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A PARTICLE STREAK TRACKING SYSTEM (PST) TO MEASURE FLOW FIELDS IN VENTILATED ROOMS

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ABSTRACT

The Particle Streak Tracking System (PST) is a fast method to measure two- and three-dimensional velocity fields in room air flows with measuring areas up to 5 m^2. The two-dimensional method works with a single pulsed white light sheet and one digital camera. For three-dimensional velocity measurements in planes a laser light sheet system using three separate laser sheets with two different wavelengths and two CCD-cameras is employed. To visualise the flow helium filled bubbles are used. A description of the set-up will be given and the data evaluation process will be explained. Measurements of two and three dimensional air flows will be presented.

KEYWORDS

Air flow pattern, full-scale experiments, measuring techniques, measuring error, particles, air flow distribution.

INTRODUCTION

Particle-Streak-Tracking method (PST) can be 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. The PST method needs only one depicted particle in the light sheet for each velocity vector. Particles can be randomly distributed in the measurement area and thus, only low particle densities are necessary for this method making it suitable for room airflow measurements. Large particles can be used to decrease the necessary light intensity in the sheet resulting in less expensive and less dangerous light sources.

For airflow measurements in ventilated rooms small helium filled bubbles with a diameter of 1–2 mm used as tracer particles. More than 500 bubbles per second are produced with a bubble generator. Th particles follow the airflow almost perfectly and there diameters can be adjusted in order to get bubbles w a density comparable to air at different room temperatures. Depending on the air temperature and the l midity the tracer particles will evaporate within 2 to 5 min and do not cause pollution problems in fi measurements. These tracer particles can be used to measure airflow velocities in planes of more than 5 n

THE TWO DIMENSIONAL PST-SYSTEM

A Xenon lamp is the light source for the sheet. The light beam passes through a mechanical shutter an focused into a set of three to six fibres with a length of 7 m. The light is emitted through cylindrical ler forming the light sheet inside the enclosure. The location of the lenses can be adjusted to the geometr requirements with respect to a uniform light intensity in the sheet. The thickness of the light sheet can varied between 10 to 100 mm at distance of 1 m from the cylindrical lenses. A mechanical shutter syster implemented into the light source allowing a pulse duration Δt which may be adjusted to the flow situa of interest. The shutter system creates a pulse sequence consisting of one long pulse followed by a sl break and then a short pulse to detect the flow direction. Due to the length of the fibres this light sys maintains mobility. The light source can be placed outside the measurement area and no heat genera will disturb the flow.

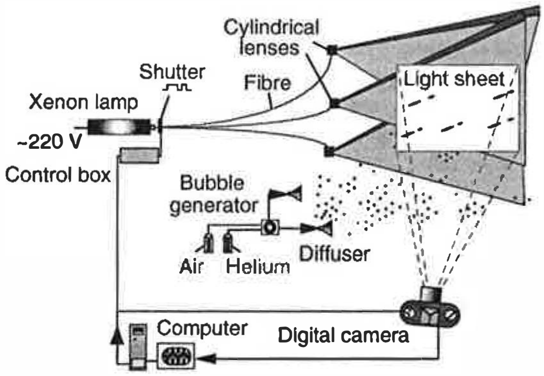

Figure 1: Two dimensional PST experimental set-up

A CCD-Camera is controlled along with the shutter system by the external computer system. The came connected to a frame grabber and is able to store up to 50 picture into the computer memory. This fea allows the measurement of instationary flow field. A detailed description of the system is given by Müll Renz (1998). Further information about the two dimensional-PST system regarding the range of app tions and the total cost is available at http://www.wuek.rwth-aachen.de/.

THE THREE 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 green laser light is pulsed either by a magnetic shutter system (min. pulse time $\Delta t = 5$ ms) or a chopper disc ($\Delta t = 10$ µs). The shutter system creates the same pulse sequence as for the two dimensional PST system.

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 and 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 the light intensity difference of the beams can be controlled by the half wave plate. Because of the different beam diameters two parallel cylindrical lenses are used resulting in three comparable sized parallel light sheets. Two digital cameras with wavelength 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 camera exposure time, as shown in figure 2.

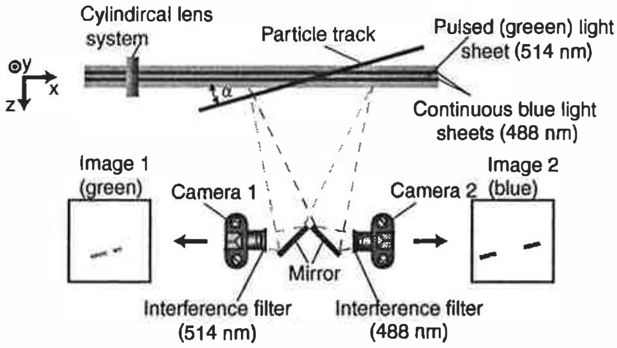

Figure 2: Three dimensional PST experimental set-up

One of these pictures (Image 1) shows the tracer lines from the pulsed light sheet. This picture will be used to determine the in plane velocity components. The other picture (Image 2) contains two tracks from each tracer with a velocity component perpendicular to the sheet passing the two continuous blue light sheets. To get the third velocity component perpendicular to the measurement plane the program analyses image 2 of camera 2. The angle α between the tracer line and the light sheet plane 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. First, all possible streak combinations in image 2 will be examined. The program looks for streak combinations in a search environment based on the light sheet parameters. Validation criteria and the related misalignments are applied to all possible streak combinations, see Müller & Renz (1998).

After a successful validation of the streaks in both images the program has to find counter parts of validated streak pairs in the corresponding images of camera 1 and camera 2. After applying a mirror operation to image 2 in order to fit the view of camera 1 the image has to be rotated and shifted using reference points in both images to get the same co-ordinate system for both images. To separate variables from image 1 and 2 a second index is used (C1, C2). All possible links of streak combinations from image 1 and 2 have to fulfil the following conditions.

$$\Delta l_p \le \frac{\frac{1}{2}\delta_{ss} - \frac{3}{5}\Delta s_{C1}}{\tan\alpha}; \quad \Delta l_p = \frac{(x_{m,C2} - x_{m,C1}) + (y_{m,C2} - y_{m,C1})\tan\beta_{C2}}{\cos\beta_{C1} + \sin\beta_{C1}\tan\beta_{C2}}$$

$$\Delta l_s < \Delta l_{3D,tol}; \quad \Delta l_s = \frac{\Delta l_p \cos\beta_{C1} + (x_{m,C1} - x_{m,C2})}{\sin\beta_{C2}}; \quad \Delta\beta = |\beta_{C2} - \beta_{C1}| < \beta_{3D,tol} \tag{2}$$

The geometric parameters Δl_s and Δl_p are shown in figure 3.

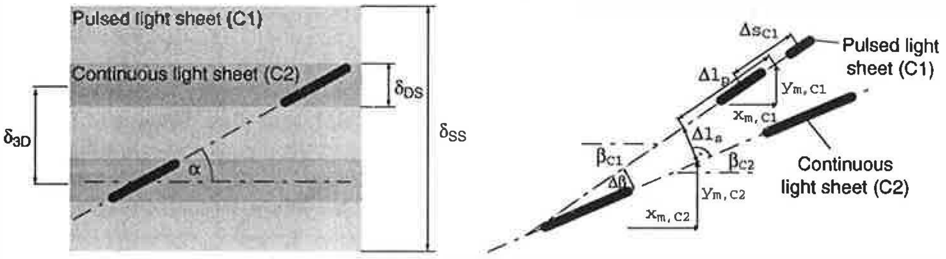

Figure 3: Top view three dimensional-PST light sheets

Still, more than one link of streak combinations from both images might appear. A check of the link qu: is necessary.

$$Q_1 = \frac{\Delta l_S}{\Delta l_{3D,tol}}; \quad Q_2 = \frac{|\beta_{i,C1} - \beta_{i,C2}|}{\beta_{3D,tol}} \tag{4}$$

After the angle α between the light sheet and a tracer line has been calculated, the velocity of the tracer ticle perpendicular to the sheet can be determined. The direction of the particles passing the light sheet ı be evaluated by an intensity analysis of the two continuous sheets.

TRACER PARTICLE BEHAVIOUR

Helium filled bubbles are used as tracer particles for the flow visualisation with diameters which caı adjusted in the range from 1 - 2 mm. To examine the behaviour of these bubbles in the flow of interesı average density of the bubbles is determined experimentally in a horizontal pipe flow. The horizontal p tion of more then 5000 bubbles pipe measured by taking digital pictures of each bubble in a light she two different position of the pipe axis. The mean displacement of all bubbles is calculated. The known 1 velocity inside the pipe allows to estimate an average falling velocity. Using a simple force balance (sphere, the average density can be calculated.

The measurements shows that the density ratio $\sigma = \rho_P / \rho_F$ can be adjusted in the range of 0,8 to 1,2 a t perature of 20 °C by changing the air, helium and bubble liquid mass flow.
The dynamic behaviour of the bubbles will be examined with the equation of motion from Techem (1ʕ for a creeping flow around a sphere with corrections from Corrsin & Lumley (1956). Based on the anal of Hinze (1959) Hjelmfelt & Mockros (1966) show several exact solutions for different tracer density ra σ. Because of the their large diameter the assumption of a creeping flow is not valid for helium filled t bles. Using measurements from Odar & Hamilton (1964) as correction factors c_A and c_H for higher par Reynolds numbers Re, the equation of motion for a single spherical particle in a moving fluid read as lows.

$$m_P \frac{dv_P}{dt} = \underbrace{\frac{3}{4}\frac{A_F}{A_P\, d_P}\, m_P\, c_W \left| v_F - v_P \right| (v_F - v_P)}_{\text{Drag}} + \underbrace{m_F \frac{Dv_F}{Dt}}_{\text{Pressure}} + \underbrace{c_A\, m_F \left(\frac{Dv_F}{Dt} - \frac{dv_P}{dt} \right)}_{\text{Apparent mass}} \underbrace{- 9 C_H \frac{m_P}{D\, \rho_P} \sqrt{\frac{\mu \rho_F}{\pi}} \int_0^t \frac{\frac{Dv_F}{dt'} - \frac{dv_P}{dt'}}{\sqrt{t-t'}}\, dt'}_{\text{Basset integral}} \qquad (6)$$

$$c_A = 1.05 - \frac{0.066}{A_C^2 + 0.12}, \quad c_H = 0.48 - \frac{0{,}52}{(A_C + 1)^3}, \quad A_C = \frac{\left| v_F - v_P \right|}{d_P \left| \frac{d\left| v_F - v_P \right|}{dt} \right|} \quad \forall \;\; Re \le 60$$

The terms on the right side of the equation correspond to the effects of drag for a viscous fluid, the pressure gradient of the undisturbed flow, apparent mass and the augmented viscous drag from the Basset history term. The drag coefficient depends on the Reynolds number and is calculated with the formula of White (1974). The influence of the Basset term can be not neglected for helium filled bubbles in air flows. The equation has to be solved numerically because of the non linear terms for the drag coefficient and the high Reynolds number corrections. A continuous changing of the flow direction is found in vortices. The motion of a particle in a rotational flow can be described approximately with a sinus curve for one local co-ordinate.

$$v_F(t) = A\, \omega \sin(\omega t) \qquad (7)$$

The particle acceleration is calculated with equation 6. During the numerical integration process the particle motion reaches a steady state after a few cycles. The program calculates the amplitude ratio $V = A_P / A_F$ and the phase shifting $\Delta\varphi = \Delta t\, \omega$ are calculated. These steady state values are shown in the frequency curves in figure 4. The variation of the frequency corresponds to a variation of the flow velocity.

The figure shows that particles with density ratio σ close to 1 will follow fluid velocity variation very well up to 100 Hz. If the density ratio σ is larger than 1.2 or smaller than 0.8 the particle motion will be damped or intensified when going to higher frequencies. In large scale fluid flows as in room air ventilation the PST system has to measure large scale turbulent motions with a low frequency. Helium filled bubbles have a reasonable frequency response for this kind of applications.

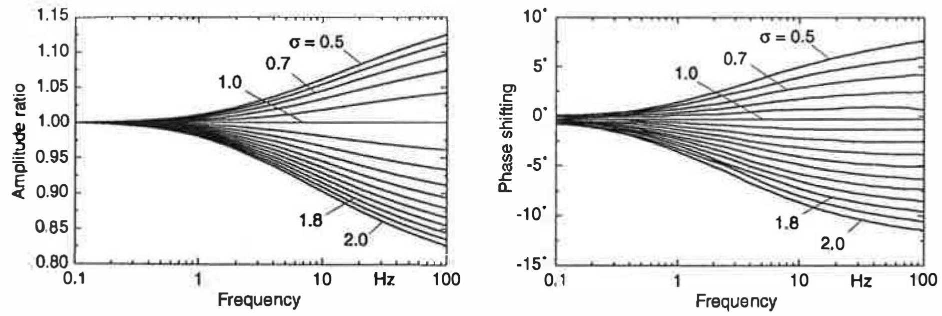

Figure 4: Amplitude ratio $V = A_P / A_F$ and the phase shifting $\Delta\varphi = \Delta t\, \omega$ of helium filled bubbles with varying density ratios $\sigma = \rho_P / \rho_F$

APPLICATIONS

As an example with the two dimensional PST system air flow velocities are measured in one plane of : 4 x 3 m^3 test room with a swirl ventilation system. The two dimensional PST measurements are take three sub areas (constant x-co-ordinate) in the room with two heated dummies and a computer. Durin post processing all sub planes are connect to one room plane and all velocity vectors are interpolated yi ing to the flow map shown in figure 5. The PST data can be easily compared to the numerical prediction

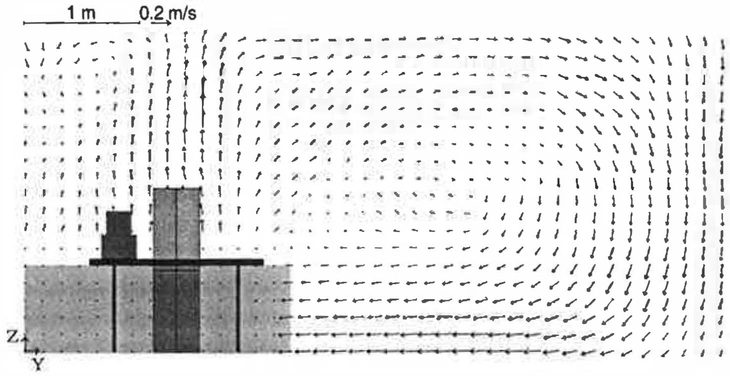

Figure 5: Measured vector flow map of a ventilated room

In order to test the accuracy of the three dimensional PST system the out of plane velocity component c steady state heat exchanger intake flow is examined. The heat exchanger and the channel expansion made of acrylglas except of the boiler tubes. The air flow velocities are measured in two vertical planes : one horizontal plane as shown in figure 6. The flow field is almost two dimensional and thus, averaging measured out of plane velocity component in y-direction of the two vertical planes should show the sa values as the related in plane measurements of the horizontal plane.
The plot in figure 6 shows good agreement of the average z-velocity of the vertical and the horizontal pla The three dimensional PST system is able to measure correctly the out of plane velocity component.

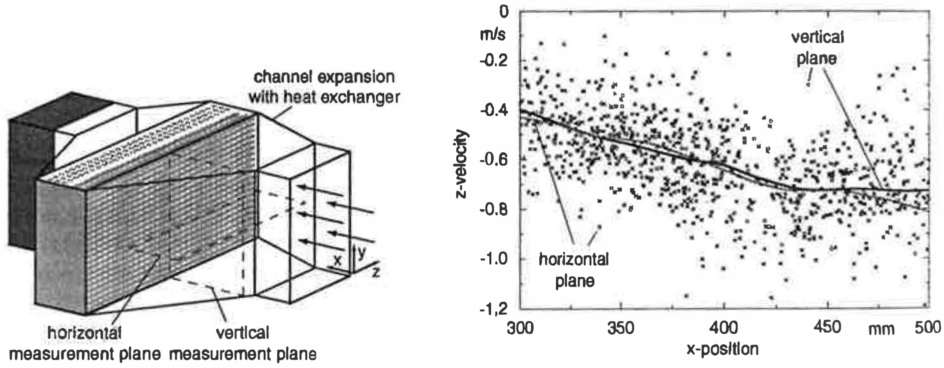

Figure 6: Test set-up and results for the three dimensional PST system

CONCLUSIONS

The 2D-PST system is able to measure room airflow velocity in large planes. The systems allows the recording of instationary flow field up to 50 frames. It is easy to handle and cause no safety or pollution problem in field measurements.

The developed 3D-PST measurement system is a fast and straight forward method to measure all three velocity components in a plane. 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.

The velocity field of a ventilated room and an heat exchanger intake flow has been measured with the PST system. For the 3D-PST a comparison of the velocities evaluated in the horizontal and vertical planes showed, that the system achieves an excellent accuracy of the velocity component perpendicular to the image plane.

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