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APPLICATION OF LASER SHEET TECHNIQUE FOR ANALYSIS OF 3D PARTICLE VELOCITY FIELDS

Paweł Mirek

Department of Heating, Ventilation and Air Protection, Technical University of Częstochowa
e-mail: pmirek@is.pcz.czest.pl

The author has applied the laser sheet technique to acquire velocity fields and mass flows at the outlet of a nozzle system, used for introducing limestone particles into a power boiler for a desulfurization process. This brings an effect in the form of multiexposure pictures, called specklegrams, which record single particle trajectories or their agglomerates in selected areas of the flow. On the basis of this the parameters of velocity field can be estimated. The author proposes a new approach to quantitative analysis of the specklegrams. It enables one to combine correlation processing with scanline particle tracking.

Key words: PIV, specklegram, velocity fields, particle trajectory

1. Introduction

The laser sheet technique, presented in Fig.1, consists in overexposing a fluid layer with seeding introduced into it by a narrow light beam, in a plane perpendicular to the observation direction. Both conventional light sources and lasers can be used for this purpose.

Owing to high spatial coherence, it is relatively easy to form a thin, parallel sheet of laser light. This makes an opportunity to form the laser light into a beam with an eliptical cross section, and to modulate it by means of a multislit rotating diaphragm. The laser beam shaped this way is directed into the measured region of gas-solids stream, and becomes the source of light for the multiexposure image. This image is an effect of the light scattering on the seed particles and may be considered, in first approximation, as a representation of the instantaneous seeding distribution. The exposure amount can be calculated by the following relation

$$n = \tau f \tag{1.1}$$

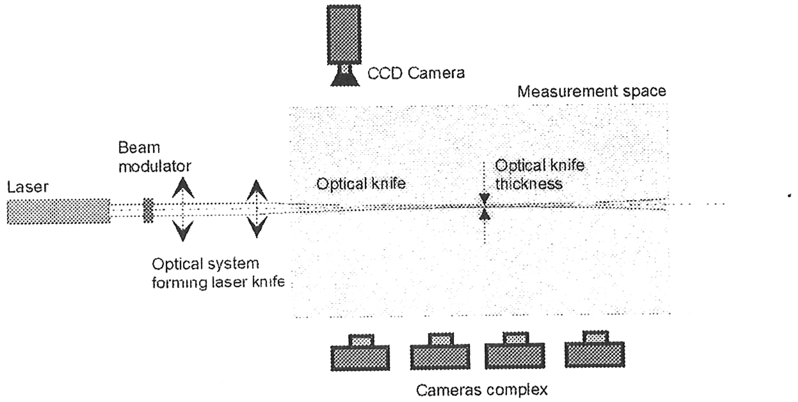

Fig. 1. Laser sheet technique

where

n – exposure amount
τ – time of exposure
f – flash frequency (of the beam modulator).

As a result of interferences of the laser light scattered by the particles, a photograph called the specklegram is obtained. The specklegram can be recorded by typical CCD cameras or, with higher resolution, photographic cameras. The speckle image can be used to study physical properties of the medium. They are described by the following properties of wave diffusion: intensity, phase shift, spatial frequency spectrum. In the case of the multiexposure specklegram there are locations of a single particle registered along its trajectory. It is also possible to register clusters in the whole image plane.

Application of the laser sheet technique to recording of the specklegram brings very good effects, when:

- light intensity is high enough for the exposure of photographic film by a given objective aperture
- seeding concentration is small enough that the laser beam is able to penetrate through the layer without excessive power loss
- laser sheet has small thickness (about 1.5 mm).

The recorded picture can be analysed using several different methods. The following methods of the analysis can be found in literature:

- Frame by frame video analysis (Kuroki and Horio, 1993; Dingrong et al., 1991; Tsukada, 1995)

- One- and two-dimensional Fourier analysis (Cathey, 1978; Otnes and Enochson, 1978; Fortuna et al., 1982; Gniadek, 1992; Newland, 1993)
- Correlation methods (Otnes and Enochson, 1978, Newland, 1993; Mark and Wernet, 1999)
- Techniques of separating particle trajectory (Kuriański, 1993; Pisarek, 1996; Woźnicki, 1996; Hering et al., 1997).

The most simple method is to search for the nearest located particles and determine the direction and length of their connecting segment. It brings satisfactory results only in the case of very small seeding concentration, when the mean distances between the particles are less then the distance covered by them between consecutive exposures of the specklegram.

The frame by frame video analysis consists in comparing the pictures recorded in successive video frames. Theoretically, it is possible to apply all these methods of identifying image objects. Practically, efficiency of this method is strongly limited by the video standard. This is because a video image is not a faithful copy of the recorded object. Another limitation is the video frequency of 50 or 60 Hz, for too low for typical velocity fields. The video technique is usually applied when shape analysis of the recorded object is of interest, e.g. examination cluster shapes which form in a circulating fluidized bed. Horio and Kuroki (1993) applied video technique for analysis of the flow structure of a 3D circulating fluidized bed. They observed development of the cluster shapes and their behaviour in the circulating fluidized bed by using internal and external picturing. The results were analysed by using the frame by frame video analysis. The same image analysis was applied by Tsukada (1995) for determination of the conditions of particle clusters forming in a dilute gas-solid suspension flow. Dingrong et al. (1991) also used the frame by frame video analysis for studying behaviour of the two-phase flow of the fast fluidized bed in a two-dimensional bed.

The optical Fourier analysis was applied by Amare and Anogo (cf Brnaben et al., 1982). The method is effective when velocities of individual particles of the analysed area are the same. The analysis can be done numerically or by using analog optical Fourier processors (Cathey, 1978). Thanks to the Fourier processors it is possible to achieve significant shortening of the evaluation time and eliminate some errors typical for FFT. This technique allows one to work effectively in the case of large seeding concentration but the method itself is very sensitive to heterogeneity of the velocity field.

In the area of applications based on the Fourier approach, the correlation and autocorrelation techniques are also applied. These techniques are very often used in the field of image analysis for determining two components of the velocity vector for double exposed images. Post, Trump, Goss and Hancock used the modified correlation technique for determining the flow field velocity vector, obtained by using two-color particle imaging velocimetry (Post et al., 1994). Unfortunately, the correlation and autocorrelation techniques do not enable one to separate a particle trajectory, and to estimate velocity of an individual particle of the seeding. Moreover, the correlation methods are more accurate than the Fourier methods. They can be applied to regions of different size. It is possible to use the correlation methods in an iterative way (Pisarek, 1996). The techniques of multiple correlation are especially useful for the analysis of multiexposure specklegrams.

The separation of a particle trajectory is one of the most difficult problems to solve. A similar problem appears in analysing a series of high noised images of a moving object in the radar technique. One of the published solutions is separating a particle trajectory while using an algorithm based on the two-dimensional Markov process (Markov fields) (Pisarek, 1986; Kuriański, 1993). Unfortunatelly, this algorithm is very slow, which significantly limits its application.

As a new approach to quantitative analysis of registered pictures, a combination of the cross-correlation and particle tracking algorithms is applied (Mark and Wernet, 1999). The routines are based on the fuzzy logic and neural networks techniques.

This paper describes a novel approach for extracting individual particle displacements. It consists in combining the multiple-correlation technique and scanline particle tracking. As a result, three components of the velocity vector of recorded particles and tracks of individual particles can be determined.

2. Experimental set-up

The author has applied the laser sheet technique for registering velocity fields and mass flows at the outlet of a nozzle system used for introducing limestone particles (sorbent) into a power boiler for a desulfurization process. In the present research, the limestone particles with diameter of about 30 μm were used as a seeding.

For visualization of the sorbent outflowing from the nozzle system, the test stand shown in Fig.2 was used.

The He-Ne laser light, with power of about 40 mW, passing through the cylindrical lens, is mechanically modulated by the multi-slit rotating diaph-

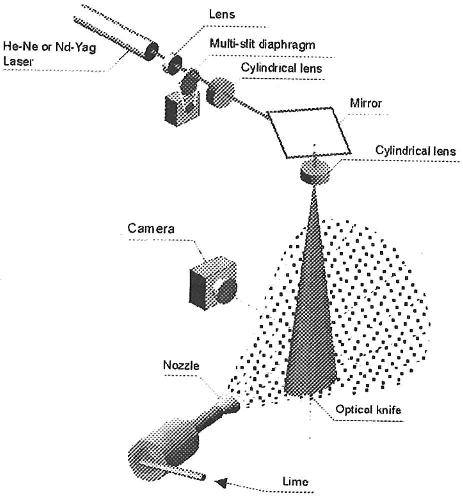

Fig. 2. Experimental set-up

ragm with frequency of 6 kHz. It is also possible to work with a non-modulated beam. The laser beam is formed into a flat light sheet (optical knife thickness 1.5 mm) by the cylindrical lens system, and then, with the help of a mirror, it is directed to the tested region.

The scattered light is recorded by a photocamera (Praktica LB2 with long focus lens Jupiter 21 M, 4/200 and two adapter rings) with the optical axis perpendicular to the laser sheet. The size of the registered area is $12 \times 18\,\mathrm{mm}^2$. Considering the light intensity, the best possible quality of the recorded images could be obtained with exposure time of 1/125 s. The images were recorded on Fuji SHG 400 and SHG 1200 photographic films and then stored in computer memory by using the scanner PRIMAX 4800 with 600 dpi resolution. The total number of the recorded images with the exposure time of 1/125 s and the strobing frequency 6 kHz was, according to (1.1), 48.

On the stand like this it is possible to measure local particle velocities, both for higher and lower outflow velocities.

3. Qualitative interpretation of the results

Particle images recorded on a photographic film are speckle structures generated by single particles or their ensembles located in a certain area. This situation takes place because of the application of a coherent light source and large numerical apertures 5.6 ÷ 8.8 of the optical system. The image size depends on both the optical system parameters and the real size of the registered object. Thus, the present method should be classified on the verge of Particle Image Velocimetry (PIV) and speckle metrology, based on the laws of wave optics.

Registered particle trajectories differ in direction, length and curvature. It is also easy to observe that along some trajectories the particles differ in size. This shows ability of the sorbent to coalesce, which limits its surface of contact with the gas. This is important for high desulfurization efficiency, which can be obtained not by increasing mass fraction of limestone but only by increasing active surface contact with fumes. There can also be clearly observed the influence of agglomerate size on the trajectory of the agglomerate motion, which is shown in Fig.3b. It enables estimation of the accelerations of particles flowing in the system.

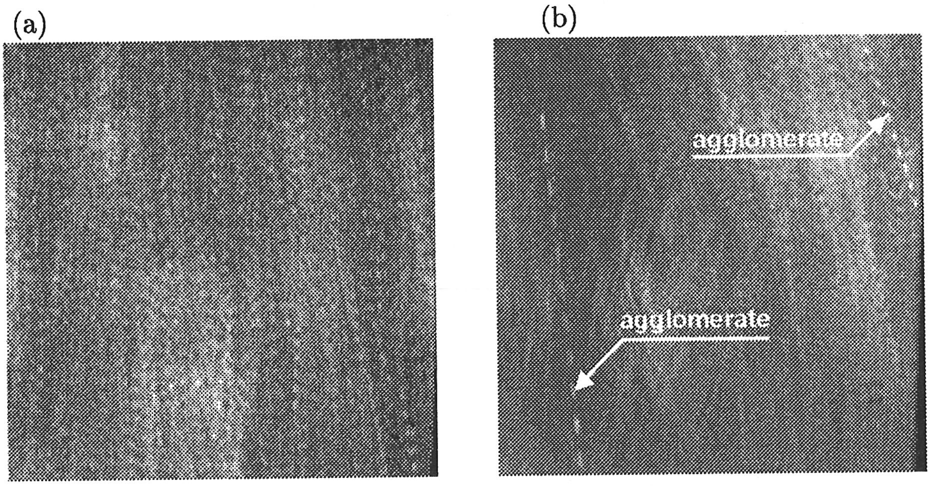

Fig. 3. Images recorded with exposure time 1/125 s and the distance about 40 mm from the nozzle system for: (a) – higher outlet lime particle velocities, (b) – lower outlet lime particle velocities

The specklegram presented in Fig.3 shows the outlet region of the nozzle system. As shown (Fig.3a), for higher outlet velocity the particle trajectories reveal mutual parallelism more frequent than for smaller velocity (Fig.3b). It can also be observed that for higher feed velocity, the size of individual particles is larger than for smaller velocity, where only bigger particle agglomerates appear from time to time. Fig.4 shows a fragment of specklegram registered on the edge of the stream, far from the outlet of the nozzle system. In this case, great diversity of the particle velocity and their crossing trajectories with the angle up to 30 degrees, and the different lengths of recorded trajectories can be observed. There can also be seen existence of the circumferential velocity components and large heterogeneity of the velocity field.

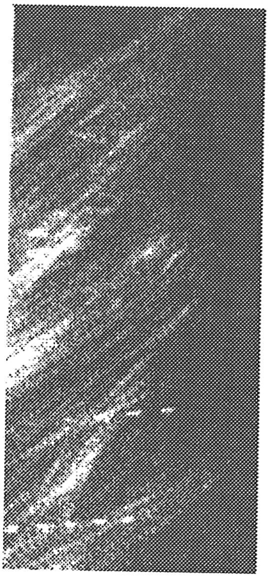

Fig. 4. Specklegram registered on the edge of the stream (20 cm from the stream axis) with the distance 60 cm from the nozzle system (low particle loading, exposure time of 1/125 s)

Owing to application of strobing, each of the single particle trajectory is modulated by a periodic function with spatial frequency inversely proportional to the length of the projection particle velocity vector on the laser sheet. Thus, it is possible to quite precisely read (relative error about 1%) the two components of the particle velocity vector. Information about the third velocity component is contained in the length of the particle trajectory recorded on the image. It is because the ratio of the recorded flash pulses to the maximum number of flashes during the recording depends on the mean particle velocity, total exposure time, laser sheet thickness, and angle at which the particle crosses the laser sheet (Fig.5). In this way, it is possible to register the three-dimensional velocity field on a two-dimensional photography, and assign each of them to specified particle sizes.

The images were recorded with max. enlargement $M = 2$. Thus, the size of

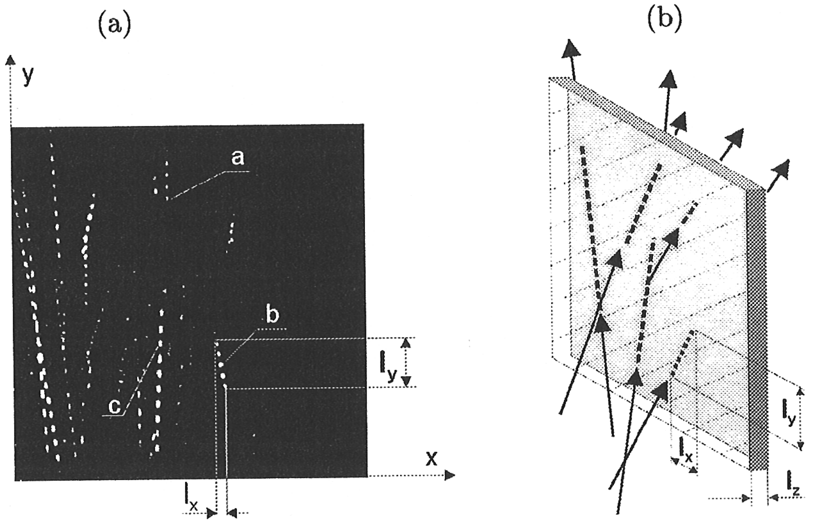

Fig. 5. Lengths of registered particle trajectories connected with various angles at which particles attack the laser sheet: (a) – specklegram example, (b) – 3D phenomenon mechanism

acquired area was $12 \times 18\,\mathrm{mm}^2$. The size of analysed images was 58×87 mm. Hence, the scale coefficient between the analysed images and real images is $k = 58/12 \cong 4.833$.

4. General assumptions of quantitative analysis of specklegrams

The techniques described in the present work give an opportunity to observe the phenomenon simultaneously and undisturbedly in different subregions of the tested region. Additionally, they provide a chance to visualize the velocity fields or mass transfer. This is very important for moulding the experimenter's correct intuition connected with the observed phenomenon.

The experiment is very simple and its results depend on the parameters of laser equipment. Efficiency of applied methods depends on the researcher's technique of reading useful information from a specklegram.

Fundamentally, there are three types of data processing techniques used in the Particle Image Velocimetry: cross-correlation, auto-correlation and particle tracking. The choice of a processing technique depends primarily on the available equipment used for recording the particle image data, the seed particle concentration and the parameters, which have to be determined (Mark and Wernet, 1999). The purpose of the present paper was to find a simple way to determine the three velocity vector components and trajectories of individual particles based on a multiexposure photography.

The laser sheet has the finite thickness l_z, which can be precisely determined. The particle crossing the light sheet marks its spatial trajectory with the length

$$l = \sqrt{l_x^2 + l_y^2 + l_z^2} \tag{4.1}$$

where

l_x, l_y – orthogonal projections of registered particle trajectory on the x and y axes, respectively

l_z – laser sheet thickness.

The quantities l_x and l_y can be readout directly from the specklegram (Fig.5). Thus, it is possible to determine the direction cosines of the velocity vector

$$\cos\angle(\boldsymbol{V},\boldsymbol{i}) = \frac{l_x}{l} \qquad \cos\angle(\boldsymbol{V},\boldsymbol{j}) = \frac{l_y}{l} \qquad \cos\angle(\boldsymbol{V},\boldsymbol{k}) = \frac{l_z}{l} \tag{4.2}$$

Analysis of the specklegram directly enables the estimation of the velocity vector components V_x and V_y according to the following expressions

$$V_x = \frac{nd_x}{k}f \qquad V_y = \frac{nd_y}{k}f \tag{4.3}$$

where

f – strobing frequency

k – scale coefficient

n – number of registered particle locations.

Both velocity components are orthogonal projections on the x and y axes of the average distances d_x and d_y between the particle locations registered during consecutive exposures (Fig.6).

The third velocity vector component can be determined by making use of the following expression

$$V_z = l_z\sqrt{\frac{V_x^2 + V_y^2}{l_x^2 + l_y^2}} \tag{4.4}$$

The problem consists in identification of the particle trajectories and determining, on the basis of selected particle trajectory, the parameters mentioned above. This is a numerical problem with large complexity. In the next paragraph the author proposes an algorithm which is a combination of the multiple-correlation technique and scanline particle tracking.

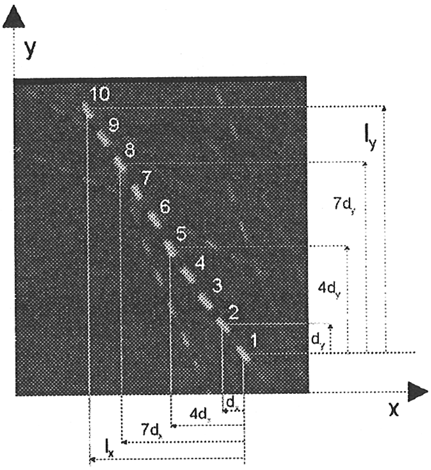

Fig. 6. Determining of l_x and l_y quantities; d_x – orthogonal projection on the x axis of the distance between two consecutive particle locations, d_y – orthogonal projection on the y axis of the distance between two consecutive particle locations

5. Correlation processing combined with scanline particle tracking

Preliminary assumptions:

- assume the most probable absolute value of the velocity vector
- find the largest size of the particle track in the whole image by using one of the edge detection methods (Prewitt, Sobel, Roberts)
- determine the histogram of the image, which allows one to establish the limit between the particles and background brightness.

First step – preparation of the image

This step can be omitted in the case of images of particles with low concentration. In that situation the tracks of individual particles can be detected with good precision, because their brightness and the background intensity are significantly different. When the concentration of particles is high, the brightness of the particles is not much higher than the background intensity. In such a case it is necessary to apply one of the edge detection methods to clearly extract individual tracks of the particles from the background. As a result the edges of the recorded particle tracks are obtained (Fig.7b). The inside regions of these tracks must be filled with white colour (Fig.7c).

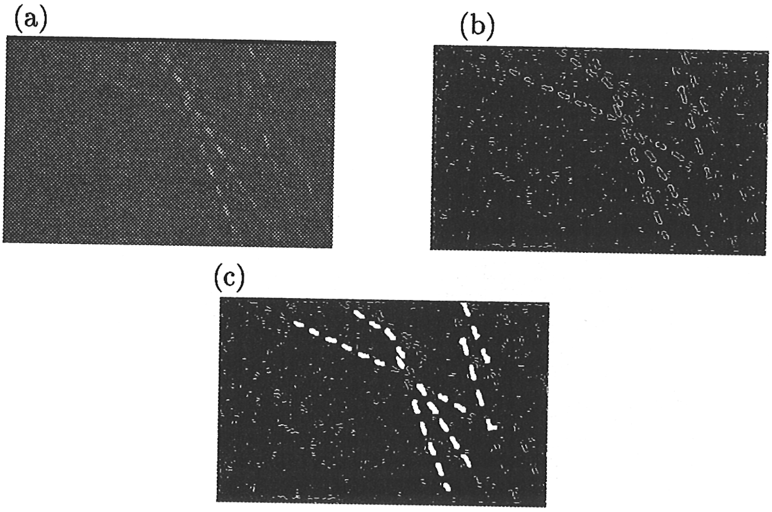

Fig. 7. Preparation of the image; (a) – original image, (b) – image processed with the edges detection routine, (c) – detected regions on the image filled with white colour

Second step – random particle selection

The whole image is analysed and one of the registered particles is chosen randomly. It is possible, because in the preliminary assumptions the histogram was determined and the range of the brightness connected with the registered particles is known. Thus, the pixels with the brightness below the assumed threshold are not considered. The chosen particle is located in the centre of the assigned co-ordinate system. The assumption is, that the particle belongs to one of the registered trajectories.

Third step – detection of the particle trajectory

The particle trajectories are detected with a rotating scanline located in the origin of the co-ordinate system called pivoting point (Fig.8a). The slope of the scanline is changing from 0 to 360 degrees.

Fourth step – determining the brightness distribution function

Each of the scanline positions determines the brightness distribution function (Fig.8b), which is analysed by the correlation function afterwards.

Fifth step – analysing with the correlation function

In the first approximation, each of the scanline position is analysed with

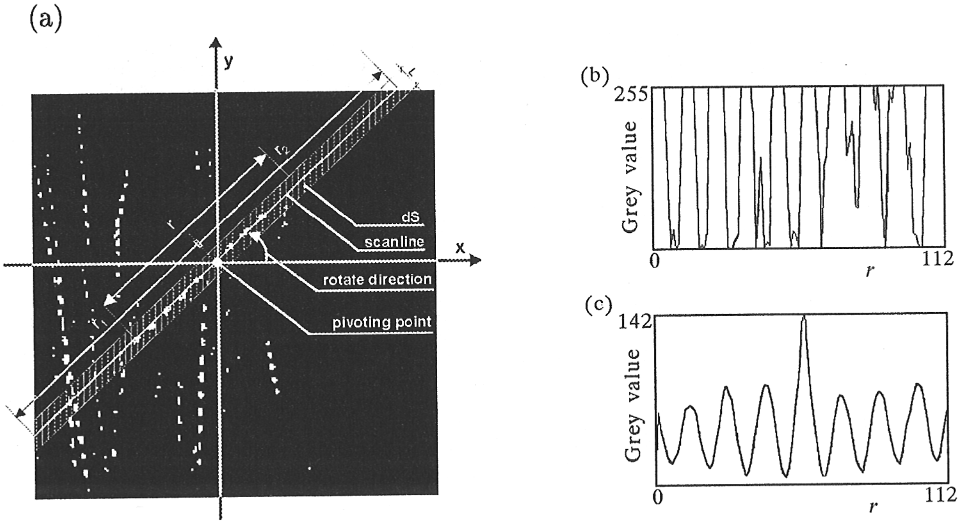

Fig. 8. Example of analysis of a specklegram; (a) – scanline with the detected particle trajectory 74 pixels long, (b) – brightness distribution function, (c) – one-dimensional correlation function

the correlation function defined as follows

$$A(\xi) = \int_{r_1}^{r_2} J(r)J(r-\xi)\,dr \tag{5.1}$$

where

$J(x)$ – brightness of individual points of the registered specklegram .
ξ – transformation parameter (coordinate in the transform of plane)
r_1, r_2 – limits of the integration.

At the beginning it is good to assume the scanline width L of the order of about one pixel. In this situation expression (5.1) is a one-dimensional correlation function (Fig.8c) and the calculation time is the shortest. It is also possible to analyse each of the line position with the help of one-dimensional Fast Fourier Transform.

Sixth step – increasing the size of the scanline

If the scanline detects that the brightness distribution is periodic, the size of the scanline width L must be changed but it cannot be greater than the largest size of the particle track, detected with the edge detection routine. From that moment functional (5.1) is applied in its two-dimensional form

$$A(\xi,\psi) = \iint\limits_{S=K(x,y)} J(x,y)J(r-\xi,y-\psi)\,dS \tag{5.2}$$

where

$J(x,y)$ – brightness of individual points of the registered specklegram

ξ,ψ – transformation parameters (coordinates in the transform of plane)

S – size of the correlated region, $S = K(x,y)$.

Seventh step – determining the parameters of the particle trajectory

At this moment, it is possible to determine all velocity vector components according to (4.1) ÷ (4.5), (5.1) and (5.2). If the light sheet thickness is defined, the length of registered particle trajectories is a function of this thickness and the angle at which the particles are crossing the light plane. The glancing angle can be determined as follows

$$\beta = \arctan\frac{l_z}{l} \tag{5.3}$$

where

l_z – laser sheet thickness

l – length of the registered particle trajectory.

Eighth step – removing particle tracks

After determining all parameters, the particle trajectory should be removed from the image. Because of the crossing movement of individual particles it is very important to remove only individual particle tracks not pixels located between them.

After that, it is necessary to randomly find the next particle (return to the second step) and change the location of the new co-ordinate system, e.g. location of the pivoting point.

Ninth step – drawing the particles trajectory map

On the basis of the determined parameters of individual particles it is possible to draw a particles trajectory map. It contains all the found trajectories marked as the lines with the lengths corresponding to the lengths of the particle trajectories and orrientation according to the slope of the scanline.

Tenth step – drawing the velocity vector map

Determining the velocity vector map for a multiexposure photography is very difficult because there is no information about the origins of the individual vectors. Consider, for example consider two different particle trajectories. The scanline found seven subsequent locations of the first particle and four subsequent locations of the second particle. Nobody knows, if the second particle appeared on the image during the first location of the first particle or during another. However, the origins of the velocity vector can be assigned to the middle of the particle trajectory with good approximation to draw the velocity vector map.

If the scanline finds particle trajectories belonging to two different particles it is necessary to do the segmentation of the scanline and analyse each part of the scanline separately.

A specklegram contains also short particle trajectories, which are difficult to detect. In this situation the brightness distribution function can have two or three local maxima. Here, it is necessary to constrain the field of the analysed square region to the size of the particle trajectory length. Thus, the whole image plane is now divided into small subregions. The centre of these subregions are the new locations for the pivoting points and the scanline procedure for each subregion can be repeated.

6. Conclusions

The laser sheet technique for determining velocity fields and mass flows at the outlet of a nozzle system used for introducing limestone particles into a power boiler for a desulfurization process was applied. It brings an effect in the form of recording of multiexposure pictures of single particle trajectories or their agglomerates in selected areas of the flow.

On the basis of this the following problems can be discussed:

- homogeneity of the velocity field
- influence of the agglomerate size on the trajectory of the agglomerate
- accelerations of the particles flowing in the system
- mutual location of the particle trajectories

- phenomena registered on the edge of the stream
- ability of the sorbent to coalesce.

The novel algorithm for quantitative analysis of specklegrams was proposed. It consists in using the scanline, which is the searching of the particle trajectories by their rotating and the application of the correlation technique for the determined periodic brightness distribution function.

The third velocity component can be estimated by using a finite light sheet thickness.

The algorithm enables one to determine:

- parameters of the particle trajectories (length, direction, angle at which the particles cross the laser light sheet)
- all velocity vector components of individual particles.

The method can be applied for determination of motion of fluids as well as heterogeneous systems.

There are large velocity differences between particles moving in the same area in heterogeneous systems. These particles have different sizes, so probably there are also different mass densities. Thus, velocity fields of different phases should be desribed as overlapped rather than a single velocity flow field.

Registering of the vector velocity components is possible only when the relationship between the size of the analysed area, strobing frequency, and exposure time is appropriate. When the particle trajectory is registered from one edge of the photographic image to another, it is possible to determine only two components. Determination of the three components is only possible when the particle trajectories have a finite length in the analysed region. The solution to this problem lies in applying a shorter exposure time, which is connected with making use of a high powered laser, e.g. the above-mentioned Nd-Yag laser.

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Zastosowanie techniki noża świetlnego w analizie trójwymiarowych pól prędkości ziaren

Streszczenie

Autor zastosował technikę noża świetlnego do rejestracji pól prędkości i przepływów masowych przy wylocie dyszy służącej do wprowadzania sorbentu wapniowego do kotła energetycznego w procesie odsiarczania spalin. Efektem są wieloekspozycyjne obrazy zwane speklogramami, rejestrujące pojedyncze tory cząstek lub ich aglomeratów w wybranych strefach przepływu. Na tej podstawie oszacować można parametry pola prędkości. Analiza jakościowa speklogramów może zostać przeprowadzona za pomocą zaproponowanego przez autora algorytmu, będącego połączeniem tradycyjnych metod korelacyjnych oraz techniki obrotowej lini skanującej.

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