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EVALUATION OF PULSED LASER HOLOGRAMS OF FLASHING SPRAYS BY DIGITAL IMAGE PROCESSING

P. Gebhard, F. Mayinger
Lehrstuhl A für Thermodynamik, TU München
Arcisstr. 21, 80333 München
Germany

ABSTRACT

In the last 15 years many efforts have been done to evaluate pulsed laser holograms of particle fields by applying techniques of the digital image processing. An insight in this problematic was presented by Haussmann & Lauterborn (1980). Laser pulsed holography provides one or more three dimensional scenes taken at a very short exposure time of the whole volume of interest. The recorded holograms can be reconstructed with help of a continuous laser beam and analysed at any time. In our case we record two off-axis holograms in an angle of 90° to each other. Using a separated reference beam, the holographic reconstructions can be observed directly or with help of a microscope lense mounted on a videocamera. The received images are delivered to an image processing system.

These off-axis holograms contain information about macroscopic structures as the liquid sheet near the nozzle and microscopic ones as size, position and velocity of the spray droplets more downstream the nozzle. The spray is produced by injecting subcooled or superheated liquid through pressure nozzles. 'Superheated' in this case means that the liquid temperature is higher than the saturation temperature corresponding to the ambient pressure in the injection volume. By this superheated injection the fragmentation of the liquid is not only done by mechanical forces but also supported by the growing of vapour bubbles in the metastable phase of the ejected liquid.

The main problem appearing in the evaluation of holograms of particles consists in selecting and classifying well-focussed particles while the videocamera scans the three-dimensional holographic image.

The aim of this work is to describe an approach to evaluate pulsed laser holograms of particle fields automatically and to reconstruct the spray and the velocity field of it three dimensionally on a computer.

This paper presents two computer aided, procedures for automatic evaluation and three dimensional reconstructions of pulsed off-axis holograms (single and double pulsed holograms respectively) of sprays. They base upon techniques of the digital image processing (IP) and particle imaging velocimetry (PIV) implemented in a personal computer. By using these procedures, the operator is released from the situation of taking decisions interactively during the evaluation process. This allows for a more efficient application of drop focussing and classifying criteria, resulting in a substantial increase in the accuracy of the measurements and in an effective reduction of the time dedicated to the evaluation.

EXPERIMENTAL FACILITY

The experiments were carried out in the test facility presented schematically in Fig. 1. After degasing by a treatment with ultrasonic and boiling, the test fluid is stored in the reservoir. This tank is pressurized by nitrogen in a range of 0.1 to 2 MPa. The liquid in this vessel can be heated by three electrical heater of 1.2 kW each. From an outlet in the lower part of the vessel the fluid flows though a oil heated heat exchanger for a fine adjustment of the temperature of the injection

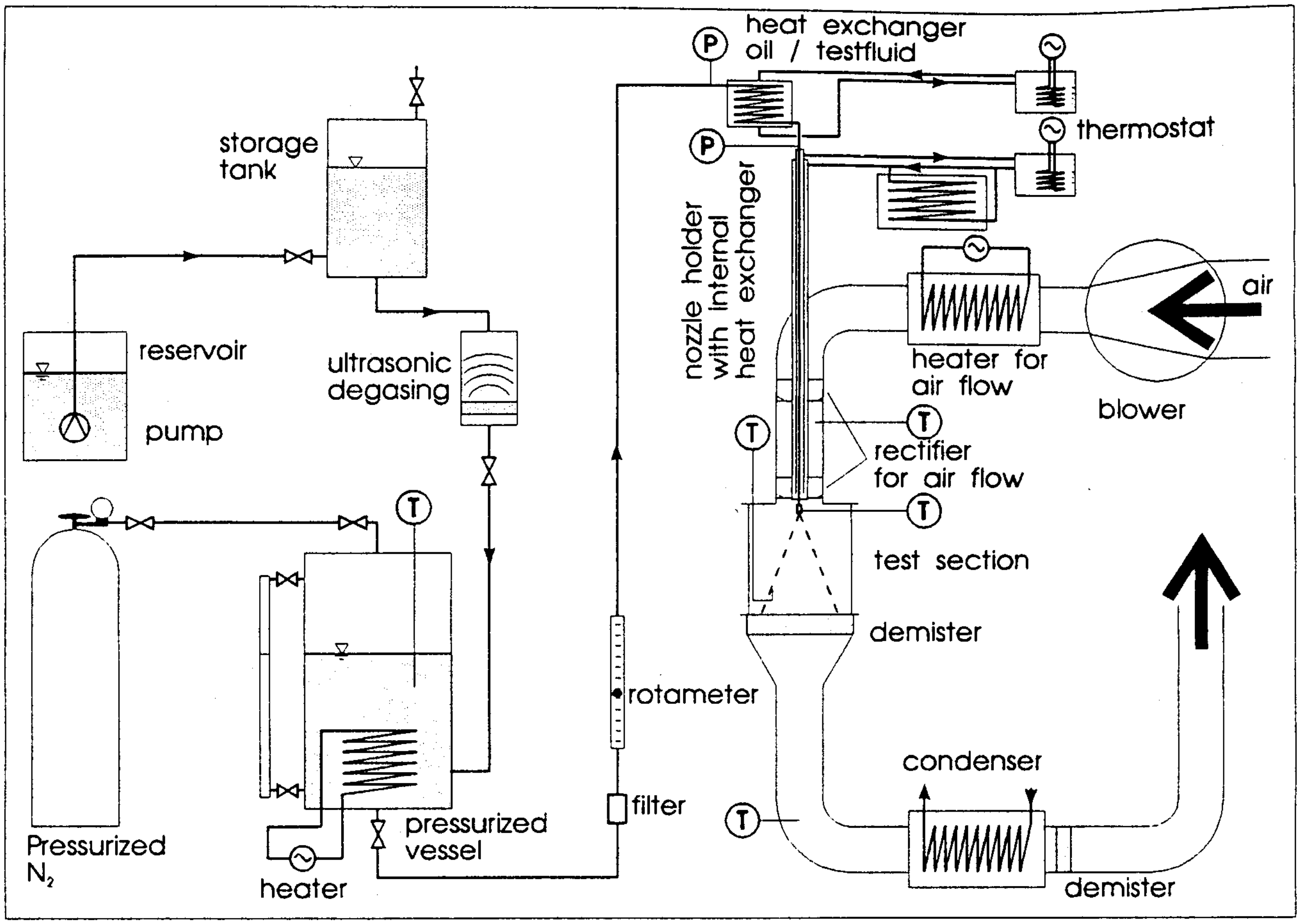

Fig. 1: Experimental set-up

fluid and reaches the nozzle.
The test section itself consits of a coflowing vertical wind tunnel capable of providing air velocities up to 20 m/s and temperatures up to 600°C.
In order to allow an optical access from different angles the experimental chamber is made of an octagon of glass of 300 mm interior diameter and 250 mm in height, designed for atmospheric pressure.
The nozzle, concentric with respect to the surrounding air flow, can be moved axially to permit the observation of any section of the spray.
More downstream the test section the produced mixture of air, test fluid and vapour is cooled down in a heat exchanger and the condensate is separated by a demister and is collected.
Measurements of temperature and pressure at different points of interest in the facility were carried out by conventional thermocouples and pressure sensors monitored by a personal computer.

THE HOLOGRAPHIC TECHNIQUE

Recording of the holograms

The root of the word holography lies in the greek language and describes the ability of the method to record the totality of the light information scattered or reflected by an object, namely the amplitude or intensity and the phase distribution. A deeper insight into this technique is made in the literature (Leith & Upatnieks, 1964; Kiemle & Röss, 1969).
The pulsed laser holography, applied in this work represents one of the more suitable non invasive measurement methods for the study of transport phenomena (e.g. heat and mass transfer) in dispersed transparent flows. It provides one or more three dimensional scenes of the volume of interest taken at a very short exposure time. The recorded holograms can be reconstructed with help of a continuous laser beam and analysed off-line at any time. Fig. 2 shows the optical set-up for the recording of two off-axis holograms perpendicular to each other. Using a separated reference beam, the

holographic reconstructions can be observed directly or with help of a microscope a s in a photograph. The reconstructed images are very clear for particle sizes $D > 10\lambda$ where D and λ are the drop diameter and the wavelength of the laser light used to record the hologram, respectively.

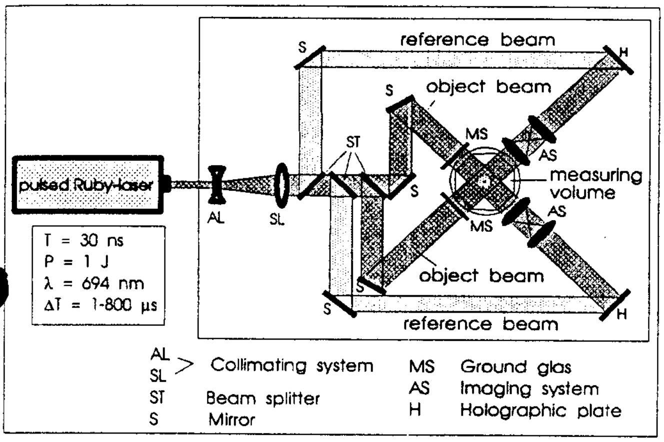

Fig. 2: Optical set-up

The laser **L** schematically showed in Fig. 2 used to record the holograms is a pulsed ruby laser which produces light pulses of an energy of 1 *Joule* in a very short time of 30 *ns*. It can be operated in single or in double pulse modus. In single pulse modus the resulting holograms contain macroscopic information about the geometry of the spray, the break up of the liquid sheet, and microscopic data like the droplet diameter and distribution in the control volume. When the laser is operated in double pulse modus the resulting holograms reconstruct two sucsessive scenes of the spray flow which provide information about the droplet velocities and trajectories. The interval between pulses can be varied from 1 to 800 μs. This technique delivers two perpendicular 3-D images of the same spray without restriction in the depth of focus range. The principal features of this holographic method are explained in detail in Mayinger (1994).

Reconstruction of the holograms

For the reconstruction we use a continous HeNe-Laser with a wavelenght of 632 *nm*. The reconstruction of both holograms is made simultaneously and the formed images are recorded by two Newicon TV-cameras, so that we obtain two views of the spray perpendicular to each other. They represent a three-dimensional (3-D) image corresponding to a "frozen" scene of the spray, as shown in the schematic of Fig. 3. The whole injection volume is subdivided into several subvolumes of a dimension of $4 \times 4 \times 4\ mm^3$.

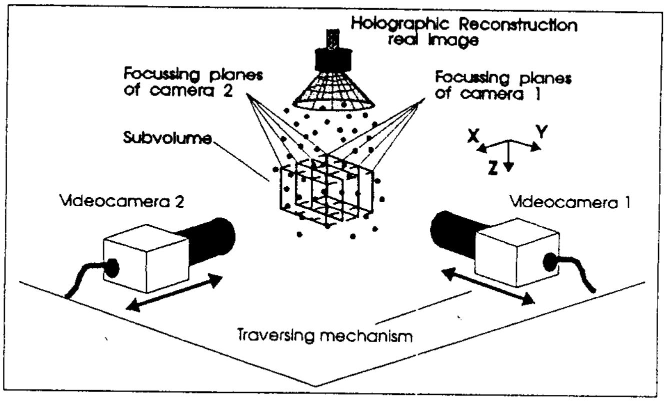

Fig. 3: Holographic reconstruction of the holograms

Because the video camera only can take two-dimensional (2-D) pictures, that is in the optical plane, it must be focussed stepwise along the depth coordinate in order to record all of the 3-D information contained in the holographic image. In this manner, the 3-D holographic image is transformed into many 2-D video pictures observed from two different directions. In order to control the position of the cameras each camera is mounted on a traversing mechanisms, which is controled by a computer.

HOLOGRAM EVALUATION

One of the principal problems appearing in the application of pulsed laser holography consists in handling the large amount of information contained in the holograms. Theoretically, holographic materials are able to store the information on position, texture and brightness of more than 10^6 particles per square millimeter. In this case, the droplet concentration is very much lower (less than 10 drops per cubic millimeter of reconstructed space). Nevertheless, one single hologram can contain information about position, size, and velocity of many thousands of droplets. Comprehensive studies of the characteristics of the droplets and their interactions with the gaseous environment necessarily require the help of computer-aided particle counting and measuring methods.

Figure 4 shows the scheme of the components of a digital image processing system used to evaluate the holographic reconstructions. Both holograms **H** are reconstructed simultaneously by illumination with a continuous parallel beam from a He-Ne-laser, which simulates the reference beam.

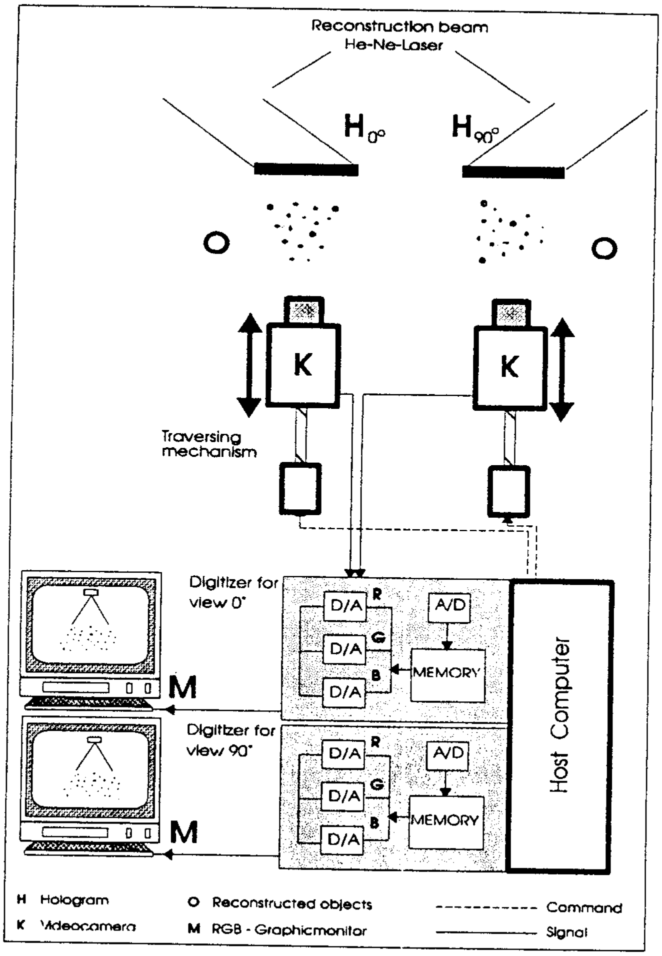

Fig. 4: Reconstruction of the holographic information and the digital image processing system.

The optical information contained in the reconstructed images **O** is scanned by the video cameras **K**, and transmitted to the digitizer **D**. Here, the signal is transformed into digital information and is stored in the digitizer frame memory, in form of an array of 512 x 512 picture elements (pixels) of 8 bits. The digitizer is directly connected to the host computer **C** by a 16 bit bus interface. The processing of the digitized picture is then carried out by the host computer using the digitizer frame memory interactively, for pixel allocation. In order to visualize the information actually stored in the digitizer frame memory, this produces a continuous RGB (false color: red, green, blue) output signal which can be observed on the graphics monitor **M**. Due to the fact that the video camera can only record two-dimensional (2-D) pictures, it must be focussed stepwise along the depth coordinate in order to process the 3-D holographic image. In this manner, the 3-D holographic image is transformed into a series of many 2-D video pictures, which are then measured and classified. Examples of representative stages of the image processing are presented in form of photographs in Figure 5.

The first module of our software transforms the original image, seen by the videocamera into a binary image. The photograph (A) shows the original image of a holographic reconstruction, (B) the gradient extraction, (C) contouring and (D) the binarization. The nozzle is included for better orientation. These processes are performed by streching the histogram of the grey values of the image and the application of a threshold filter with values obtained from a histogram evaluation. By these operations we get binary coloured images which are the basis for the following evaluation algorithms. An enlargement (A1) of the droplet zone of picture (A) is showed to illustrate the process of noise filtering ((A2) to (A3)) and the final result in (A4). A comprehensive description of hologram evaluations by applying digital image processing can be found in Chávez & Mayinger (1992).
After receiving this binary images the second module makes the determination of the droplet positions in the space. This task is performed by coordination transformation which should be extended by the influence of the different media on the way of light, which leads to a double diffraction of the beam, and the distortion of the lenses of the observing cameras. During the calibration of the system we noticed, that the radial and the tangential error of distortion of the used microobjective lenses (Nikkor 105 mm) was lower than one single pixel on the surface of the camera chip. So we neglect this error during our processing and focus on solving the problem of the double diffraction of the path of the light on the surfaces of glass window of the test section shown in Figure 6. In our case during the recording of hologram the scattered light of the object travels through the hot air inside the test section, passes the window and the cold air of the laboratory.

In our software we use for the determination of the radial displacement on the camera chip caused by the diffracton on the interfaces between the different substances an iterative algorithm developed by Maas 1992. This model works for 3 substances, from which the separating one consists of plane parallel faces, in our application the window of the test section.

The third module performs the stereomatching, this means the determination of the position of the particles in space which is a very important step in the evaluation of the holograms. The droplets differ in size and shape, but this feature based matching is a weak criteria for the correllation between both views, because of the influence of the illumination and the va-

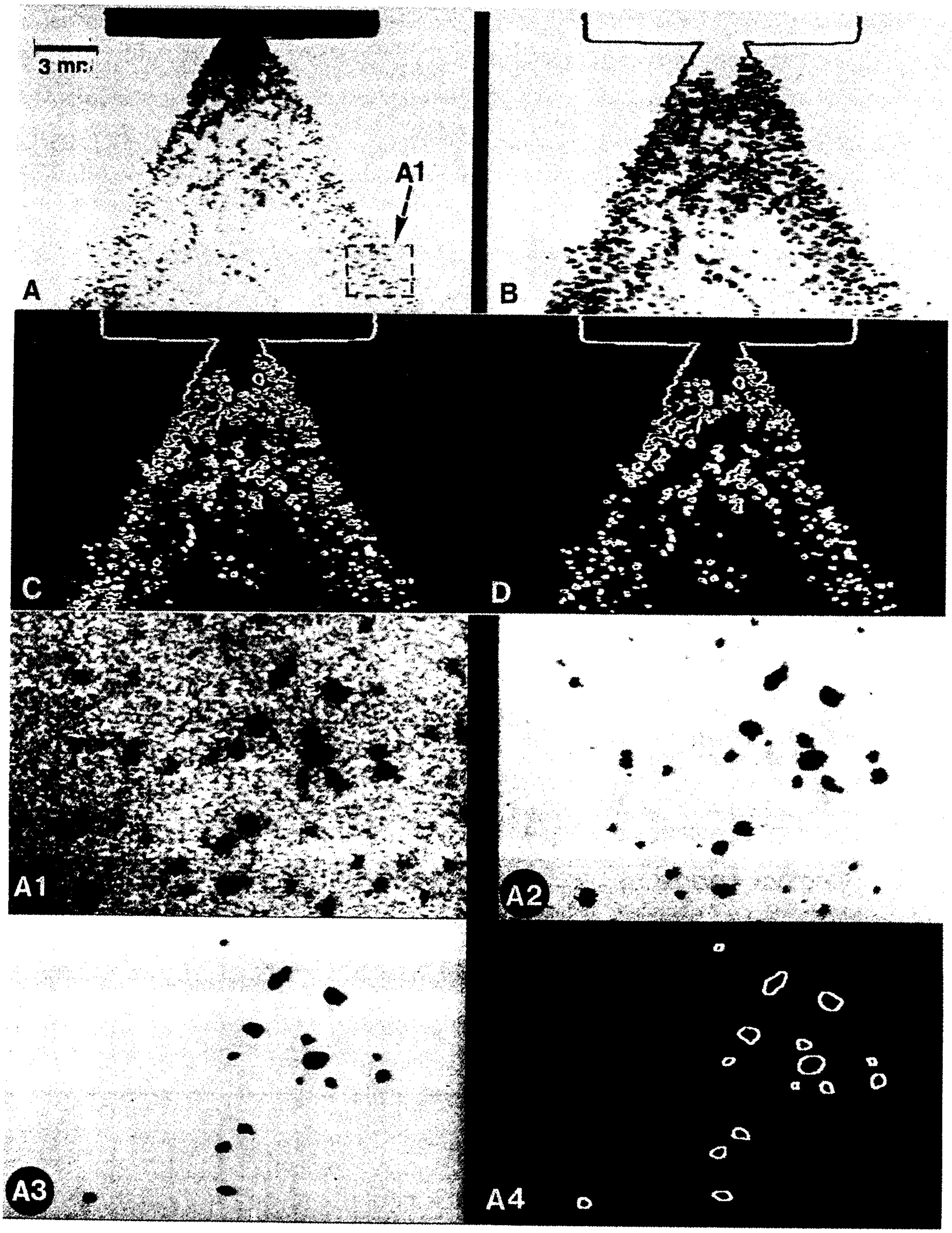

Fig. 5: Representive steps of image processing of a slice cutted from a holographic reconstruction

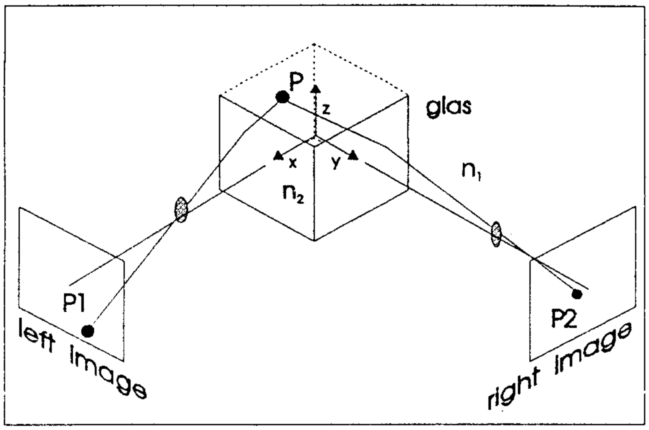

Fig. 6: Model for the description of the problem caused by the diffraction of the way of light

riation in the shape between both views. Generally the experience shows, that two cameras are not enough to determine the particle positions with a sufficient accuracy due to the large number of ambiguities (physical possible matches). That is why often a third or a fourth camera is used.

In our case we have another secondary criteria to aid the matching process. We can determine the depth coordinate of the droplet by applying the focussing criteria. The determination of the positions of the droplets in the control volume is made by a coordinate transformation provided the knowlege of the position and the depth of the focussing plane of the observing video cameras.

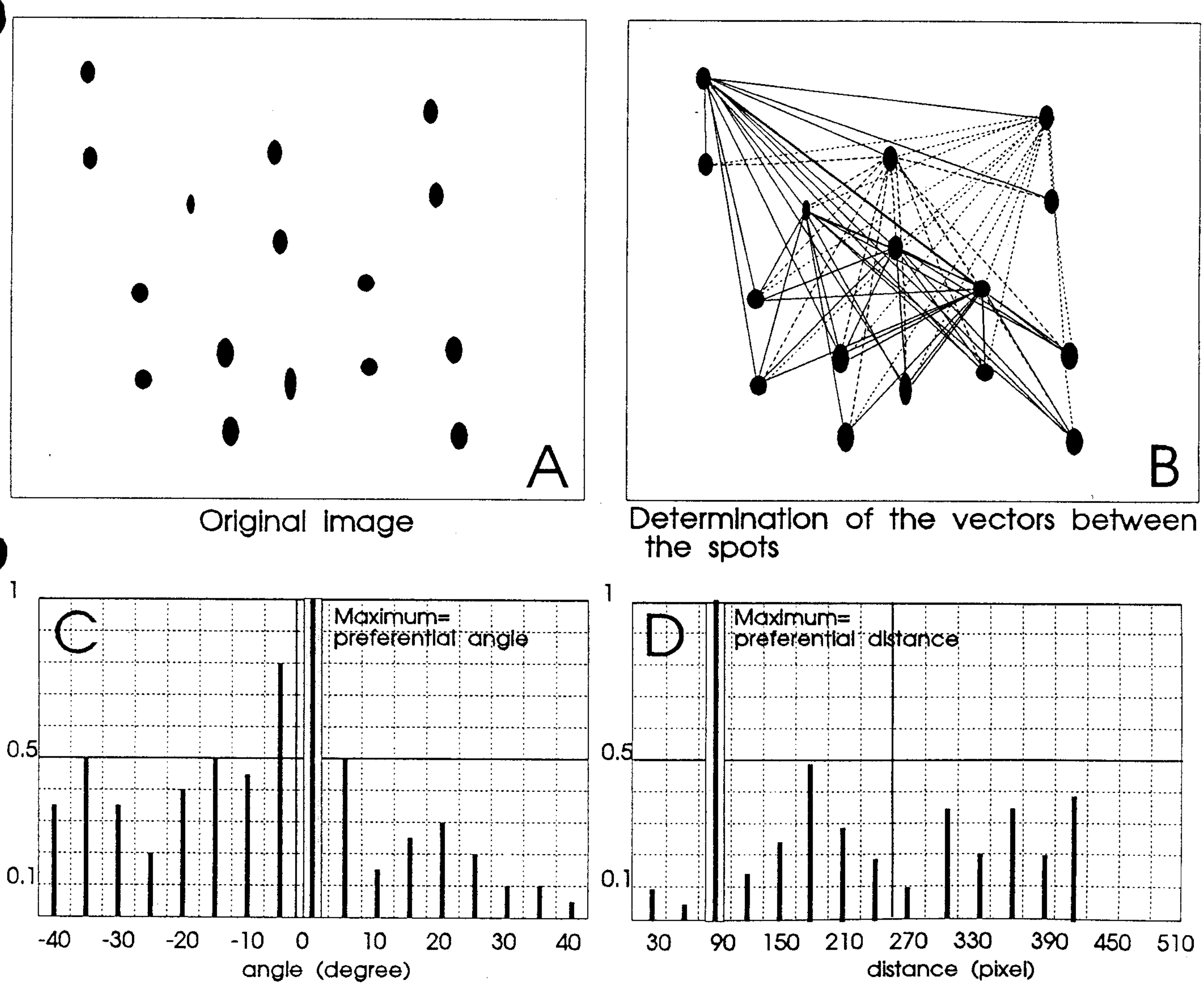

FIGURE 7: Steps for recognition of spot couples corresponding to two successive positions of droplets using module 1 of the subroutine VEL. A) source image, B) calculation of the spot center points and velocity trajectories, C) and D) Frequency analyses

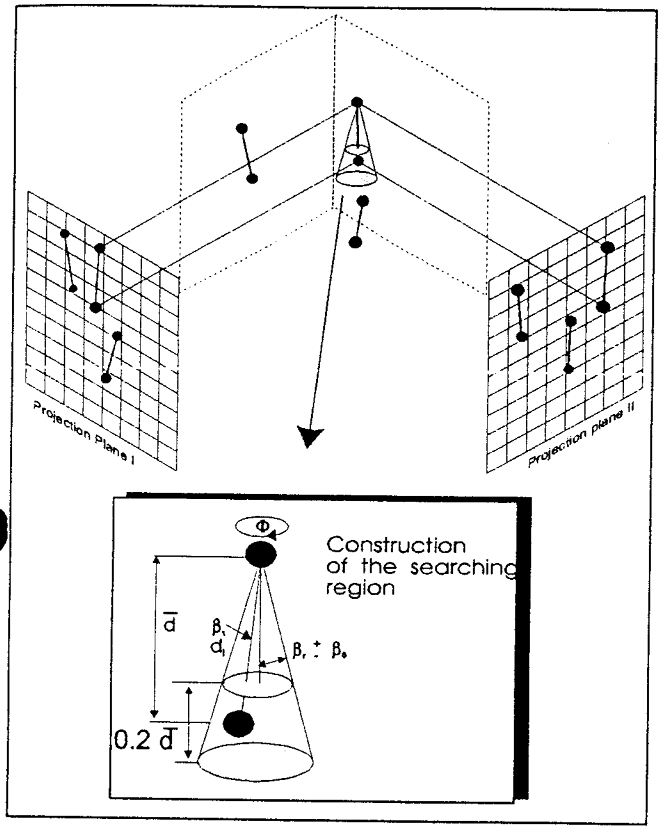

Fig. 8: Searching the second position of the same droplet by building up a searching volume providing the knowledge of the frequency analysis of the first module of VEL

From double pulsed holograms one obtains information about velocities and trajectories of the droplets. The holograms represent a conglomeration of spot couples, in which each couple represents a spray droplet imaged at two successive positions corresponding to the time intervall ($1-800 \mu s$) between the two exposures used to record the hologram. In order to evaluate the double-pulsed images, the routine VEL was developed. The task of this program consists in identifying the spot couples from the pictures taken by the video camera, in measuring the distance between the center points of the two successive droplet images, and in computing the droplet trajectories related to focussing plane of the observing videocamera. Representative stages of the image processing are presented in form of pictures in Fig. 7. It consists of two modules: a spatial frequency analyzer and a measuring algorithm. Without regard to color or form and with the previous assumption that picture **A** was obtained from a double pulsed holographic reconstruction, and that the elements of **A** represent droplets which are falling down between a guessed angle of $\pm 45°$ with respect to a vertical line, the first module of VEL has to recognize automaticly the two positions of each droplet. First the coordinates of the spot center points S and the vectorial distance $\bar{\mathbf{d}}$ between each two center points are calculated as illustrated in picture **B** of Fig.7. The vectorial distance $\bar{\mathbf{d}}$ can be splitted in a distance **d** and an angle β towards the vertical. Then a frequency analysis converts the spatial distribution of β into a normalized frequency distribution with the maximum F_{max} used as a norm. With the information of this preferential angle, a second frequency analysis with the distance **d** as the independent variable is carried out. The diagrams in Fig. 7 **D** and **E** show the two variables evaluated from picture **A** of the same figure. The preferential angle β_p and the preferential distance $\mathbf{d_p}$ appear as peaks in the diagrams and form the mean velocity $\bar{\mathbf{v}}$.

This algorithm is applied to both views of the videocameras and we get an average velocity projected into the focal planes of the videocameras. By the evaluation of both mean velocities $\bar{\mathbf{v}}$ in both views we construct an real angle in space, called β_r, which consits of an cylinder coordinate Φ and the angle β_r.
To get the real velocity in space we developed a second module for the subroutine VEL in order to find out the real droplet velocities. For this realization the magnitude $\mathbf{d_p}$ of $\bar{\mathbf{v}}$ is incremented by the tolerance $\pm 0.2\mathbf{d_p}$ and its corresponding angle β_r is also incremented by the tolerance $\pm \beta_0$, which can be varied between 7 and 15° allowing for strong variations of the droplet trajectories. Using these variations the algorithm builds up an searching volume to find the second position of the same droplet. The scheme in Fig. 8 illustrates the working method of the second module of VEL. Herein V_i and β_i mean the real magnitude and direction of the velocity corresponding to the imaged positions of the droplet, respectively. This algorithm works with a high relaibility, because we found an unidirectional flow of the droplets in respect to the build subvolume.

RESULTS AND DISCUSSION

As an example of the applicability of the discussed recording and evaluation technique some results are presented. In Fig. 9 shows an extract from an experimental matrix. We performed experiments with a hollowed coned swirl nozzle with an diameter of the orifice of 0.6 mm. The used test fluid is destilled and degased water. The injection pressure ranges in our experiments from 0.15 to 0.8 MPa and the temperature varies from $20°C$ (subcooled liquid) up to $130°C$ (superheated with respect of the pressure in the test autoclave of 0.1 MPa.

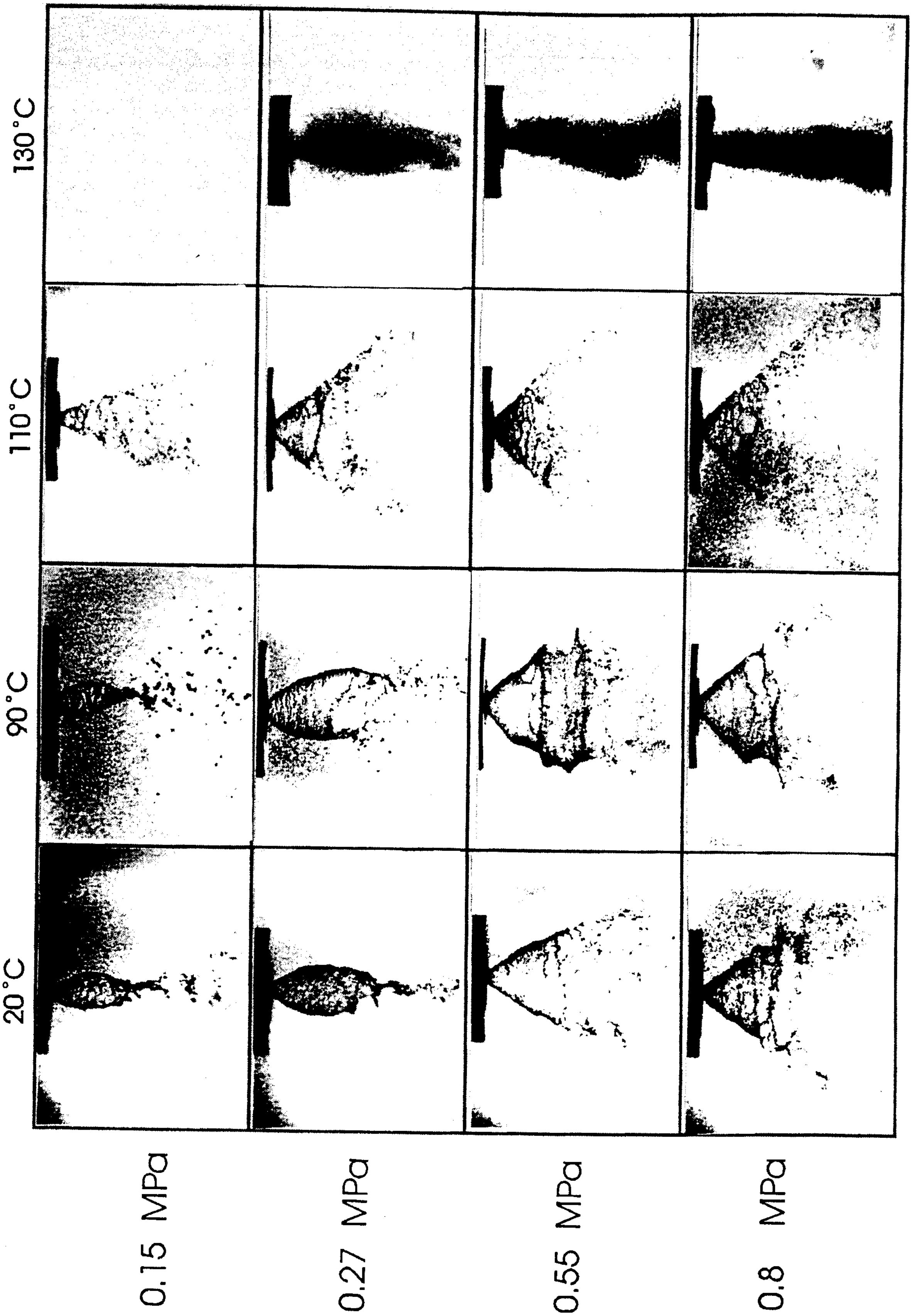

Fig. 9: Photographs of a water spray at different injection conditions concerning pressure and temperature.

Fig. 10 shows a schematic sketch of the flow and the spray downstream a hollowed cone nozzle. The spray may be devided into three zones: the continuous liquid veil zone, formed by the swirling test fluid, the breakup zone, where the droplets are formed and the droplet zone. The form of the liquid sheet, characterized by the spray angle α and the breakup length L_z, plays an important role; it is reponsible for the final form of the spray and the size of the droplets. Due to the unstable breakup of the liquid sheet, the produced droplets are of very different sizes and move with different velocities.

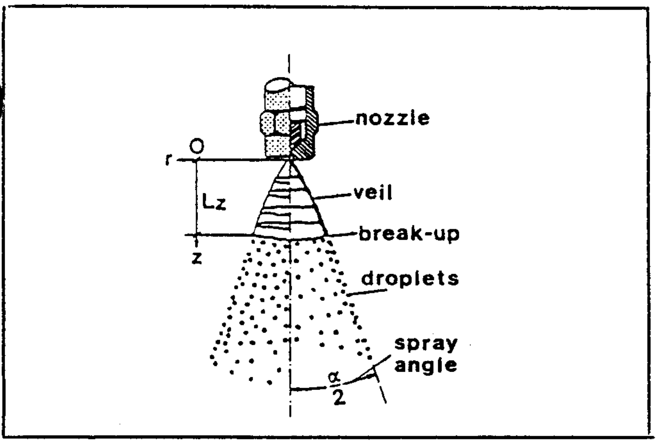

Fig. 10: Scheme of the spray of a hollowed coned nozzle

Spray cone

In Fig. 11a and b two characteristic features of the liquid veil are shown. 11a shows the angle α of the spray as a function of the pressure at different injection temperatures, 11b shows the breakup length at the same parameters.

For subcooled and superheated injecting we can see, that the spray angle α increases with higher injecting pressure and reaches a borderline asymptotically. This effect is propagated by the higher radial velocity in the liquid veil and the resulting centrifugal forces. For subcooled liquid the spray angle also increases with a higher temperature because of the lower viscosity, which leads to a higher velocity in the swirl chamber of the nozzle and also higher centrifugal forces. For increasing temperatures and passing the subcooled limit of $100°C$ the spray angle decreases, because due to the pressure loss in the channels of the swirl chamber the flow reaches two-phase flow conditions and disturbs the forming of an proper liquid sheet more downstream the nozzle.

Fig. 11b. shows the typical plot for the breakup length as a function of the pressure. First L_z increases to a

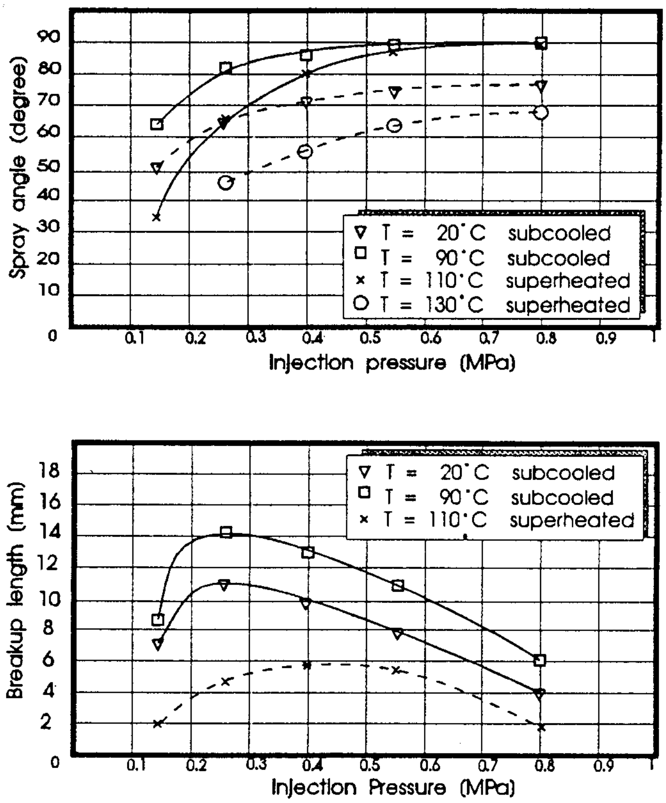

Fig. 11: Spray angle and breakup length as a function of the injection pressure at different temperatures of the test fluid. Solid line represents subcooled dashed line superheated liquid in respect of the ambient pressure in the test section.

maximum and for higher pressure the liquid veil becomes shorter. The desintegration of the liquid sheet is caused be instabilities, which form a wavy surface of the veil. This instabilities are propagated and amplified by the shear force on the phase interface between liquid and ambient gaseous phase.

Drop size

Fig. 12 summarizes in form of the mean Sauter Diameter of the drop diameters of a great amount of measured data. For a higher pressure the drop size decreases because of the higher inertial forces and the higher energy which leads to a better desintegration of the liquid sheet. For higher temperatures in the subcooled region and in the case of slightly superheated liquid the dropsize decreases because of the lower viscosity. For a superheating of more than $25°K$ the forming of vapour bubbles is the more important effect which causes the desintegration of the liquid sheet. This leads to a very fine Sauter Diameter in the spray, which represents the volume to surface ration in the spray.

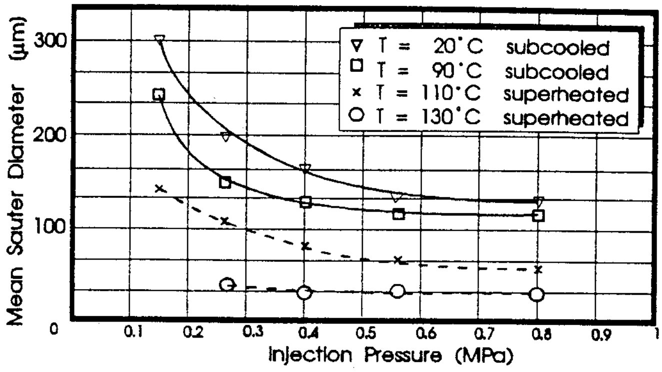

Fig. 12: Mean Sauter Diameter as a function of the injection pressure at different injection temperatures. Solid line represents subcooled dashed line superheated liquid in respect of the ambient pressure in the test section.

Droplet velocity

Fig. 13 shows the droplet velocity as a function of the injection pressure at different injection temperatures. In the subcooled nd the superheated temperature region no significant influence of the temperature on the droplet velocity is remarkable.

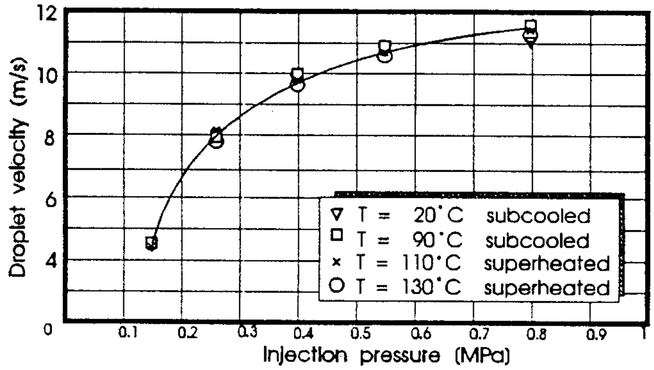

Fig. 13: Droplet velocity as a function of the injection pressure at different injection temperatures measured-near the nozzle. Solid line represents subcooled dashed line superheated liquid in respect of the ambient pressure in the test section.

Accuracy

The main source of uncertainty in the measurement method lies in the pixel representation of circular objects (droplets), especially when these objects contain less than 10 pixels (independent of the absolute pixel size). By setting the resolution of the area measurement method to 5 pixels, a maximum error of $\pm3\%$ was obtained by comparing a circular area with a pixel ensemble in which the amount of pixels was varied between 6 and 40 pixels. In this work, the smallest drop images contain 14 pixels (ϕ 30 μm) and the largest ones 148 pixels (ϕ 310 μm). For larger objects or structures, the error is less than 1%.

Due to the fact that we take some thousands of droplet into account the accuracy of the mean velocity is quit high about 5%. The individual velocity is more depending on the quality of the stereomatching and the yield of the found couples.

CONCLUSION

This work presents a fully-automated 3-dimensional particle imaging velocimetry technique, which is based on the evaluation of pulsed laser holograms. The large amount of data, contained in a hologram, can be analysed blindly without provided knowledge about the flow in the measuring volume. The code works with a good accuracy and can be implemented on an inexpensive digital image processing system with usual digitizers (512×512 pixels, 8 bit depth). By application of this technique we can measure not only macroscopic structures like the dimension of the liquid sheet but also microscopic structures like droplet size and velocity.

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