a direct reconstruction of the density field from the measured deviations by combining both the tomographic reconstruction and the spatial integration [1]. Assuming that the paraxial approximation applies, the equation 1 can be discretized as a linear system:

$$\varepsilon = TD\rho = A\rho \tag{2}$$

where the observation operator A combines the spatial derivative of the density D and the tomographic operator T associated to the imaging process. Following [1] and [15] we adopt a direct regularized method where the reconstructed density field is defines as the minimizer of the criterion:

$$F(\rho) = \|\varepsilon - A\rho\|^2 + \lambda\|\nabla\rho\|^2 \tag{3}$$

The regularization parameter is automatically estimated thanks to a L-curve approach [9]. The resulting inverse problem is solved as a minimization problem of a regularized criterion using a conjugate gradient method [8]. The set of algorithms is encoded on GPU architecture (Graphics Processing Units) to reduce the computing time and allow the reconstruction of large fields.

In this article, we present a practical application of this method for the measurement of a hot jet flow in an industrial wind tunnel environment, which integrates all the constraints and difficulties induced by such an installation.

2 A wind tunnel application: a hot plume in a co-flowing air flow

The application of 3DBOS technique in real conditions is conducted in the ONERA's F2 wind tunnel localized in Fauga-Mauzac center. This subsonic facility can reach a velocity of 100m/s and the test section is 1.4m wide, 1.8m high and 5m long. Large window panels provide very good access for optical diagnostics. A combination of screens honeycombs, acoustics dumper and a contraction ratio of 12 contribute to a turbulence level inferior to 0.05%. An illustration of the wind tunnel is shown in Figure 2.

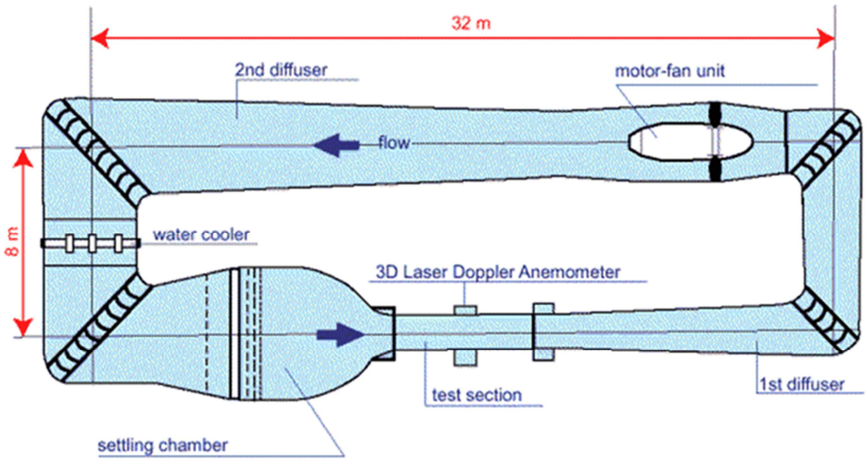


Fig. 2 Sketch of F2 wind-tunnel of ONERA

The model under study (see figure 3) consists in a 54 mm diameter pipe surrounded by a fairing. The pipe is feed with 60 bar air, warm-up by a heater. The hot air exiting from the pipe is fully developed. The jet mass flow rate and temperature are measured. A whole set of conditions has been conducted, varying the wind tunnel speed (between 20 to 50 m.s^{-1}), the wing's angle of attack (between 0 to +3°), the pipe mass flow rate (between 80 to 160 g.s^{-1}) and also the jet temperature (between 30° to 140°C).

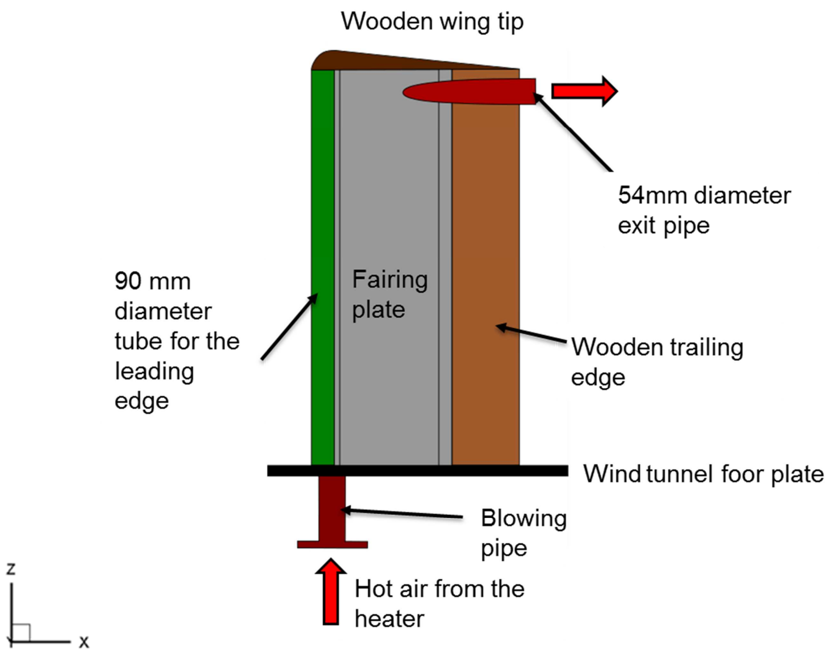


Fig. 3 Sketch of F2 wind-tunnel of ONERA

For 3DBOS acquisitions, we set up 12 JAI 5Mpxl cameras, equipped with a 50 mm lens around the model on a half ring shape. 9 cameras are linked on a crossbars ladder mount on the left and the 3 others are mounted on the top of the test section as shown on figure 4. All the cameras are linked to a computer via a Gigabit Linksis SRW2016 hub Ethernet. According to the camera distribution around jet flow, the volume under study consisted in a rectangular box of 350 x 160 x 160 mm^3.

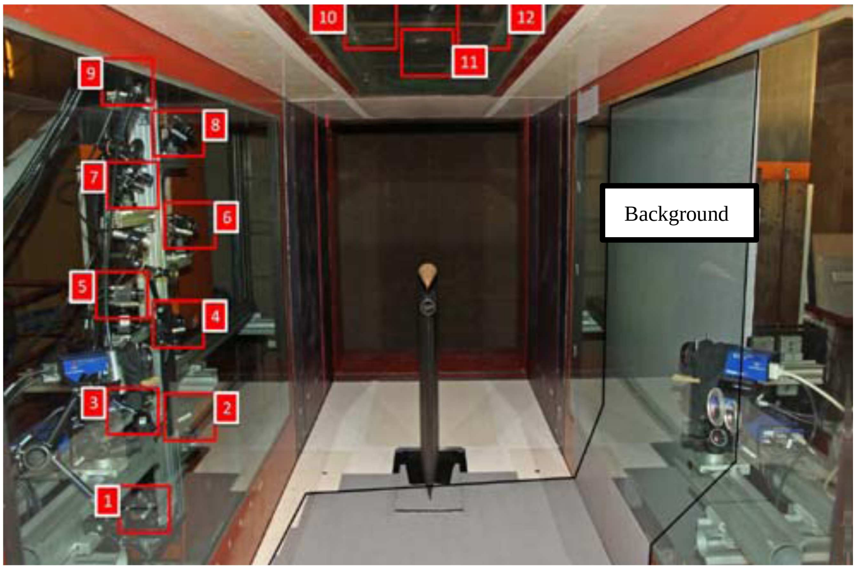


Fig. 4 3DBOS system adapted for F2 wind tunnel

The background, formed with a semi-random distribution of 1 mm diameter white dots, cover the test section floor and an additional panel outside (see figure 4 and figure 5). In order to freeze the flow, a Quantel Nd:YAG 2x200 mJ laser (Big Sky Laser Twin BSL 200) is used to light the background. The beam is separated into 4 by a division plate before entering into liquid guides. Then, each beam is spread out by an 18 mm lens and directed to the background thanks to a plane mirror. Due to the hub poor bandwidth, we are limited to an acquisition frequency of 0.2Hz to retain non damaged images. The 8 ns laser flash occurs during the 64 µs exposure time of the cameras. The cameras and the laser are synchronized by a 24 output PulseBlaster pulse generator.

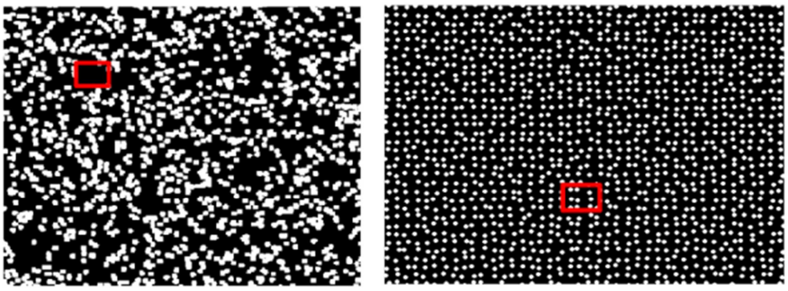


Fig. 5 Choice of the background pattern. On left: classical random pattern; on right: the proposed semi-random pattern. The leftmost red rectangle has the size of a typical interrogation window

The implementation of the 3D field reconstruction from BOS images acquired with the system described above requires both a prior step of a challenging geometric calibration (described in [14]) and a step of pre-processing to extract the input data. After image pre-processing in order to correct the distorting effects from intrinsic calibration performed in advance, the BOS data is processed with FOLKI-SPIV, the optical flow treatment software developed at ONERA [13]. Fields of pixel displacements obtained (see for the leftmost example in figure 6) are then operated by considering geometrical calibration to retrieve the deviations of data in the three directions. These maps are finally combined in the 3D reconstruction software described earlier. After optimization of the quadratic regularization criterion, a 3D density field is calculated and presented in figure 6. Moreover, an analysis of the performance of the method shows that the sensitivity of the technique depends greatly on the optical conditions in place. In our case, the method adapted here allows detecting displacements induced by aero-optic effects generated by a temperature difference of about 10°C.

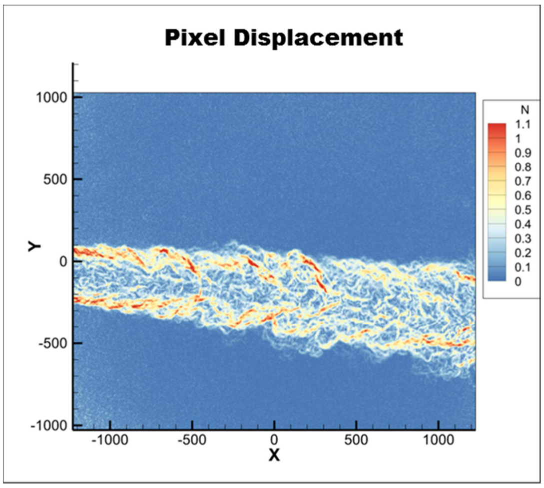
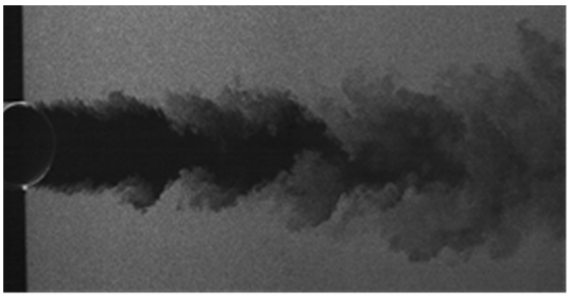


Fig. 6 On left: Pixel displacement measured by BOS (camera N°5) – On right: 3D reconstruction of the jet by 3DBOS shown by isodensities (Case: Q=80 g/s – Tj = 100°C)

In addition to 3D BOS acquisitions, alternative measurements are set up.
First, a stereo-PIV campaign is done in order to characterize the interaction between jet flow and surrounding cold air. These measures provide an additional representation of co-current jet and bring validation elements of the 3DBOS method. A double pulsed Litron YAG, 2 x 400 mJ laser is set up on the top of the test section. A combination of three plane mirrors and a beam expander provides a laser sheet in the streamwise direction, in the jet center. Two 4 Mpxl Pro X Cameras controlled by Lavision Davis software are used (see also figure 4). The streamwise flow is seeded with olive oil via a Laskin Nozzle and we used 1µm diameter particles of DEHS for the pipe flow. The leftmost illustration on figure 10 presents a tomographic illustration of jet flow blowing up in a surrounding seeded flow. The PIV processing is achieved by Folki-SPIV.
In a second step, the two systems, 3D BOS and stereo-PIV, are combined to take quasi-simultaneous acquisitions. For information, such a nearest experiment was already done in a 2D approach by [16] to describe wake flow downstream of a heated cylinder. In our experiment, the BOS pulse generator is used to synchronize both BOS and stereo-PIV systems. The PIV process is started just after the end of BOS acquisitions in order to avoid the glare of any optical sensor. The delay between BOS and stereoPIV acquisitions is about 100 µs whereas the PIV double frame delay is about 10 µs. This appreciable delay induces a small spatial gap between results.
Finally, temperature measurements are acquired via a thermocouples sampling. Three different planes are investigated in the weak of the pipe in X=10 mm, 150mm and 300mm. A rake of 4 thermocouples, shown on figure 7, is used to explore a 100 x 100 mm² mesh with a resolution of 5 mm. The acquisition frequency is 0.5 kHz and the timeout interval is 15s. In each point, the mean temperature is the result of 500 samples acquired.



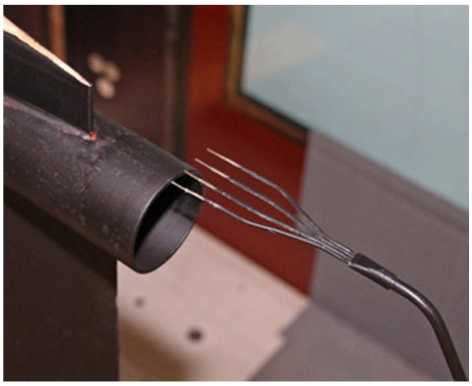


Fig. 7 Left: an illustration of jet flow revealed by external seeded wind tunnel flow; Right: thermocouple rake used for thermal measurements in action

3 A wind tunnel application: a hot plume in a co-flowing air flow – Results and discussions

By using the 3DBOS method described earlier, the unsteady jet flow is reconstructed and presented in figure 8. The reconstructed volume is discretized based on 15 Mcells mesh with a 1mm resolution. Despite the small number of projections used, the result is quite consistent with the topology of a hot jet driven by an ambient flow and achieved density levels are comparable to the expected values in the case studied. The use of a mask is essential in order to increase the accuracy of reconstruction. Nevertheless it induces clearly a small gap of density near its boundary. For both inlet and outlet boundary, we use a free condition which allow an accurate reconstruction of the jet on boundaries.

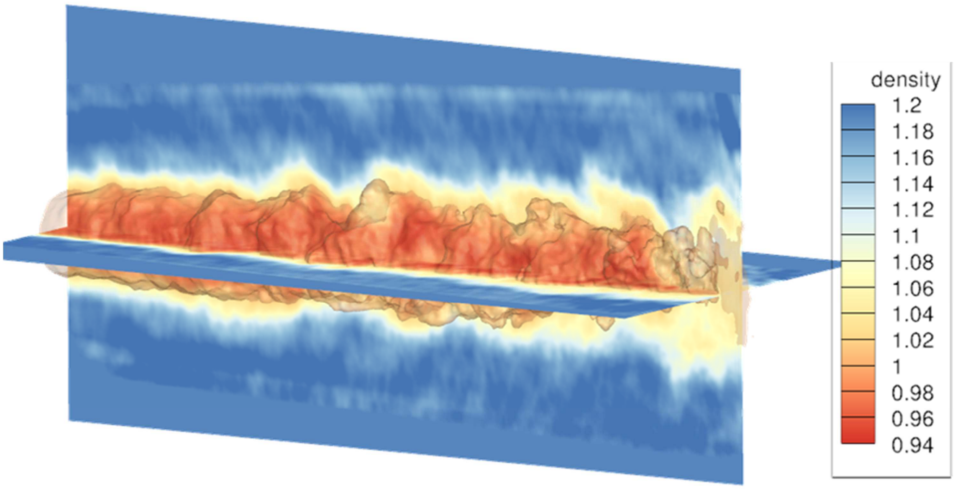


Fig. 8 3D reconstruction of density field – T_{jet} =100 °C; Q_{jet} = 80 g/s; V_{ext} = 20 m/s

In order to validate density data obtained, we can consider the negligible influence of pressure on density in this configuration. In this way, temperature maps can be extracted directly from the density field. We need to compare both databases on mean flow fields. Temperature maps acquired with thermocouple comb are presented on figure 9 where we can easily follow the hot jet core evolution with the development of a mixing layer around.

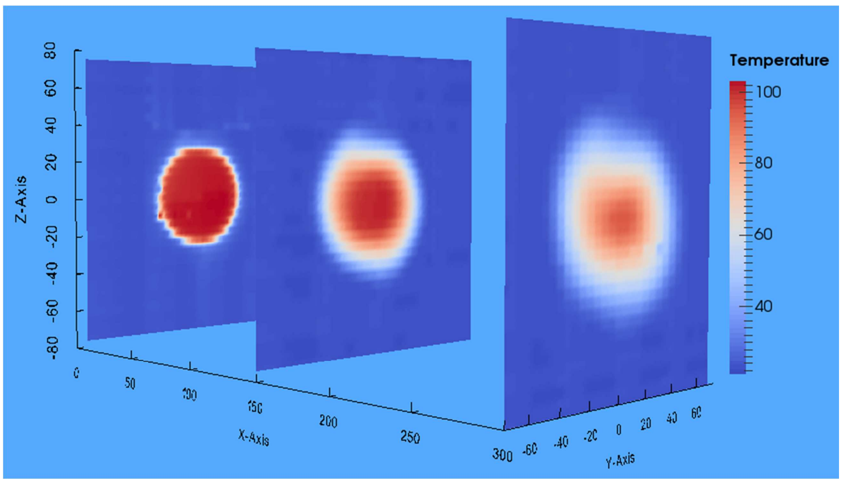


Fig. 9 Temperature maps along the jet flow – T_{jet} =100 °C; Q_{jet} = 80 g/s; V_{ext} = 20 m/s

Downstream of the flow, temperature field become clearly asymmetric due to wing tip influence. This behavior is confirmed by PIV results illustrated by the figure 10. In particular, we can observe through turbulent kinetic energy level the development of the mixing layer and the swirling behavior of the plume introduced by the wing tip flow. The mean density field is obtained with 50 unsteady displacements maps and temperature field is deduced considering a mean pressure measured in the vicinity of the profile. To compare correctly each temperature maps, we build a dimensionless temperature as in order to take into account the evolution of the wind tunnel flow temperature T_{ext}:

$$T_n = \frac{T - T_{ext}}{T_{jet} - T_{ext}} \tag{4}$$

The figure 11 shows a comparison between temperature profiles obtained with thermocouples measurements and temperature profiles extracted from 3D field based on BOS data (reconstructed on a 116 Mvoxels volume with a resolution of 0,5mm). Results show a very good consistency despite a lack of amplitude of about 7% for BOS data. This is mainly due to the small number of displacement maps used for mean field calculation.

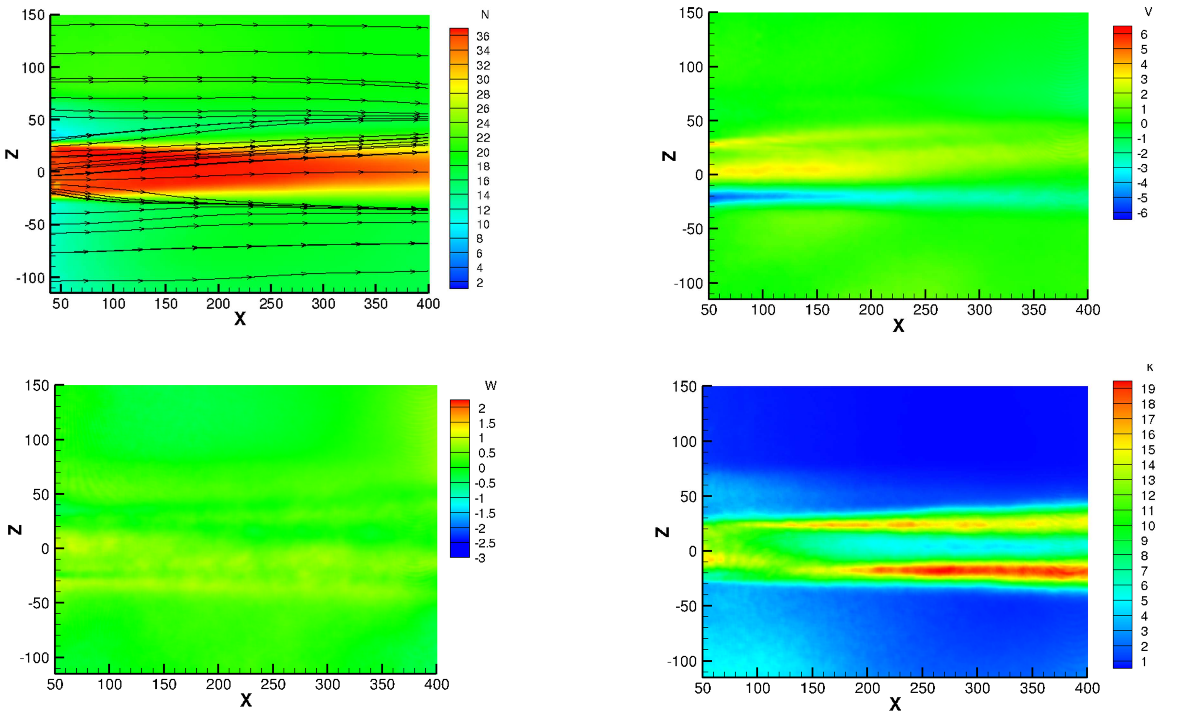


Fig. 10 Velocity field described by stereoPIV technique – Mean velocities in m/s and turbulent kinetic energy in m²/s² – T_{jet} =100 °C; Q_{jet} = 80 g/s; V_{ext} = 20 m/s

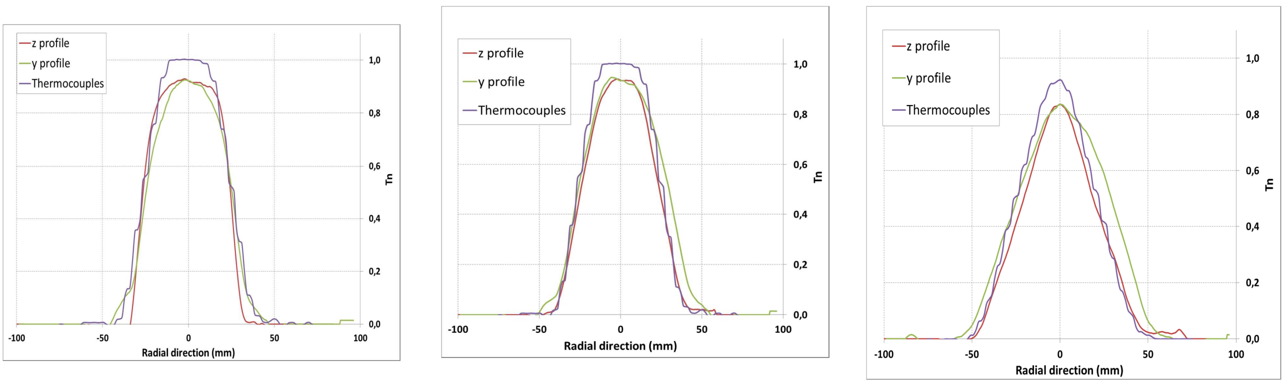


Fig. 11 Comparison of the dimensionless temperature measurements at several transversal planes

Finally, the last part of the experiment combines 3DBOS and stereoPIV which could give an instantaneous view of both velocity and density field of the jet. This kind of combined measurements is now essential in experimental description of fluid mechanics as it must largely increase our comprehension of the relationship between the momentum and heat transfer for convective flows. The figure 12 presented the instantaneous stereo-PIV and 3DBOS results illustrated by respectively the vorticity and the density maps in the same plane. For information, the 3DBOS reconstruction is done on a mesh with 31 Mcells and a resolution of 1mm. A parallel comparison of both maps shows that the distribution of vorticity is localized in the mixing layer developing around the jet core and revealed by density results.

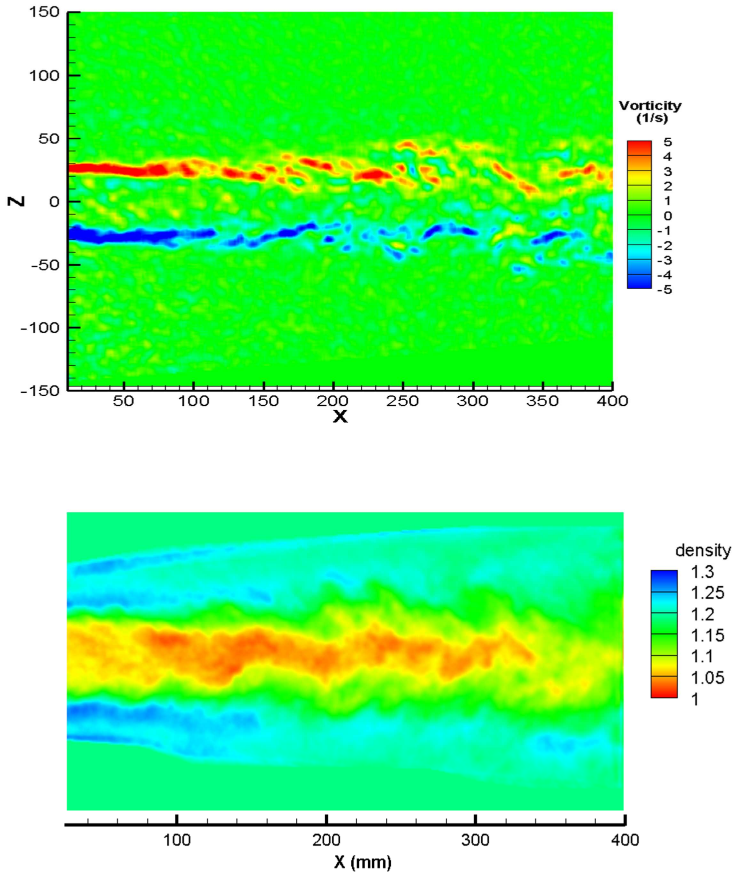


Fig. 12 Instantaneous combined measurement - Top: vorticity map (1/s) obtained by stereoPIV; below: a extracted map of density (kg/s) at the same time (100 µs of delay)

4 Conclusions

A direct method for 3D reconstruction of the density field from BOS data has been described. In the case of convection flows, this technique allows reconstructing the flow topology as well as, the temperature field at the origin of density variations if considering a few more assumption. The adaptation of the BOS3D method for large wind tunnels is presented through an experiment conducted in the wind tunnel F2 on a hot jet co-current. During this campaign, several techniques have been implemented sequentially or in parallel to obtain a 3D map of the flow velocity, temperature and density. In particular, a comparison between 3DBOS reconstructions and temperature profiles shows a very interesting consistency which underlines the great interest of the BOS3D in the context of experimental fluid mechanics.

References

[1] Todoroff V. (2013) Mesure d'un champ de masse volumique par BOS3D. Etude d'un dispositif expérimental et des méthodes de traitement pour la résolution du problème inverse, PhD thesis, Université de Toulouse, France

[2] Raffel M., Heineck J.T., Schairer E., Leopold F., Kindler K. (2014) BOS Imaging for full-scale and in-flight testing, *Journal of the American Helicopter Society*, Vol 59

[3] Ota M., Hamada K., Kato H., Maeno K. (2011) Computed-tomographic density measurement of supersonic flow field by colored-grid background oriented schlieren (CGBOS) technique, *Measurement Science and Technology*, Vol 22, pages 104-111

[4] Leopold F., Ota M., Klatt D., Maeno K. (2013) Reconstruction of the Unsteady Supersonic Flow around a Spike Using the Colored Background Oriented Schlieren Technique, *Journal of Flow Control, Measurement & Visualization*, n°1, pages 69-76

[5] Iffa E., Aziz A., Malik A. (2010) 3D time resolved temperature and concentration measurement using Background Oriented Schlieren, ISFV14

[6] Ihrke I. (2007) Reconstruction and rendering of tim-varying natural phenomena, PhD thesis, Max-Planck-Institut für Informatik

[7] Ota M. (2014) Simultaneous Multi Angle Measurement of Natural Convection by Colored-Grid Background Oriented Schlieren (CGBOS) Technique, 16 th ISFV, Okinawa, Japan

[8] Labat C. et Idier J. (2008) Convergence of conjugate gradient methods with a closed-form stepsize formula, *Journal of Optimization Theory and Applications*, Vol 136, pages 43-60

[9] Idier J. (2008) Bayesian Approach to Inverse Problems, Wiley

[10] Ihrke I., Magnor M. (2004) Image-based tomographic reconstruction of flames. D.P. R. Boulic (ed.) Eurographics/ACM SIGGRAPH Symposium on Computer Animation

[11] Atcheson B., Ihrke I., Heidrich W., Tevs A., Bradley D., Magnor M., Seidel H.-P. (2008) Time-resolved 3D Capture of Non-stationary Gas Flows, ACM Transactions on Graphics, Proc. SIGGRAPH Asia

[12] Champagnat F. (2011) Fast and accurate PIV computation using highly parallel iterative correlation maximization, *Experiment in Fluids*, 50, 1169-1182

[13] Vuillot F., Lupoglazoff N., Rahier G. (2008) Double stream nozzles flow and noise computations and comparisons to experiments, Proceedings of the 46th AIAA Aerospace Sciences Meeting and Exhibit

[14] Le Sant Y., Todoroff V., Bernard-Brunel A., Le Besnerais G., Micheli F., Donjat D., Nicolas F. (2014), Multi-camera calibration for 3D-BOS, International Symposia On Applications Of Laser Techniques To Fluid Mechanics, Lisbon

[15] Todoroff V., Le Besnerais G., Donjat D., Micheli F., Plyer A., Champagnat F. (2014), Reconstruction of instantaneous 3D flow density fields by a new direct regularized 3DBOS method, International Symposia on Applications of Laser Techniques to Fluid Mechanics, Lisbon, Portugal

[16] Bencs P., Szabo S., Bordas R., Zähringer K., Thevenin D. (2011), Simultaneous measurement of velocity and temperature downstream of a heated cylinder, ASME 2011 Pressure vessels and piping division conference PVP2011, PVP2011-57789, Baltimore, USA