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Particle-Streak-Velocimetry for Room Air Flows

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Synopsis

This paper presents a measurement technique to perform quantitative visualization of room air flows. The visualization is done by discrete particles, namely helium-filled soap bubbles, illuminated in a plane light sheet generated by a point light source in combination with a special lens. The recording is done stereoscopically with 3 standard cameras by streak photography. The scanned negatives are analysed digitally.
The method is able to give the three-dimensional instantaneous velocity field of room air movements, also in real-scale.

Introduction

The aim of the presented work is to realise a measurement technique for performing quantitative flow visualisation of room air flow patterns, in laboratory rooms as well as in field studies. Solid tracers, here helium-filled soap bubbles, are added to the flow and transported with the air streams. Supposing the tracer's movement to be identical to the one of the ambient air, a whole velocity vector field can be extracted at one instant by recording the tracer trajectories on photographic film.

1. Experimental Technique

1. 1. Method

The air stream together with the tracer particles is photographed using relatively long exposure times. This results in thin elongated streaks on the negative, see Fig. 1 & 2.

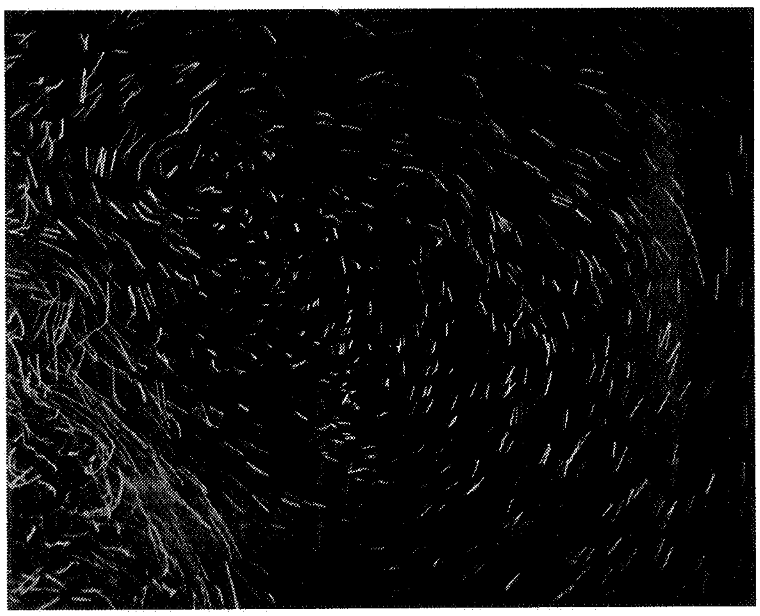

Fig. 1 : example of tracer streaks; a vortex in a room, 1.0 x 0.8 m extract of an image covering 2.5 x 1.7 m

Assuming that during the exposure the velocity vector of the particle is constant, the instantaneous velocity can be regarded as the ratio of length to exposure time.
As with this simple principle neither the third velocity component nor the direction of the flow can be extracted, the photographic set-up is extended to three cameras (see sect. 1.3 & 3.5)

1.2. Lighting

A halogen metal vapour arc lamp (250 W) in combination with a special biconvex, cylindrical lens, is used to generate a planar light sheet of a constant thickness of 12 cm. Just the bubbles situated in the light sheet are visible on the film. The lamp is air-cooled to avoid disturbance of the air flow situation by this heat source.

1.3. Photographic technique

Standard reflex cameras (36 x 24 mm) are used, with black and white film (3200 ASA).
The use of standard non-metric cameras instead of special metric cameras for this photogrammetric investigations reduces the cost of the set-up while requiring more computational calibration effort to give adequate results.
To reconstruct the three-dimensional coordinates out of two-dimensional images, at least two simultaneous recordings are necessary. But the information on the flow direction cannot be extracted out of two views of a (non chopped) particle trajectory since the order in time is lost on the photographic film.
To solve this directional ambiguity, a third image is recorded with another camera. This third camera is triggered simultaneously with the two others. But the exposure time is different, so that the streaks on that film have just one of their two endpoints in common with the recordings of the cameras right and left. This common end point correspond to the beginning of the recorded movement.

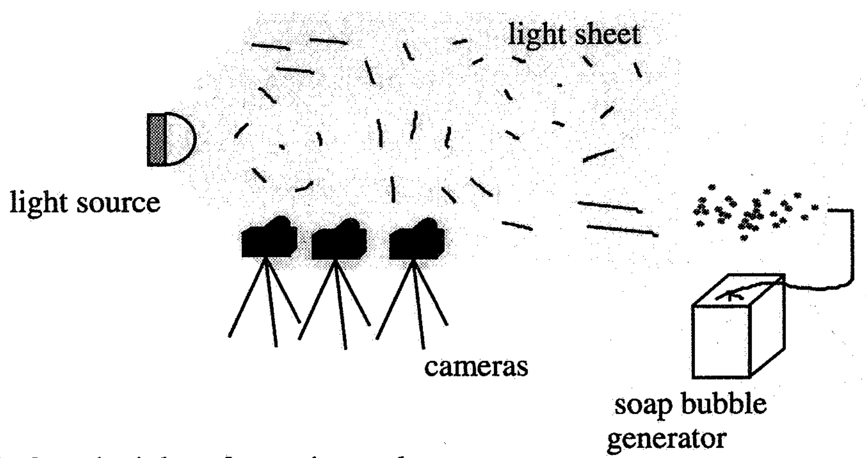

Fig 2 : principles of experimental set-up

2. Image digitization and pre-processing

The negatives are digitized using a slide scanner connected to a Macintosh Computer. The resolution is about 1000 dpi, giving a 1520 x 1024 pixel, 256 greyscales image out of a 36 x 24 mm negative.

The resulting digital images are analysed separately. Depending on the specific scene, digital enhancement of the images is necessary. So a high-pass filter is used to eliminate uneven illumination of the measurement zone.
The segmentation (separation of image information, namely the particle streaks, and image background) is done by applying a single threshold to the filtered image.
On the resulting binary image, all objects are analysed to determine their position, size, length, width and orientation. Only possible particle streaks, namely long and slender objects are retained and the coordinates of their endpoints are calculated.
At this stage, still many objects survive that do not represent a particle movement but are due to light reflections or any kind of background objects.
These 'wrong streaks' are eliminated in a later stage by the combined analysis of the three pictures.

3. Stereophotogrammetric Analysis

3.1. Basics

The ideal photographic recording is a central projection which transforms an object point P (X,Y,Z) to its image point p' (x', y'), as shown in Fig. 3. The mathematical description is given by the collinearity equations :

$$x' = -c\frac{a_{11}(X-X_0)+a_{12}(Y-Y_0)+a_{13}(Z-Z_0)}{a_{31}(X-X_0)+a_{32}(Y-Y_0)+a_{33}(Z-Z_0)}$$

$$y' = -c\frac{a_{21}(X-X_0)+a_{22}(Y-Y_0)+a_{23}(Z-Z_0)}{a_{31}(X-X_0)+a_{32}(Y-Y_0)+a_{33}(Z-Z_0)} \qquad (1)$$

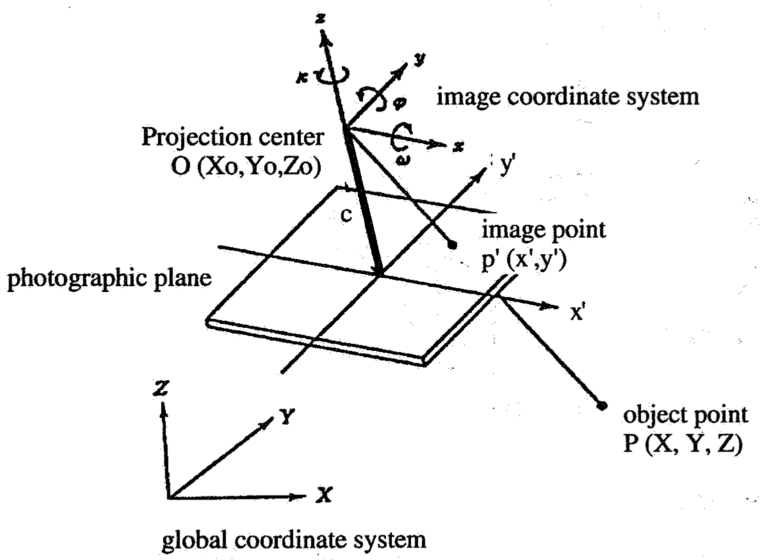

Fig. 3 : photographic recording

For a more accurate modelling several terms have to be added to this equation. Lens distortion effects and an offset (x_h, y_h) of the principle image point (intersection point of the optical axis and the image plane) compared to the image coordinate system are considered by extending the collinearity equations to :

$$x = x_h + x' + \Delta x \qquad y = y_h + y' + \Delta y \tag{2}$$

In the present work a two-parameter lens distortion model is used to correct for radial-symmetric distortion (see also [Brown], [Wolf], [Maas]):

$$\Delta x = x' (k_1 r'^2 + k_2 r'^4) \qquad \Delta y = y' (k_1 r'^2 + k_2 r'^4) \tag{3}$$
$$r'^2 = x'^2 + y'^2$$

x,y	image coordinates
x',y'	image coordinates without lens distortion and offset correction
X,Y,Z	global coordinates
X_0, Y_0, Z_0	global coordinates of the projection centre
c	image distance (distance projection centre to film plane)
a_{ij}	coefficients of the rotational matrix (functions of ω, ϕ and κ)
x_h, y_h	image coordinates of the principal point
$\Delta x, \Delta y$	lens distortion terms

3.2. Calibration

Due to the unknown exact orientation (Xo,Yo,Zo, ω, ϕ κ) of the camera, of the film in the camera (c, x_h, y_h), as well as of the unknown lens distortion parameters (k_1, k_2), a calibration is necessary for each recording ("photo-variant").
The "on-the-job" calibration consists in recording object points of known position (X,Y,Z), finding their image coordinates (x,y), and calculating all unknown parameters by combining equations (1), (2) and (3) . Due to the non-linearity of these equations, an iterative solution is necessary.
A set of 44 light-emitting diodes is placed in the room to serve as calibration points.

3.3. Stereo-pair matching

To perform the calculation of the three room coordinates of any point of a particle trace, first the matching between the extracted traces in the right and in the left picture has to be done.
The matching is done just considering the geometric set-up of the cameras. Having the image of the trace in the first picture, all possible locations of the trace image in the second picture can be calculated. Each trace in the second picture fulfilling this geometric condition is considered to be a possible partner.

3.4. Calculation of the 3D coordinates.

Having the information for each endpoint of a trace in both pictures the three-dimensional location (X,Y,Z) of that point in room coordinates can be reconstructed by equations (1), (2),(3).
The particle trajectory is now known by the three coordinates of its two endpoints. Knowing the used exposure time, one can calculate the three velocity components.
But the positive direction of this velocity vector cannot be extracted by having just two views of the whole streak. For this purpose, the image of the third camera is used.

3.5. Solving the directional ambiguity

The particle traces, reconstructed from the pictures of the left and the right cameras, as described in 3.4, are projected virtually into the third image. In this step the calculated calibration parameters of that camera are used. These virtual traces correspond to a different exposure time as used for the third image. All three images having been triggered simultaneously, one of the endpoints of this virtual trace will correspond with one of the endpoints of the real trace in image 3, the other will not. This common endpoint is the starting point of the movement.

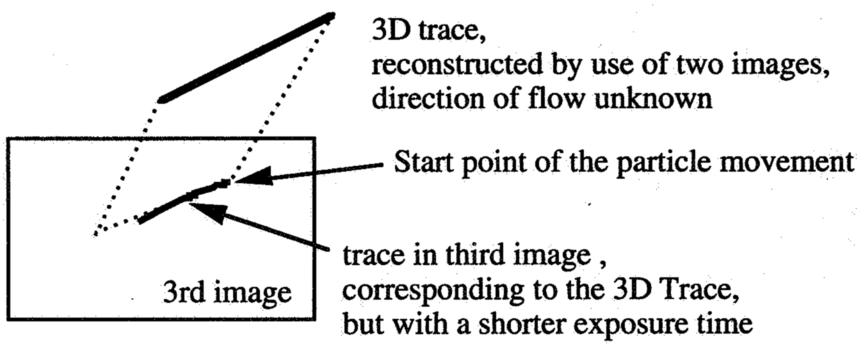

Fig. 4 : elimination of the directional ambiguity; in the example shown, the flow would be from upper right to lower left. Traces start at their right ends.

4. Interpolation

The scattered data can be interpolated to any point within the surveyed domain. Based on [Shepard], a two-dimensional interpolation function is used to interpolate independently the u,v, and w components of the velocity vectors. Due to the small extent in Z direction (the light sheet is just 12 cm thick, compared to X and Y extensions of several meters) the variations of u,v and w in Z direction are neglected and all vectors are transposed to the middle Z-plane.
To improve the interpolation, it is useful to add known boundary velocities to the measurement data, as for example the zero velocity at fixed walls.

5. Example

5.1. Set-Up

The following situation has been set up to test the presented method:

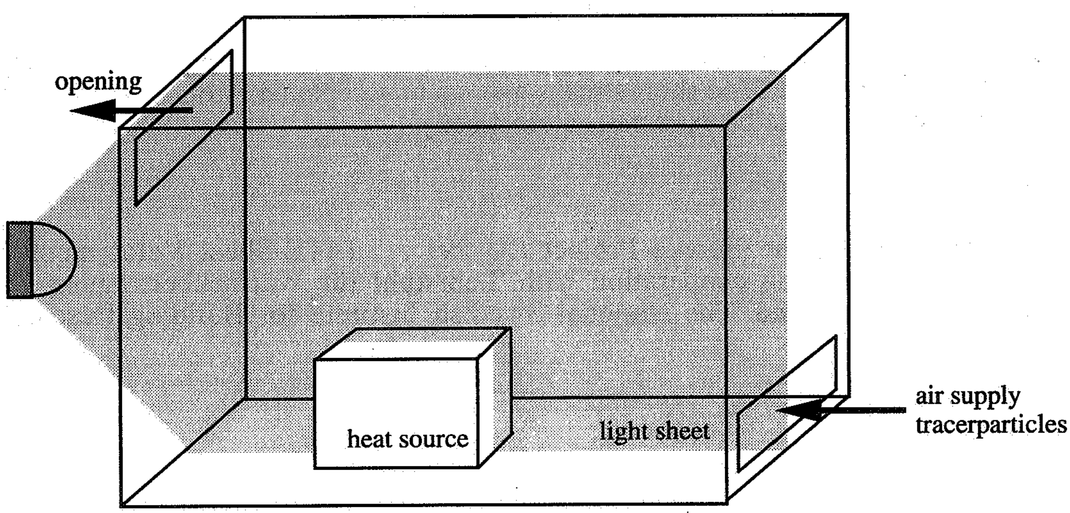

Fig. 5: test situation: heat source 300 W, overall dimensions 2.4 x 1.7 x 1.2 m

The frontside and the left side of the test room are made of glass to permit the optical access for the cameras and for the light sheet.

5.2. Results

Figures A1.1 to A1.3 show the digized images for one set of three pictures. The exposure time is 0.25 seconds for the right and the left cameras and 0.176 for the middle one.

Figure A2 shows the velocity vectors extracted out of this set. The (grey) colour scale illustrates the third velocity component w.

The flow field shown in the previous figure is completed by additional vectors (Fig. A3). These vectors result from a supplementary analysis focused on the inlet. The exposure times (0.06, 0.06 and 0.03 sec.) were shorter, better suited to the higher velocities near the inlet.

Figure A4 shows the interpolated velocity field. The interpolation is based on the data of Fig. A3 and on boundary data.

6. Conclusions

Digital stereophotogrammetric particle streak velocimetry is possible for room air flows.

It combines flow visualization and quantitative measurements. The area that can be analysed within one measurement covers several square meters and can be further extended by a suitable combination of the parameters light (increasing intensity, minimizing reflections) , tracer (size, light scattering properties) and image resolution.

For the analysis, the necessary image filtering and segmentation steps (sect. 2) depend on the lighting conditions. For complex flow situations or bad lighting conditions special appropriate image processing algorithms or more user interaction may be necessary.
The three-dimensional photogrammetric analysis (sect. 3) works correctly for all situations.

The dynamic range (ratio of the highest to the lowest measurable velocity within one recording) is expected to be of the order of ten. Too short streaks give an unacceptable error, while too long streaks do not reflect enough light to be extracted automatically.

Acknowledgements

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References

Brown D.
Close-Range Camera Calibration,
Photogrammetric Engineering, Vol. 37, No. 8, pp 855 - 866 , 1971

Maas H.G.
Digitale Photogrammetrie in der dreidimensionalen Strömungsmesstechnik,
Institut für Geodäsie und Photogrammetrie, ETH Zürich, Mitteilungen Nr. 50, 1992

Wolf Paul R.
Elements of Photogrammetry, Ed. 2
Mc Graw - Hill, New York, 1983

Shepard, D.
A two dimensional interpolation function for irregularly-spaced data
23 rd ACM Nat. Conf. Proceed., 1968, pp 517 - 524.

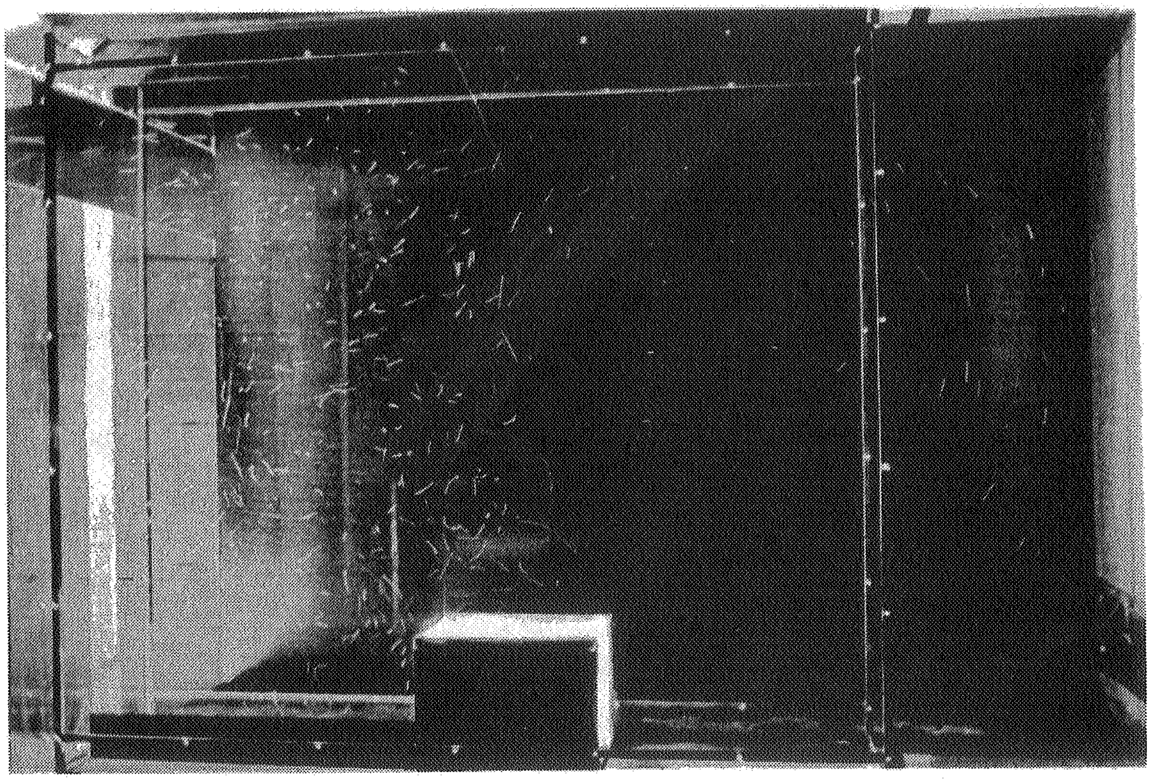

Fig. A1.1 Image of the right camera

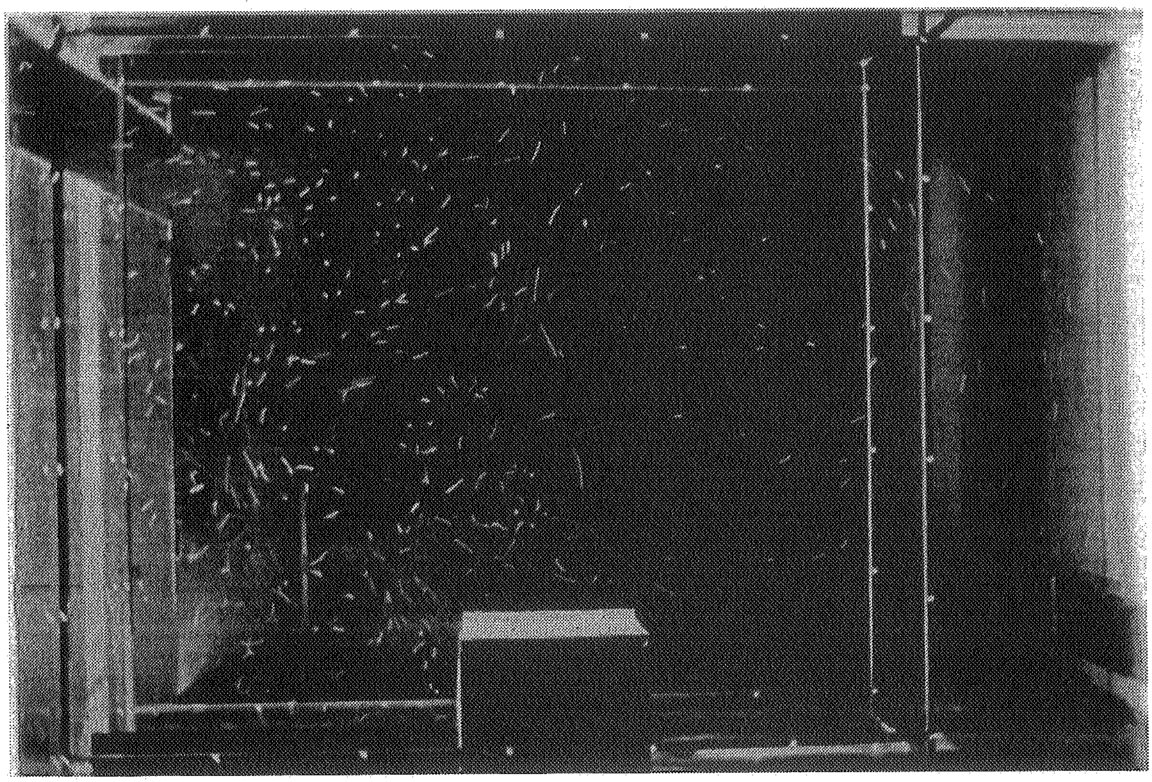

Fig. A1.2 Image of the left camera

Fig. A1.1 - A1.3 Set of three digital images :
exposure times (0.25, 0.25 and 0.18 seconds)

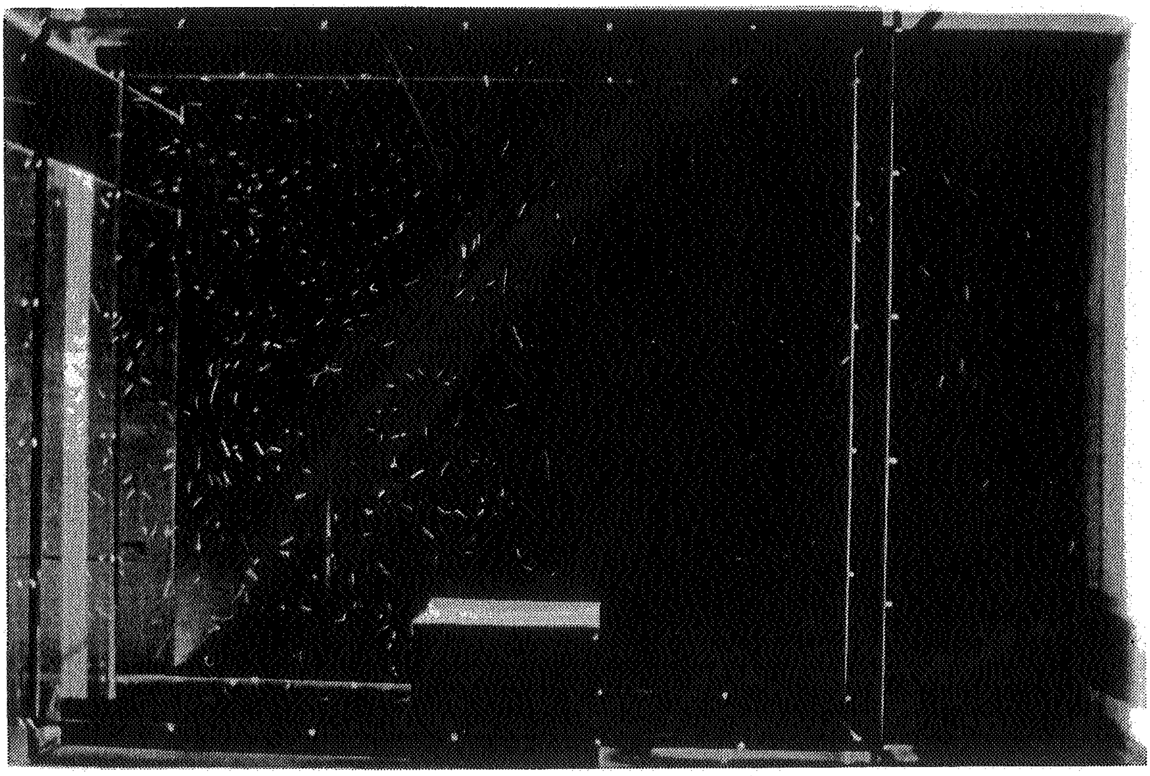

Fig. A1.3 Image of the middle camera

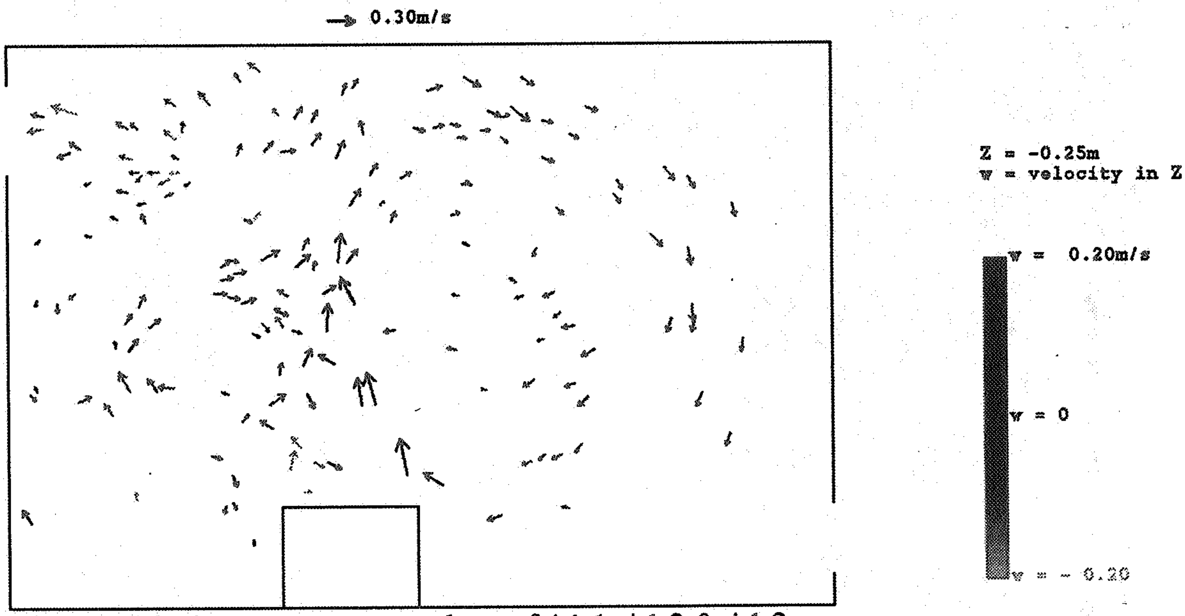

Fig. A2 Velocity vectors extracted out of A1.1, A1.2 & A1.3

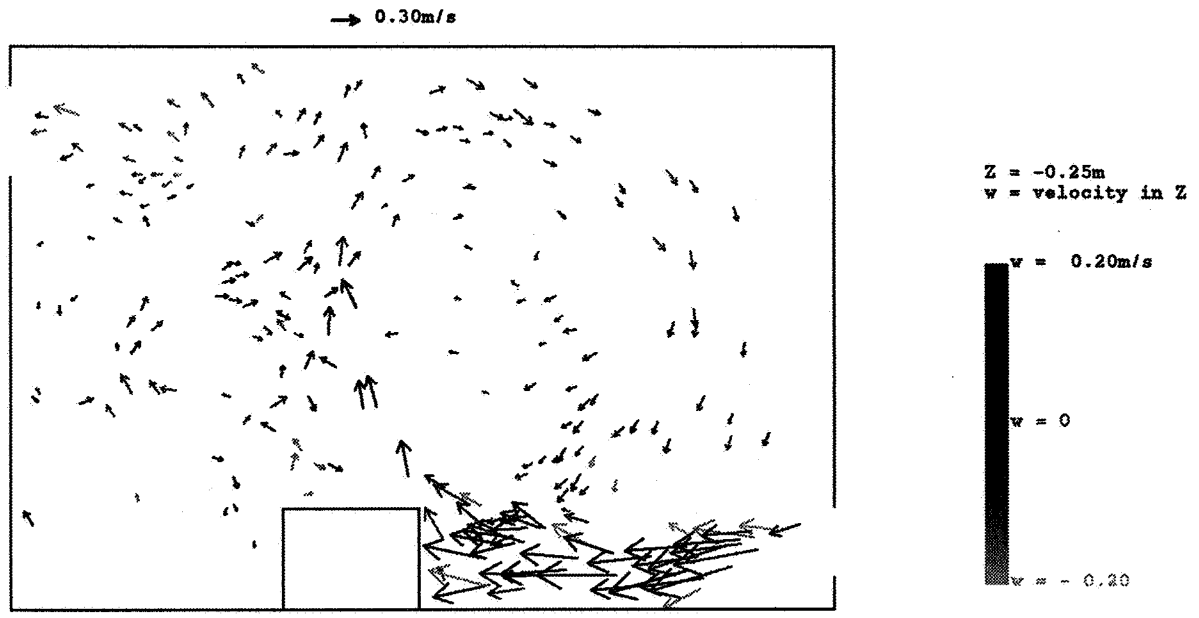

Fig. A3 Velocity Field : completed by measurements of the inlet region

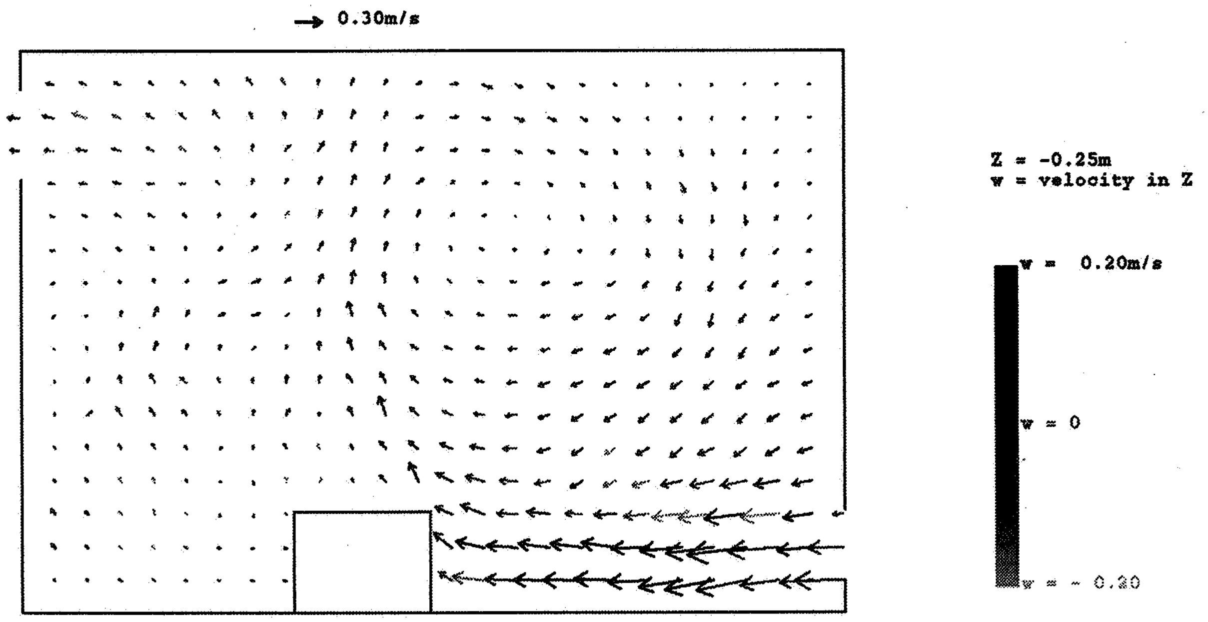

Fig. A4 Interpolated velocity field