A LOW COST PARTICLE STREAK TRACKING SYSTEM (PST) AND A NEW APPROACH TOTHREE DIMENSIONAL AIRFLOW VELOCITY MEASUREMENTS.

D. Müller, U. Renz

Lehrstuhl für Wärmeübertragung und Klimatechnik (WÜ..,
RWTH-Aachen, Germany

ABSTRACT

The Particle Streak Tracking System (PST) is a fast method to measure two and three dimensional velocity fields in enclosures. For two dimensional measurements a low cost light sheet system is developed based on a commercial xenon lamp. The light is transmitted through six flexible fibres linked to three cylindrical lenses forming the pulsed light sheet without local heat production. To visualise the flow small tracer particles (e.g. helium filled bubbles) are used. The image processing program is implemented in a modern operating system in order to achieve a convenient interface for the picture evaluation process.

For three dimensional velocity measurements in planes a laser light sheet system applying three separate light sheets with two different wave length and two CCD-cameras are employed. A description of the set-up will be given and the evaluation process will be explained. A analysis of the system limitations will be presented.

KEYWORDS

Air flow pattern, Full-scale experiments, Measuring techniques, Particles.

INTRODUCTION

Particle-Streak-Tracking (PST) and Particle-Image Velocimetry (PIV) are used in many technical applications to measure the velocity of tracer particles following the flow of interest. To get accurate measurements of the flow field the tracer particle have to be chosen with respect to the fluid, the desired velocity spectrum, the size of the measurement plane and the picture analysis technique.

Most PIV techniques use correlation methods to calculate the displacement vector of the particles on double exposure pictures. One particle moving in the light sheet gives two points in a double exposure PIV picture. The distance of these two points and the known pulse time give the tracer velocity during the double exposure time. One picture contains many randomly depicted particles and no evaluation criteria can be applied to identify two separate points as a particle displacement vector. Statistical correlation methods have to be used to find the average displacement of a group of depicted particles. These methods need a group of 5 to 20 depicted particles for every vector in a small area of the measurement plane. To get a reasonable amount of vectors in a plane it is neçessary to provide a high number of tracer particles and a uniform particle distribution in the flow field.

In room airflow the desired measurement plane area should be more than two square meter in order to examine this kind of flows in a reasonable time interval. For PIV measurements with 40*20 Vectors in an area of $2\ m^2$ using a light sheet thickness of 0.01 m more than 400.000 particles per cubic meter have to be emitted in the enclosure. With increasing particle diameter and camera distance it will be difficult to detect the particles in the light sheet because the reflected light will be blocked by the particles located between sheet and camera.

The Particle-Streak-Tracking (PST) methods needs only one depicted particle in the light sheet for every displacement vector. Particles can be randomly distributed in the measurement area and thus, only low particle densities are necessary for this method. Larger particles can be used to decrease the necessary light intensity in the sheet resulting in less expensive light sources. Also, the light sheet thickness can be increased for a further decrease of the necessary particle density.

For airflow measurements in enclosures small helium filled bubbles are used as tracer particles with a diameter between 2 and 3 mm. More than 500 bubbles per second are produced with a bubble generator from sage action, inc., USA. These particles follow the airflow almost perfectly as the diameter can be adjusted in order to get bubbles with a density comparable to air at different room temperatures. Depending on the air temperature and the humidity the tracer particles will evaporate within 2 to 5 min. These tracer particles can be used to measure airflow velocities in planes of more than 2 m^2 and do not cause pollution problems in field measurements.

LOW COST 2D-SYSTEM

A xenon lamp is the light source for the sheet. The light beam passes through a mechanical shutter and is focused into a set of 6 m long fibres. The light is then emitted through three cylindrical lenses forming the light sheet inside the enclosure. The location of the three lenses can be adjusted to the geometrical requirements with respect to a uniform light intensity in the sheet. The thickness of the light sheet is around 0.1 m in a distance of 1 m from the cylindrical lenses. A mechanical shutter system is implemented into the light source. The pulse duration Δt can be varied by a control signal from a computer program and may be adjusted to the flow situation of interest by the gear between the electrical engine and the chopper wheel. This shutter system creates a pulse sequence consisting of one long pulse followed by a short break and then a short pulse to detect the flow direction. Due to the long fibre this light system maintains mobility and the light source can be placed outside the measurement area. No heat generation will disturb the flow where the measurements will be taken.

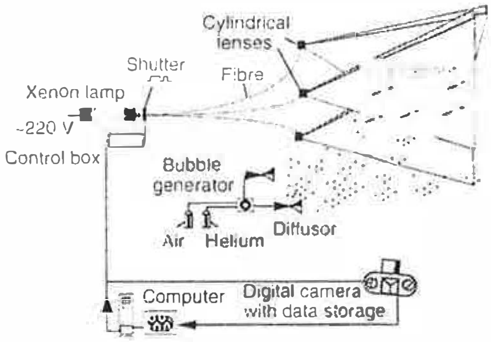


Figure 1 Low cost PST system

Different types of CCD-Cameras can be used to take digital pictures from the bubble motions in the light sheet with a resolution up to 2000*3000 pixels. The CCD-Camera is controlled along with the shutter system by the external computer system. In this study Kodak DCS 200 cameras with a resolution of 1524*1012 pixels will be used.

PICTURE EVALUATION PROCESS

During the camera opening time, one or more pulse sequences will be generated by the shutter system. The number of pulse sequences will control the amount of streaks in the digital picture. The evaluation of the digital images of the tracer particles is performed automatically by a program code developed at WÜK based on the program NIH-IMAGE for Apple Power PC. This program code searches streak combinations in the digital picture which have the characteristics of a pulse sequence.

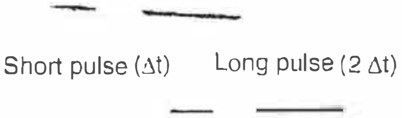


Figure 2 Typical streaks (PST)

To find this streak combination automatically in the digital picture with 255 grey values has to be converted into a binary one. The binary picture should only show the streaks and no light reflection from the enclosure. Two or more pictures from one experimental set-up can be used to generate a mask by taking the darkest grey value of every pixel in all images. The randomly distributed streaks will vanish in the mask. Only light reflection which will appear on every picture of one set-up will be left as surface of lighter grey. This mask is subtracted from every PST image. After filtering to reduce noise the program chooses a threshold value based on the grey value histogram for creating a binary image. For pictures with streaks of different grey values caused by the light sheet intensity distribution or different particle velocities it is possible to analyse the picture using a set of threshold values automatically.

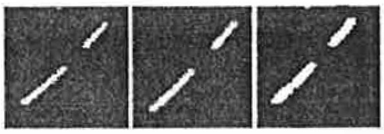


Figure 3 Grey value picture, filtering, threshold.

The program searches inside the binary picture for connected areas and fits an ellipse to each area (Rodieck, 1995). As result of this fit every area is characterised by the following parameters.

l_i - length (major axis)
t_i - thickness (minor axis)
x_i - ellipse centre x position
y_i - ellipse centre y position
α_i - ellipse angle

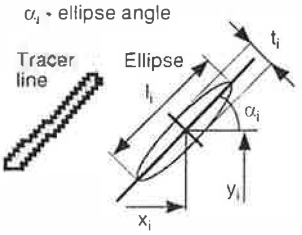


Figure 4 Ellipse fit for streaks

The algorithm looks for a short (S) and a long (L) streak with a distance equal to the length of the short streak. If such a configuration is found different criteria will be checked to prove that this streaks are caused by the same particle in the light sheet.

1. $l_{i.L} - 2\, l_{i.S} < \frac{l_{tol}}{100}\, l_{i.L}$

2. $\left| \alpha_{i.L} - \arctan \frac{y_{i.L} - y_{i.S}}{x_{i.L} - x_{i.S}} \right| < \alpha_{tol}$

3. $|t_{i.L} - t_{i.S}| < \frac{t_{tol}}{100}$

4. $\frac{l_{i.L}}{t_{i.S}} < S_{tol}$

5. $P_1 = \frac{\sqrt{\Delta x_i^2 + \Delta y_i^2}}{2.5}$

$$P_2 = \sqrt{\Delta x_i^2 + \Delta y_i^2} - \frac{l_{i.L} - l_{i.S}}{2}$$

$$P_1 - P_2 = \frac{P_{tol}}{100} P_1$$

The first check compares the length of the short and the long streak. the second test calculates the angle difference between the long streak and the centre points of both streaks. Test number three compares the streak thickness. test number four examines the shape of the long streak and the last check validates the break between the two streaks to be as long as the short streak. To get the best result in the evaluation process the quality of different criteria's will be calculated and saved for every vector. All quality criteria are evaluated relative to the selected tolerance levels (tol). If one streak belongs to more than one vector then the vector with the lower sum of the quality criteria Q value will be valid. A picture can be analysed at different threshold values.

$$Q_1 = \frac{100}{l_{tol}} \left| \frac{l_{i.L} - 2\, l_{i.S}}{l_{i.L}} \right|$$

$$Q_2 = \frac{\left| \alpha_{i.L} - \arctan \frac{y_{i.L} - y_{i.S}}{x_{i.L} - x_{i.S}} \right|}{\alpha_{tol}}$$

$$Q_3 = \frac{100}{t_{tol}} \frac{|t_{i.L} - t_{i.S}|}{\max(t_{i.L} - t_{i.S})}$$

$$Q_4 = \left(\frac{l_{i.L}}{l_{i.S}} - S_{tol} \right) / \frac{l_{i.L}}{l_{i.S}}$$

$$Q_5 = \frac{100}{P_{tol}} \frac{|P_1 - P_2|}{P_1}$$

$$Q = \sum_{i=1}^{5} Q_i \;\; : \;\; 0 \leq Q \leq 5$$

After a successful validation of all streak combinations the velocity of each particle can be calculated by applying the known opening time of the shutter system and the distance of the camera to the light sheet in combination with the focal distance of the camera lens and the sheet. The distance between the centre points of the long and the short streak can be calculated with a scale factor known from the experimental set-up. The time between this two points is 2.5 Δt and the velocity of each tracer particle can be calculated. The evaluation process for one picture takes less than one minute.

The user can define two reference points in the picture with known global positions. The program converts all picture locations to global enclosure locations applying the reference points. the picture and the camera set-up. A series of pictures at different locations can be combined to one plane.

The vector data from one or more pictures can be interpolated with different methods. A simple averaging method as well as the interpolation method proposed by Abrahamson (1988) is included in the program. All results are saved as vector flow maps and different data files to be compatible to programs such as FieldView.

Under stationary flow conditions it is possible to get velocity measurements of different planes within the measurement area and thus. it is possible to get an overview of the airflow pattern in a large field during a short measurement period. All measurements can be taken applying a global reference frame system for the reconstruction of the whole flow field.

LIMITATIONS

The maximal resolution of the digital camera limits the accuracy for calculating the distance of the two tracer track centres. If the location error for each track is one pixel the error Δs for s depends on the minimum length of a valid streak n_{min}.

$$E_{Pixel} = \frac{4}{5\,n_{min}}\,100\% \qquad \left[n_{min} = 8 \rightarrow E_{Pixel} = 10\%\right]$$

If a particle passes the light sheet before the first light pulse starts or leaves the sheet during the second pulse the pulse sequence will be incomplete resulting in a changed length of one streak.

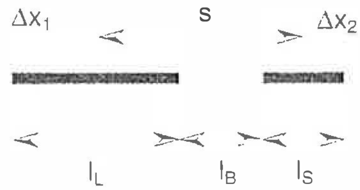


Figure 5 Streak length error Δx_1 and Δx_2

This error is controlled by the first validation criteria because it defines a maximum streak length error. The error Δs is for a known ratio of the true and the measured length of a streak as follows.

$$E_{Cover} = \frac{\Delta x_{1,2}}{5\,l_L}\,100\% \quad \left[\frac{\Delta x_L}{l_L} = 0.2 \rightarrow E_{Cover} = 4\%\right]$$

If a particle moves on a curve through the light sheet the real distance of the two centre points of the streaks is longer than the calculated distance s.

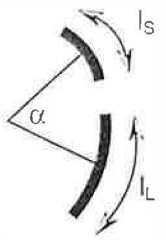


Figure 6 Curved particle streaks

This error is limited by all validation criteria because the ellipse fit calculates different ratios for the streak length and thickness for curved streaks.

$$E_{Angle} = \frac{\alpha}{360^\circ}\,\frac{\pi}{\sin\frac{\alpha}{2}}\,100\% \left[\alpha = 40^\circ \rightarrow E_{Angle} = 12\%\right]$$

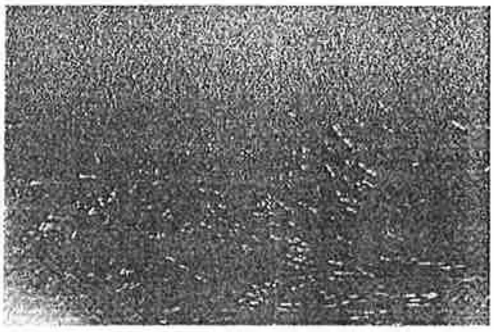
Using reasonable validation criteria (more than 10 pixel for a streak, streak length ratio 20%, streak angle difference 20%) will lead to an error less than 10% for the two dimensional PST system.

APPLICATIONS

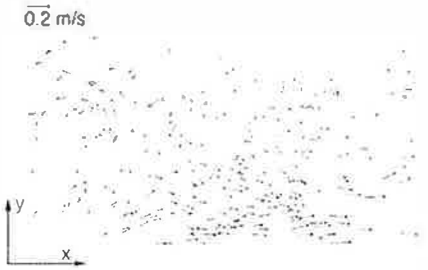
The described PST-System is able to measure low air flow velocities in enclosures and technical devices that give optical access to the flow. Two velocity components are simultaneously measured in a plane with an area up to 4 m^2. No laser light is needed and thus, the system is easy to handle and it is transportable for field measurements. The inexpensive light source is not located near the measurement area to avoid any heat generation that is able to disturb the air flow. The system uses helium filled bubbles as tracer particles suited for field measurement of air flow pattern in buildings because these tracer particles cause no pollution problem and vanish after a short period of time.

The following figure shows a PST picture, a flow map of all evaluated vectors and an interpolation result.

PST picture:



Validated vectors:



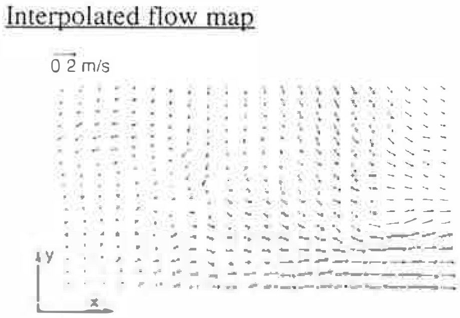


Figure 7 Example of a room airflow measurement

3D-LASER LIGHT SHEET SYSTEM

To get three dimensional measurements two different groups of experimental set-ups can be used to evaluated the particle movement perpendicular to the light sheet.

The first group uses stereo photogrammetric image processing with two or three cameras placed on different locations in a certain distance to the light sheet. By calibrating the different camera views of the light sheet the three dimensional location of each tracer particle can be reconstructed by collinear equations for stereo photogrammetry transformations. Scholzen (1997) used this method for room airflow measurements. Photogrammetric image processing requires an accurate experimental set-up and a high picture resolution to get a small error for the third velocity component.

Three dimensional methods of the second group include a depth information in the light sheet. Some methods use two overlapping colour coded light sheets applying a spatial correlation analysis, Brücker (1997) or the PST method, Müller (1996). Dinkelacker (1992) determined the third velocity component using a intensity graded light sheet.

The new method for the determination of the third velocity component is based on the two dimensional PST system. An Argon-Ion Laser is the light source for three sheets with two different colours. The laser beam passes a beam splitter and is divided into a blue (488 nm) and a green (514 nm) beam. The blue laser light is pulsed either by a magnetic shutter system (min. pulse time Δt = 5 ms) or a chopper disc (Δt = 10 µs).

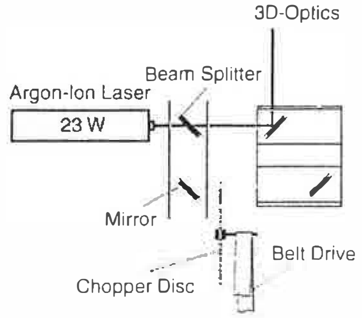


Figure 8 Laser with beam splitter and chopper disc

Two adjustable mirrors reflect the light to the 3D optical system which can be placed at a different room location.

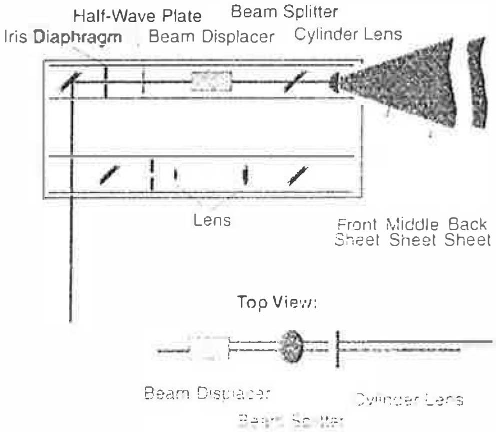


Figure 9 3D optic system for three coloured laser light sheets

The pulsed light passes an iris diaphragm, a lens system to increase the beam diameter three times and it is reflected by a mirror and a beam splitter to the cylindrical lens forming the middle pulsed light sheet. The green laser beam passes an iris diaphragm, a half wave plate to adjust the light polarisation for the beam displacer. Two parallel green laser beams leave the beam displacer. The distance of the beams is 2.7 mm and light intensity of the two beams is controlled by the half wave plate. Both beams pass the beam splitter forming two non pulsed thin light. All beams pass the same cylindrical lens resulting in three parallel light sheets.

Instead of one additional light sheet of a different colour this method applies two additional sheets located inside of one colour coded centre sheet. Two digital cameras with wave length filters for each light sheet colour are used to record two different pictures from every tracer particle passing through the three light sheets during the cameras exposure time.

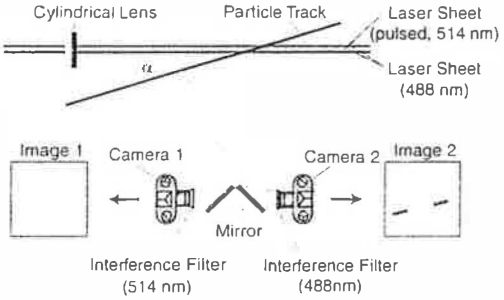


Figure 8 3D - PST experimental set-up

One of these pictures shows the same tracer lines as described for the two dimensional PST-System. The other picture contains two tracks from each tracer with a velocity component perpendicular to the sheet passing the two continuous green light sheets.

The angle α between the tracer line and the middle light sheet can be found by a simple geometrical relation using the known distance of the two light sheets and the displacement of the two track centres in image 2.

After the angle between the light sheet and a tracer line has been calculated, the velocity of the tracer particle perpendicular to the sheet can be determined. The direction of the particles passing the sheet must be evaluated by the non centre position of the two green and the blue sheets or a intensity analysis of the two continuous sheets.

SHEET DESIGN

The light sheet design is an important issue for successful three dimensional PST measurements. Figure 9 shows the sheet parameters. The minimum length of one streak is n_{min}, the magnification factor measurement plane / digital picture is V_f, the dynamic ratio n_{max}/n_{min} is D (velocity dynamic factor), the ratio of the camera 1 and 2 opening times is P and the angle between light sheet and tracer track is α.

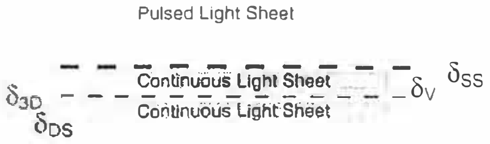


Figure 9 Sheet design parameter

To measure a minimum angle α_{min} it is necessary that a particle passes both light sheets during the camera 2 opening time leading to the first design criterion.

$$\delta_{3D} + \delta_{DS} \leq \frac{4}{V_f} P\, n_{min} \tan \alpha_{min}$$

The maximum angle α_{max} gives a relation for the minimum thickness of the pulse light sheet to assure that a particle does not leave the sheet during the pulse sequence. To get a good accuracy of the third velocity component the distance and the length of the streaks from the continuous light sheets are limited to n_{min} and 0.5 n_{min} leading to further design criteria for δ_{3D} and δ_{DS}.

$$\delta_{3D} \geq \frac{4}{V_f} n_{min} \tan \alpha_{max}$$

$$\delta_{DS} \geq \frac{n_{min}}{2\, V_f \cos \alpha_{max}}$$

$$\delta_{3D} \geq \frac{n_{min}}{V_f \cos \alpha_{max}}$$

These sheet parameters are only the limitations for three dimensional measurements and do not describe the possibility of a successful measurement of a particle located somewhere in the sheet at the beginning of the pulse sequence. To optimise the sheet design it is necessary to compute the number of successful measurements of particles starting at a random location inside the sheet moving at a random speed with a random angle α. The following figures are computed using one set of sheet parameters.

$$\delta_{DS} = 0.5\, \delta_{3D} \; : \; D = 3 \; : \; P = 2$$

$$n_{min} = 10 \text{ Pixel} \; : \; V_f = 1000 \frac{\text{Pixel}}{\text{m}}$$

$$\alpha_{min} = 5^\circ \; : \; \alpha_{max} = 50^\circ$$

Increasing the pulsed sheet thickness δ_{SS} leads to a higher possibility of a successful two dimensional PST measurement because less particles leave the pulsed sheet during the camera opening time. Nevertheless, the possibility of measuring the third velocity component decreases as more particles do not pass the two continuous light sheets, see figure 10.

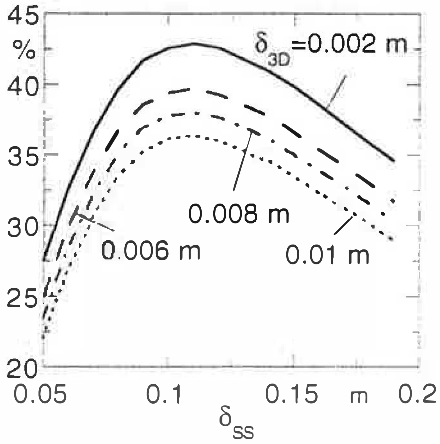


Figure 10 Possibility of three dimensional PST measurements for different sheet thickness δ_{SS}

For the chosen parameters it is reasonable to use a pulsed sheet thickness δ_{SS} of 0.1 m. Figure 11 shows the variation of the continuous light sheet distance δ_{3D}. A small value for δ_{3D} assures that more particles can pass both light sheets but the accuracy for large values of α will decrease because of the limited digital picture resolution. Almost 70% of the valid two dimensional measurements get a value for the third velocity component. If the two continuous light sheets are displaced the possibility for a successful measurement will decrease.

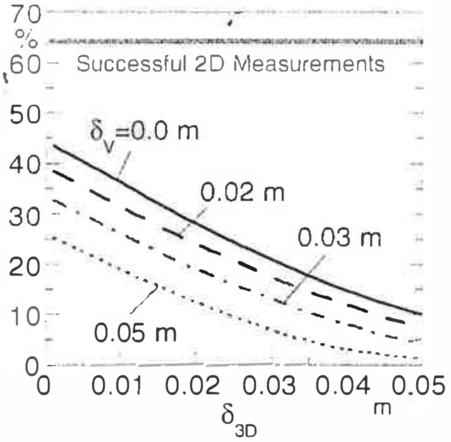


Figure 11 Possibility of three dimensional PST measurements for different sheet thickness δ_{3D} (δ_{SS}=0.1 m)

For low particle densities the opening time of camera 2 can be increased more than one pulse sequence in one picture can be applied. In this case almost all valid two dimensional measurements will have a streak pair for the determination of the third velocity component. Also, knowing the mean flow direction causes higher values for the possibility for three dimensional PST measurements.

PICTURE EVALUATION PROCESS

The picture of camera 1 contains the same streak sequences as the pictures for the two dimensional system thus, the identical evaluation process can be applied. The second camera records two streaks from every particle passing both continuous light sheets. Figure 12 shows four streak pairs passing these light sheets of different light intensities.

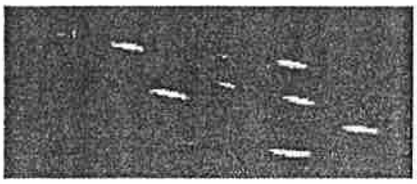


Figure 12 Camera 2 PST picture

After the analysis of the streak sequence picture the program searches for the appropriate streak combination in the picture of camera 2. Every streak combination has a certain distance for the suitable streak sequence based on calculated flow angle α and the known light sheet thickness.

$$\varepsilon = \frac{\delta_{SS}}{2 \sin \alpha}$$

Assuming a straight particle moving inside the light sheet the appropriate pulse sequence for the streak combination is located in a distance ε parallel to its centre line. The ratio of the two streak grey values assign the direction of the third velocity component.

APPLICATIONS

Because of the complicate optical and laser system the three dimensional PST system is not suitable for field measurements but it can be used for laboratory measurements of room airflows as well as for other application to get high accuracy measurements of all airflow velocity components in a plane.

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