Characterisation of the interaction between a boundary layer and a cavity using Digital Particle Velocimetry with Optical Flow

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ABSTRACT

An Optical Flow technique based on the use of Dynamic Programming has been applied to Particle Image Velocimetry yielding a significant increase in the accuracy and spatial resolution of the velocity field. Results are presented for an interaction between a laminar boundary layer and a cavity.

The experimental characterisation of the interaction between a boundary layer and a cavity was developed in order to valid a three dimensional computation code based on the L.E.S. method (Large Eddies Simulation). The main application of this work is the study of the pollutant transport and dispersion in a canyon street.

INTRODUCTION

The aim of this investigation is to explore the possibility of using an optical flow technique in measuring fluid flow velocity. Classical flow visualisation is based on direct observation of tracer particles. Analysis of subsequent images searching for local displacements allows quantitative measurement of two-dimensional flow fields. The optical flow method offers a new approach for analysing flow images. It largely improves spatial accuracy and minimises the number of spurious vectors. Application of this method may help in quantitative analyses of several challenging problems of fluid mechanics, as well as in full plane validation of their numerical counterparts. This technique has been tested for calibrated synthetic sequences of images (Quénot et al., 1997). It was observed that the accuracy remains better than 0.5 pixels/frame.

The study of the interaction between a boundary layer and a cavity is an approach in characterisation of flow regimes within the urban canyon (Hunter et al., 1991).

Much attention has been directed to the study of the various canyon flow regimes (DePaul and Sheih, 1986; Oke, 1988) since air flow is responsible for the transport of properties such as pollutants, heat and moisture. A number of studies have referred to the existence of a vortex cell within an urban street canyon when ambient winds aloft are perpendicular to the street.

Canyon geometry is an important determinant of characteristic airflow observed within urban canyons. Three principal flows regimes are ”skimming” flow, ”wake interface” flow and ”isolated roughness” flow, following the nomenclature of Oke (1987). The transition between flows is determined by canyon geometry and can be described in terms of threshold height/width (H:W) ratios for an arbitrary length (L/H) ratio.

Previous studies used a k-e model of air flow to confirm the wind tunnels observations. The model was based on that developed by Paterson and Apelt (1989) to predict pressure experienced by walls of buildings within cities. It solves the Navier-Stokes equations for momentum and the equations for the transportation and dissipation of turbulent kinetic energy.

An approach Large Eddies Simulation was proposed (Chabni, 1997) which predict the large eddies structures characterised by a higher turbulent kinetic energy and it models only the little scales (not accessible to the numerical discretisation). The aim of our study is to provide experimental results in order to valid the numerical model. The results obtained by optical flow technique was compared with those obtained by classical DPIV (Digital Particle Image Velocimetry) based on cross-correlation (Hiller et al., 1993) and then with the numerical results.

Optical Flow for DPIV

Optical flow computation consists in extracting a dense velocity field from an image sequence assuming that the intensity is conserved during the displacement. Several techniques have been developed for the computation of optical flow. In a survey and comparative performance study, Barron et al. (1994) classify them in four categories: differential, correlation based, energy based and phase based. Not all of these are well suited for the DPIV problem. Many of these require long image sequences that are not easily obtained experimentally. The technique that was chosen for DPIV application was introduced by Quénot (1992) as Orthogonal Dynamic Programming (ODP) algorithm for optical flow detection from a pair of images. It has been extended to be able to operate on longer sequences of images and to search for subpixel displacement (Quénot, 1996). The ODP based DPIV will referred to as ODP-DPIV. Compared with other optical flow approaches or to the classical correlation based DPIV, the ODP-DPIV has the following advantages: (i) it can be applied simultaneously to sequences of more than two images; (ii) it performs a global image match by enforcing continuity and regularity constrains on the flow field. This helps in ambiguous or low particle density regions; (iii) It provides dense velocity fields (neither holes nor border offsets); (v) local correlation is iteratively searched for in regions whose shape is modified by the flow, instead of being searched by fixed windows. This greatly improves the accuracy in regions with strong velocity gradients.

The orthogonal algorithm

Strip to strip alignment

The algorithm is based on the search of a transformation that relates the second image to the first one and minimises the Minkowski distance.

The matching is global and does not require any previous segmentation or features extraction. The main idea is to transform the search problem for two-dimensional displacements into a carefully selected sequence of search problems for one dimensional displacement, thereby decreasing greatly the complexity.

First, the two images are identically sliced into several parallel overlapping strips (Fig. 1). Then, for every pair of strips, an optimal match is searched for with displacement allowed only in the slicing direction and identical for all the pixels in the same column in the orthogonal direction (Fig. 2)

A dense field of displacements (between column vectors) is found for every pair of strips minimising the distance *L* between them with help of a dynamic programming algorithm. This gives us a displacement value at every point of the central fibre of all strips. Then displacement values for all other pixels of the image are interpolated from the pixel values of the central fibre of the nearest strips. a dense displacement field is obtained for the whole image. This displacement field is then smoothed before the following steps of the algorithm are applied.

Orthogonal iterations

The displacement field found in the first step is used to deform the second image relative to the first one. An image $I'_2(i,j)$ is built from the (dx(i,j), dy(i,j)) displacement field and the image $I_2(i,j)$ as $I'_2(i,j)$ =.......). The image $I'_2(i,j)$ instead of $I_2(i,j)$ is compared and now aligned to $I_1(i,j)$. Then the previously steps are repeated with the slicing performed in the orthogonal direction and the alignment results are used to update and refine the (dx, dy) displacement field. The combination of a horizontal and vertical pass results in an alignment in both directions. After the both passes are executed, the initial orthogonal shift is reduced in both directions. to refine the accuracy of the matching result, the whole process is reiterated several times in a pyramidal fashion by reducing spacing and width of the strips.

Dynamic Programming is used in the orthogonal algorithm because it appeared to be the most efficient way for performing an optimal strip to strip matching.

Experimental device

The experiments were performed in a wind tunnel for different mean velocities from 1 to 5 m/s.

The velocity profiles in the boundary layer were obtained by hot wire and Laser Doppler Velocimetry. The cavity placed at 200 mm from the leading edge has the characteristic dimensions: H=50 mm, L=100 mm, l=300 mm, were H is the height, L the length and l the width of the cavity.

Experimental results

At the entry of the cavity, the boundary layer is still laminar and it is matching with a Blasius profile. Measurements made past the cavity showed that the boundary layer was no longer laminar. A spectral frequency analysis of the hot wire signals was realised which showed that the frequencies were in the low frequency domain (<200 Hz). This perturbation of the boundary layer was due to the exit of the vortex structures from the cavity.

The velocity field inside the cavity was measured using an Argon laser and a Pulnix digital camera. *Lycopodium* particles were used as seeding.

The velocity field was computed using ODP-DPIV and DPIV techniques. An example of a velocity field corresponding to the left part of the cavity (A) obtained by DPIV for a mean velocity of 1 m/s is presented in Fig.3 For the same pair of images, the results obtained using optical flow, is presented in the Fig. 4.

We can observed the good concordance between the two velocity fields.

A numerical result corresponding to the experimental configuration is presented in Fig. 5. Two counter rotating vortex are observed with eddies of smaller dimensions turning around them. The flow visualisation (Fig. 6) confirm the perturbation of the laminar boundary layer observed numerically.

In the same conditions of mean flow velocity and at the same location a couple of images was recorded using smoke as seeding (Fig. 7). In these conditions, the DPIV based on the cross-correlation technique is unable to perform an accuracy velocity field. However the DPIV based on the optical flow could furnish interesting results in these seeding conditions (Fig. 8). Even if the image processing was made in the same flow conditions and at the same location, it is difficult to compare the velocity fields obtained with *Lycopodium* particles and with smoke because the flow inside the cavity is very unsteady. Experiments with smoke used as seeding are currently performed in simple experimental configurations in steady flows in order to valid the optical flow method in these experimental conditions.

CONCLUSION

An Optical Flow technique based on the use of Dynamic Programming has been successfully applied to Digital Particle Image Velocimetry yielding a significant increase in the accuracy and spatial resolution. Results have been presented for an interaction between a boundary layer and a cavity modelling the flow in a canyon street. Using this algorithm, a dense velocity vector field for every pixel of the image could be obtained.

Preliminary experimental investigations show that optical flow method can be successfully applied to extract velocity fields on smoke seeding image sequences on which classical cross-correlation DPIV fails.

Future work will be conducted in order to obtain a better characterisation of the results quality: statistical estimation of the accuracy of the velocity field from the particle density, the smoothness of extracted field and the reconstruction error.

An important future development of the optical flow technique is its extension to three-dimensional velocity fields computation for which Dynamic Programming search is very well suited.

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FIGURES

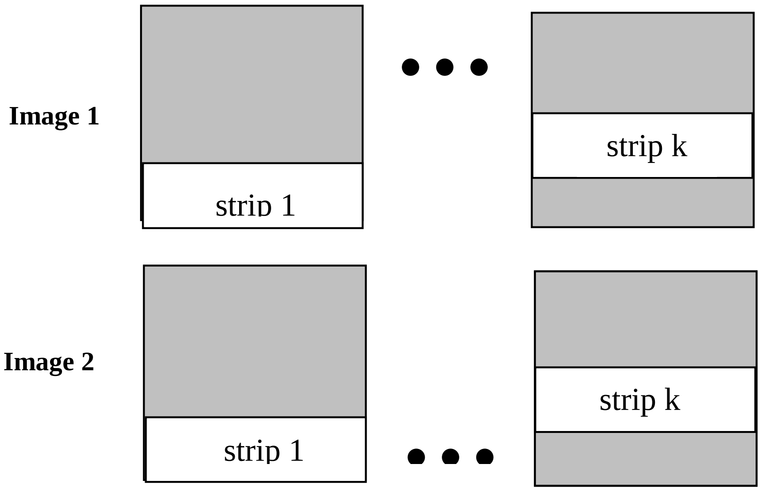

Fig1. Image slicing

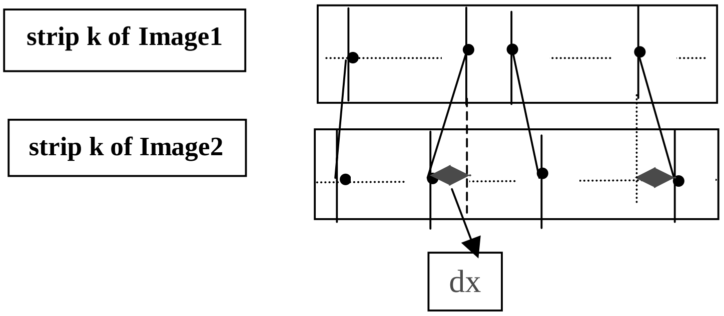

Fig2. Strip alignment

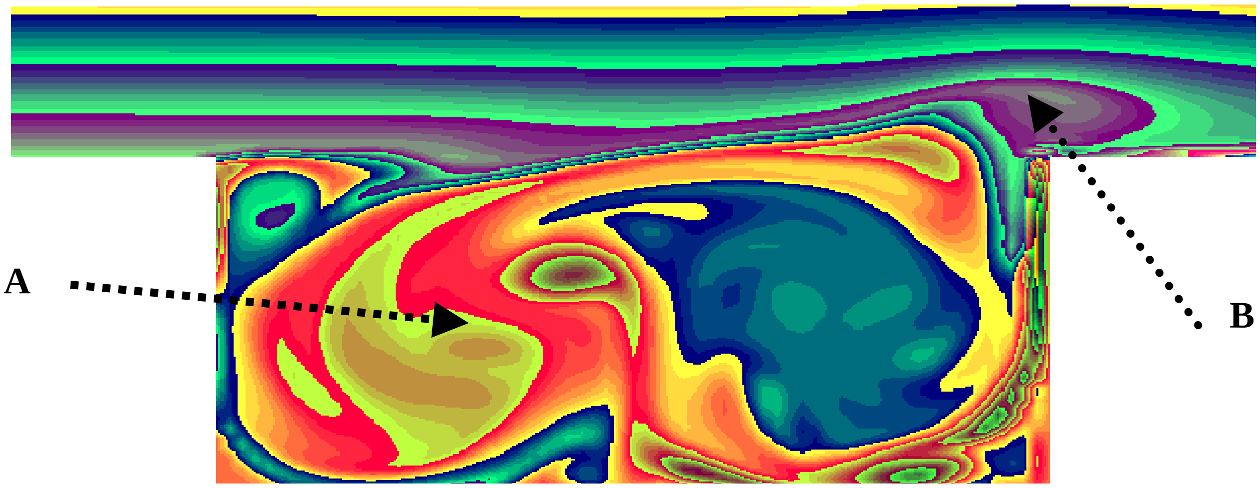

Fig.5 Numerically vorticity field

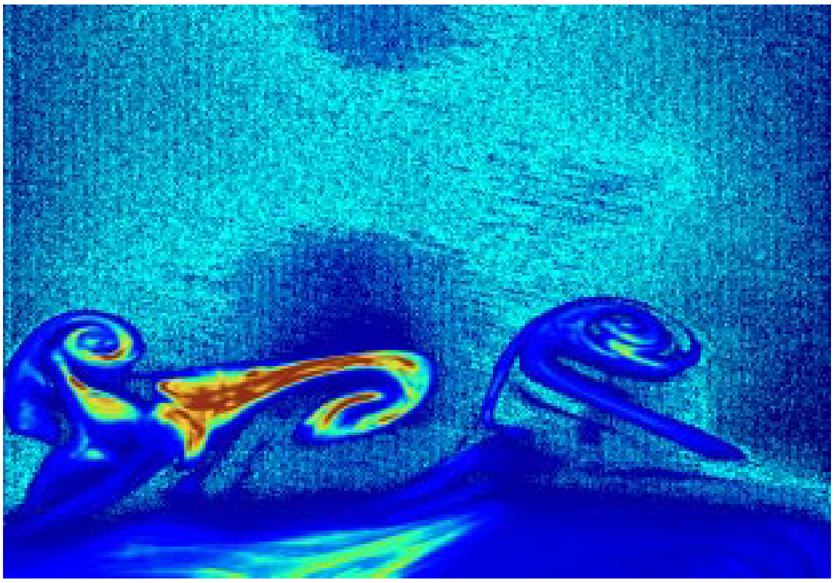

Fig.6 Vortex structures at the interaction region (zone B)

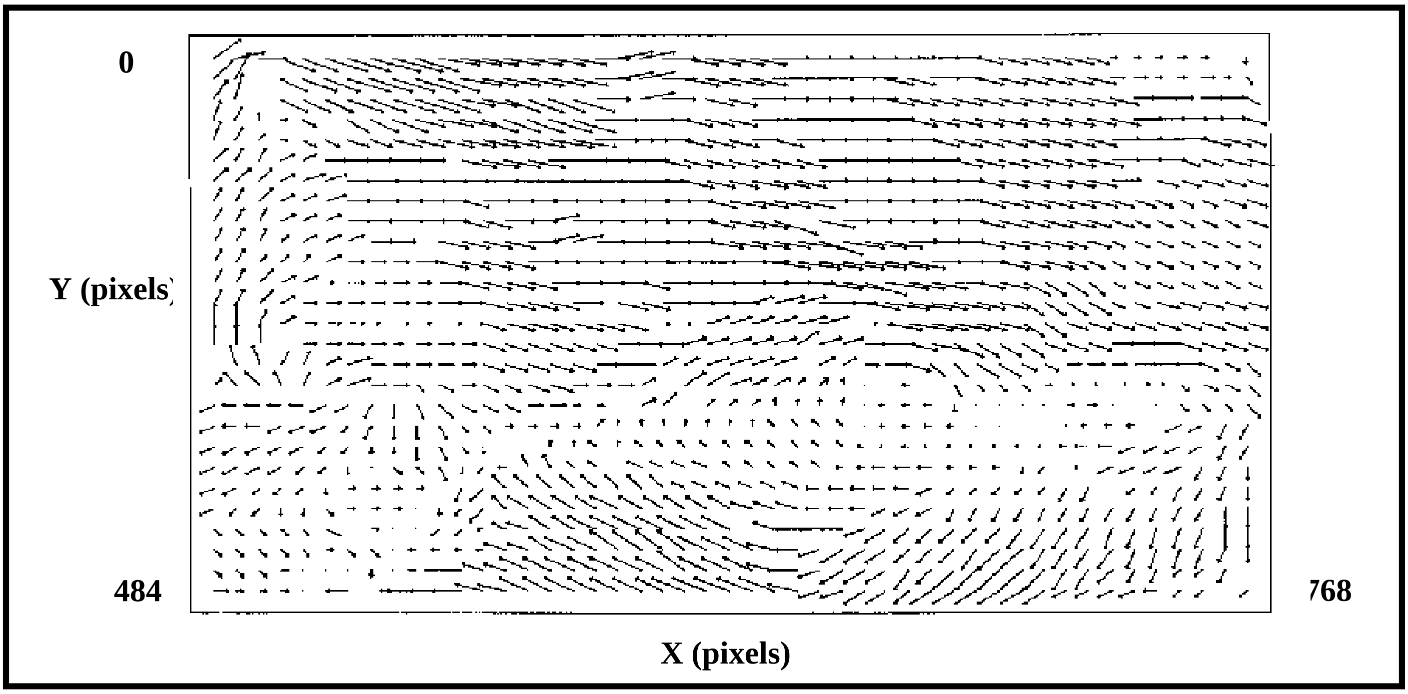

Fig 3. Flow velocity field obtained using DPIV based on cross-correlation

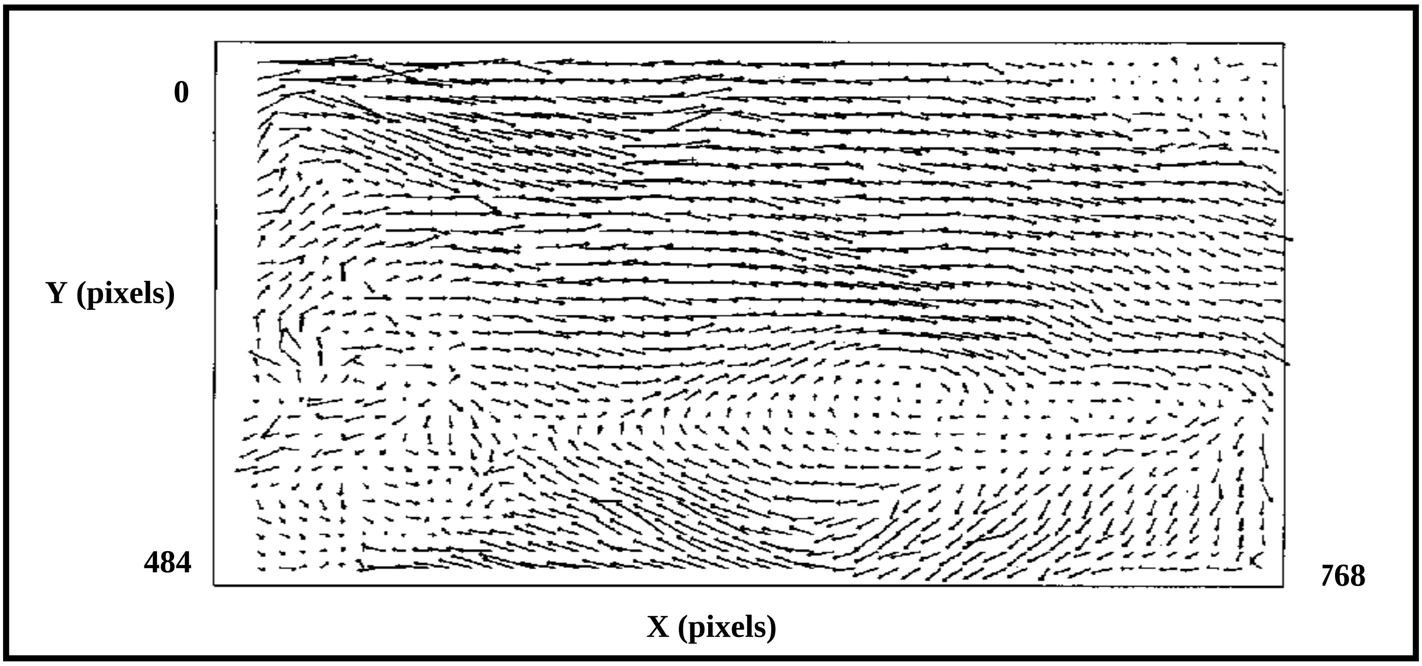

Fig. 4 Flow velocity field obtained using DPIV based on Optical Flow

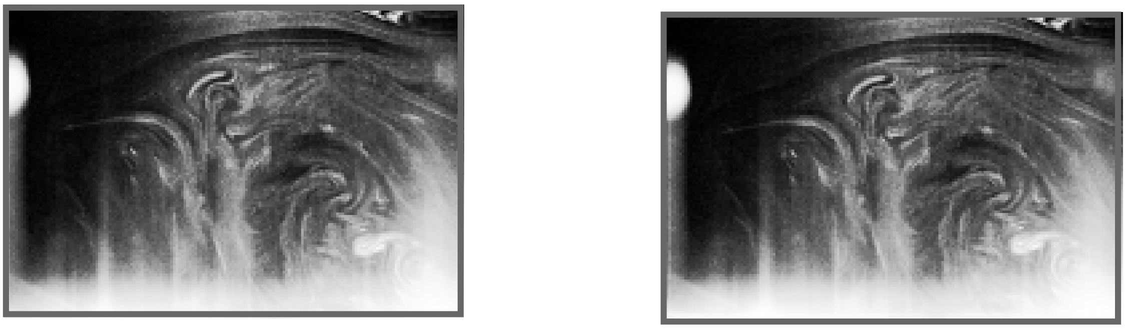

Fig 7. Couple of images inside the cavity (same location as in Fig. 5-6) using smoke as seeding

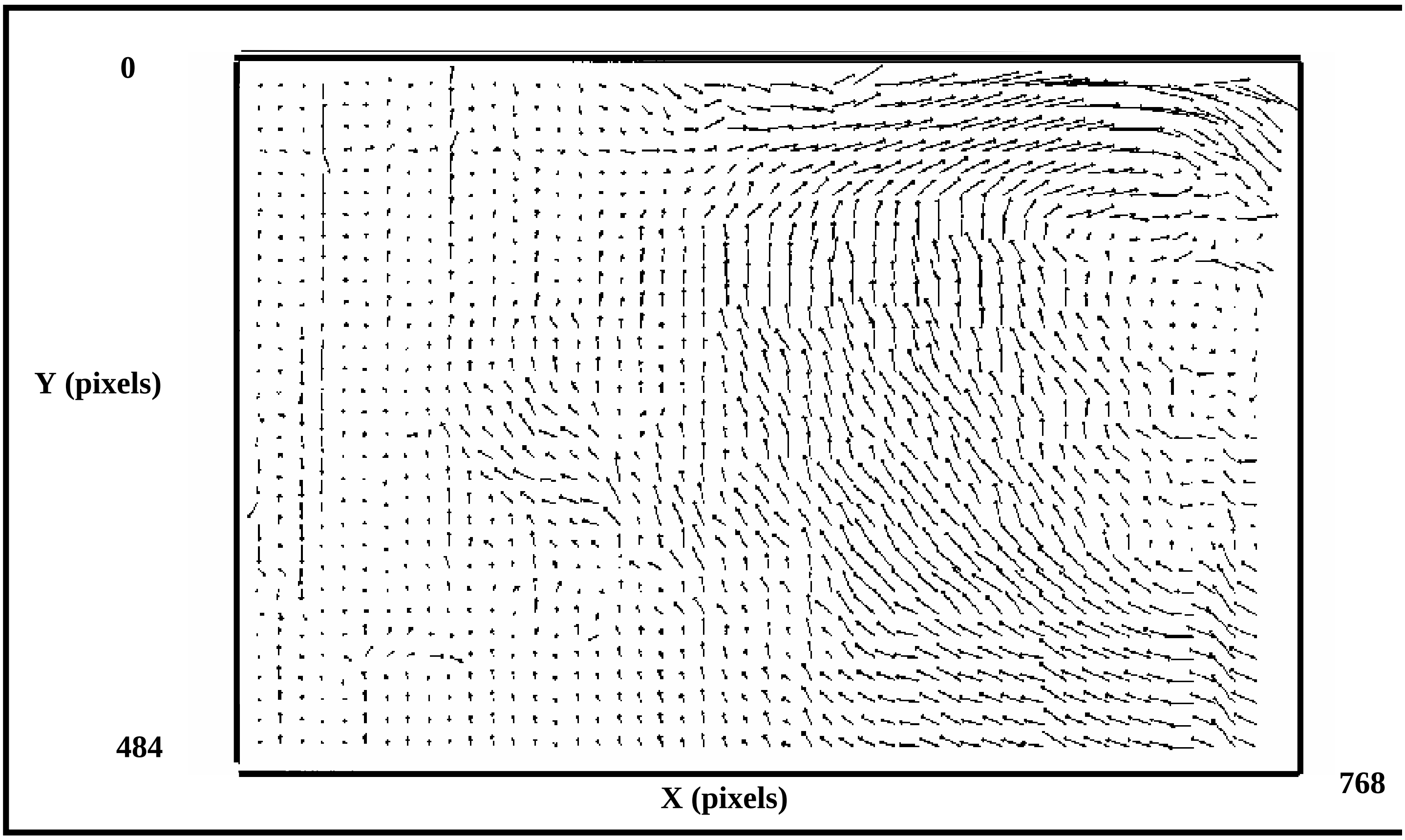

Fig.8 Flow field velocity using DPIV based on Optical Flow and using smoke as seeding