EVALUATION OF PULSED LASER HOLOGRAMS OF SPRAY DROPLETS USING DIGITAL IMAGE PROCESSING

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ABSTRACT

The evaluation of pulsed laser holograms of particle fields has been improved substantially by using digital image processing. The use of computer aided methods allows the application of more efficient focussing and classifying criteria throughout the whole evaluation process. In this work, a system for automatic evaluation of pulsed holograms is described. It was implemented on a personal computer and is also suitable for applications in small optical laboratories. Software procedures for the evaluation of single and double pulsed holograms with special emphasis on the particle identifying and focussing techniques are also described. Finally, the results of the evaluation of a series of 30 holograms of spray droplets are presented.

INTRODUCTION

In the last 10 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 (1979)*. The evaluation of holographic reconstructions of particle fields consists in scanning the three dimensional image with a videocamera, in identifying well focussed particles within the depth of field of the imaging optics (e.g. microscope objectives), and in measuring and classifying the selected particles with respect to the depth coordinate. With this information it is possible to reconstruct the history of the particles (i.e. their trajectories and time of residence in the control volume) and, depending upon their changes in shape, size, number and concentration, to deduce the intensity of, for example the mass transfer or other transport properties associated with these changes.

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. From the conglomerate of particles imaged on the camera sensor at a given value of the depth coordinate, only a few of them which satisfy a given selecting criterion are allowed to remain in scene for later processing. *Ligthart & Groen (1982)* discussed the possibilities of a series of filtering algorithms, which can be applied as a criterion to select the particles. Some of these algorithms are used today by the autofocus pocket cameras. Recently, *Schäffer & Umhauer (1987)* presented a method for total evaluation of double pulsed in-line holograms. In this method, the operator searches well focussed particles while a computer controlled videocamera stepwise scans the holographic image. Finally, with help of image processing techniques the selected particles are measured and classified. Now, the tendency is to release more and more the interactive participation of the operator and in this manner to avoid the permanent repetition of human decisions along the whole evaluation process.

This paper presents two computer aided procedures for automatic evaluation of pulsed off-axis holograms (single and double pulsed holograms respectively) of spray droplets. They base upon techniques of the digital image processing implemented on 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.

SCOPE OF THE WORK

The aim of this work is to describe an approach to evaluate pulsed laser holograms of particle fields automatically. Two computer aided procedures were developed for automatic evaluation of single and double pulsed laser holograms respectively of sprays. These procedures were confectioned by using standard techniques of the digital image processing which, together with our own developed identifying and measuring algorithms, configurate the evaluation routines. The holograms to be evaluated are of öff-axis" type as can be deduced from the holographic arrangement presented in Fig.1. They contain information about size, position and velocity of the spray droplets and about the form of the spray cone. The spray is produced by injecting subcooled liquid of the refrigerant R113 (Trifluorotrichloroethane) through a 60° simplex (hollowed cone type) pressure nozzle of 0.6 mm in bore diameter (Lechler, Co.), into an environment formed by its own saturated vapor. Fig.2 shows a schematic picture of the spray flow.

Special emphasis is given to the discussion of our technique developed to scan the holographic image, the criterion adopted to select well-focussed droplets and, in the case of double pulsed holograms, to identify those spot pairs in the scanned image corresponding to droplets imaged at two successive positions (double exposure of the same holographic plate). Results of the evaluation of a series of 30 pulsed holograms of the R113 spray at different injection mass flow rates (0.8, 1.37, 2.0, 2.72, 3.86 g/s) and vapor pressures (0.15, 0.20, 0.25 MPa) are also presented as an example of application.

OPTICAL SET-UP AND EXPERIMENTAL FACILITY

Holographic Technique

The pulsed laser holography 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 taken at a very short exposure time (~ 30 ns) of the whole volume of interest. The recorded holograms can be reconstructed with help of a continuous laser beam and analysed at any time. Fig.1 shows the optical set-up for the recording of off-axis holograms. Due to the use of a separated reference beam, the holographic reconstructions can be observed directly or with help of a microscope as in a photograph. The resulting reconstructed

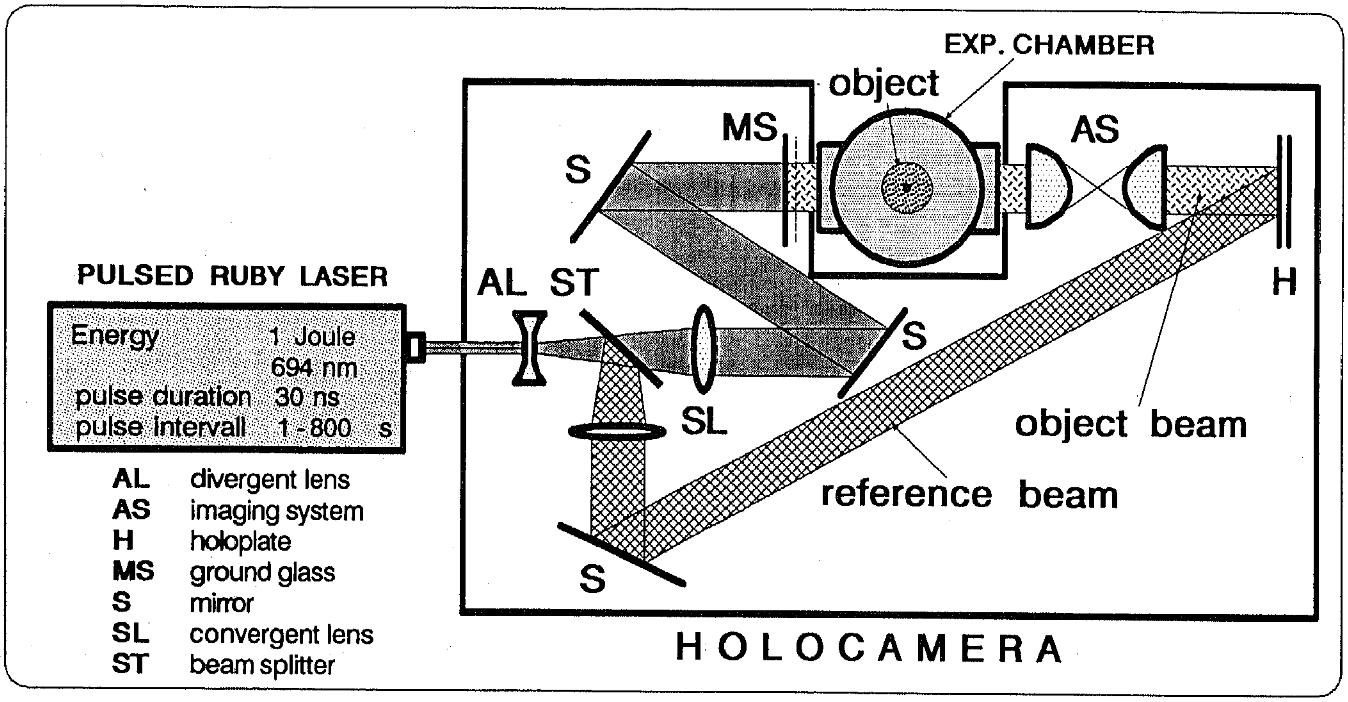

Fig.1. Holographic Arrangement

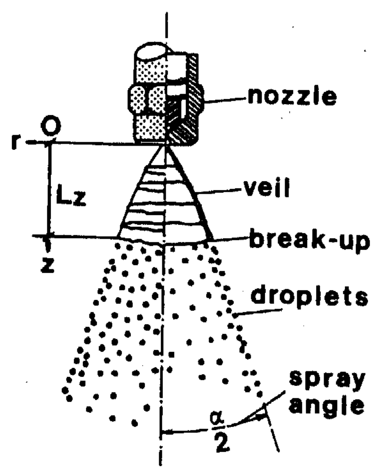

Fig.2. Description of the Spray Flow

images are very clear for particle sizes within the range of $d > 10\lambda$ where d and λ are the drop diameter and the wavelength of the laser light used to record the hologram, respectively. Position and velocity of the particles of the dispersed phase can then be obtained from the reconstructions. The principal features of the method and some advanced adaptations are explained in detail by *Trollinger (1975)* and *Chávez & Mayinger (1988)*.

Experimental Facility

Figure 3 shows a flow diagram of the experimental facility. The test chamber is represented in the center of the picture. It consists in a thermally insulated cylindrical autoclave measuring 206 mm in interior diameter and 650 mm in hight, which was designed for pressures up to 2 MPa. Two quartz glass windows (ϕ 100 mm) installed in the cylindrical wall provide the optical access. The spray is injected from the top of the vessel through the hollow cone nozzle. The nozzle, concentric with respect to the cylindrical wall, can be axially moved to permit the observation of any section of the spray. The lower third of the vessel is filled with liquid refrigerant R113 which is heated by an electrical heater (1.2 kW) installed on the lower plenum, to produce the saturated vapor environment in the injection space of the autoclave. A funnel is placed between the boiling liquid and the spray. It collects the spray droplets and leads them to the outlet.

The two pressure vessels (a liquid reservoir and a pressurizer) at the right side of the test chamber are used for conditioning and supplying the liquid to the experimental chamber. The rest of the facility components are a water cooler and a storage tank. The cooler receives the liquid from the experimental chamber and restores its temperature to the room temperature. Finally the liquid is led to the storage tank. This tank functions also as condenser for the exhausted vapor from the test chamber and as a venting tank. Measurements of temperature and pressure in the different points of interest in the facility were carried out with conventional thermocouples and pressure sensors monitored by a personal computer.

IMAGE PROCESSING OF HOLOGRAPHIC RECONSTRUCTIONS

One of the principal problems appearing in the application of pulsed laser holography consists in evaluating the large amount of information contained in the holograms. Theoretically, holographic materials are able to storage the information of position, texture and brightness of more than 10^6 particles per square millimeter. In our case, the particle concentration is very much lower (a few drops per cubic centimeter of reconstructed space). Nevertheless, one

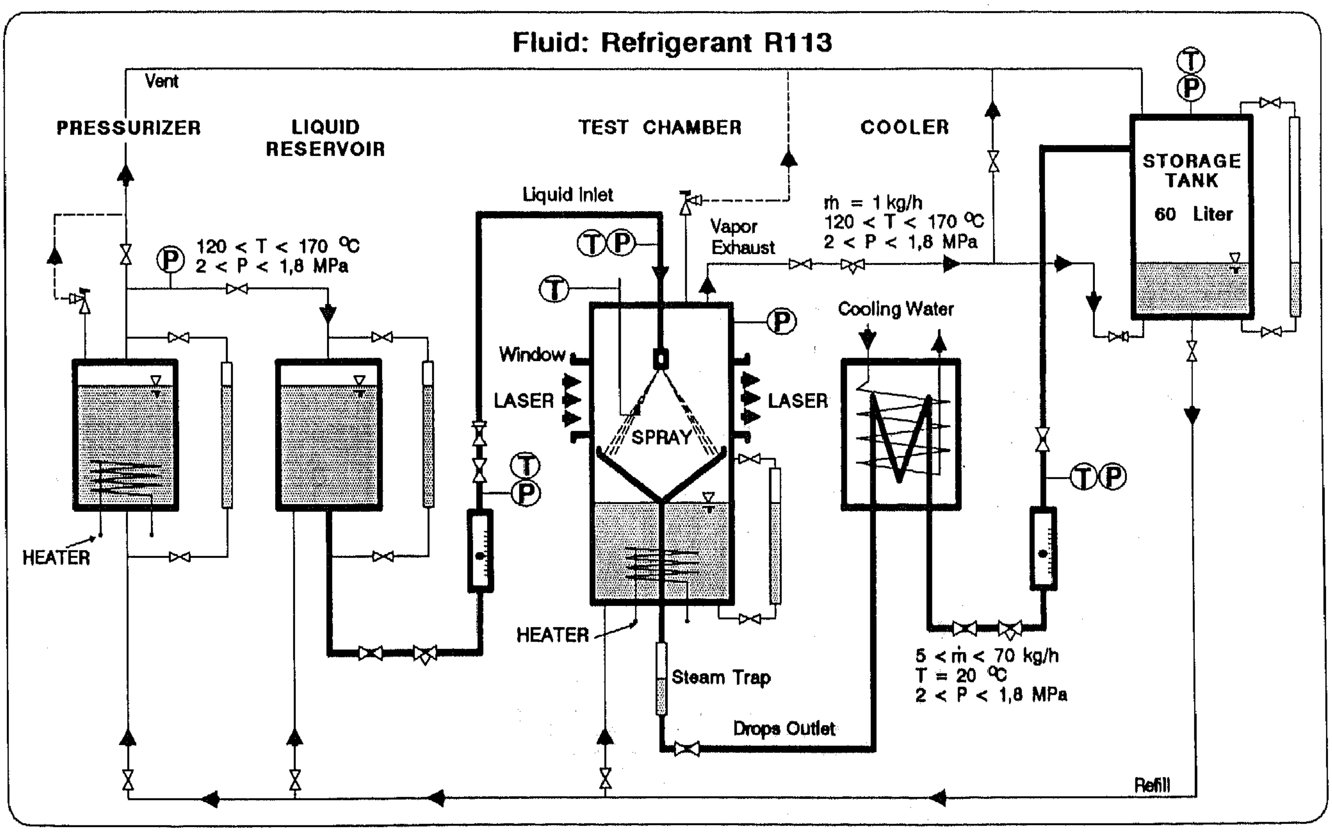

Fig.3. Experimental Facility

single hologram can contain information about position, size, and velocity of some 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. Fortunately, the rapid development of the computer technology in the last years, as well as the miniaturization and mass production of computer components has made many applications of the digital analysis and processing of images possible. Many tasks of the pattern recognition, handling of image data, and computer graphics, which were earlier reserved only for large computing centers and TV companies, can be today also carried out in small optical laboratories with help of the personal computer.

Image Processing System

The components of the digital image processing system are shown in the flow diagram of Fig.4. The hologram **H** is reconstructed by illumination with a continuous parallel beam from a He-Ne-laser, which simulates the reference beam. The optical information contained in the reconstructed image **I** is scanned by the video camera **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. This means, that each picture appears as a pixel matrix in which the colour of each pixel can be represented by one of 2^8 possible grey tones. The digitizer is directly connected to the host computer **C** by a 16 bit bus interface, allowing for fast communication. 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**.

Scanning of Holographic Images

The pictures to be scanned are obtained from single or double pulsed holograms. They represent a three-dimensional (3-D) image corresponding to a "frozen" scene of the spray, as shown in the schematic of Fig.2. In this scheme, **r** and **z** are axis symmetrical, cylindrical coordinates with origin **O** at the nozzle outlet. Single pulsed holograms contain information about the geometry of the spray, the break-up of the liquid sheet, and the droplet distribution in the control volume. Complementary, double pulsed holograms inform about the droplet velocities and trajectories. Typical pictures obtained from pulsed holograms are presented in Fig.5.

Due to the fact that the video camera can only take two-dimensional (2-D) pictures, it should be focussed stepwise along the depth coordinate in order to record the whole 3-D information of the holographic image. In this manner, the 3-D holographic image is transformed into many 2-D video pictures. In order to achieve a one-to-one relation between the spatial coordinates **r**, **z** of the holographic image and the planar coordinates **X**, **Z** of the

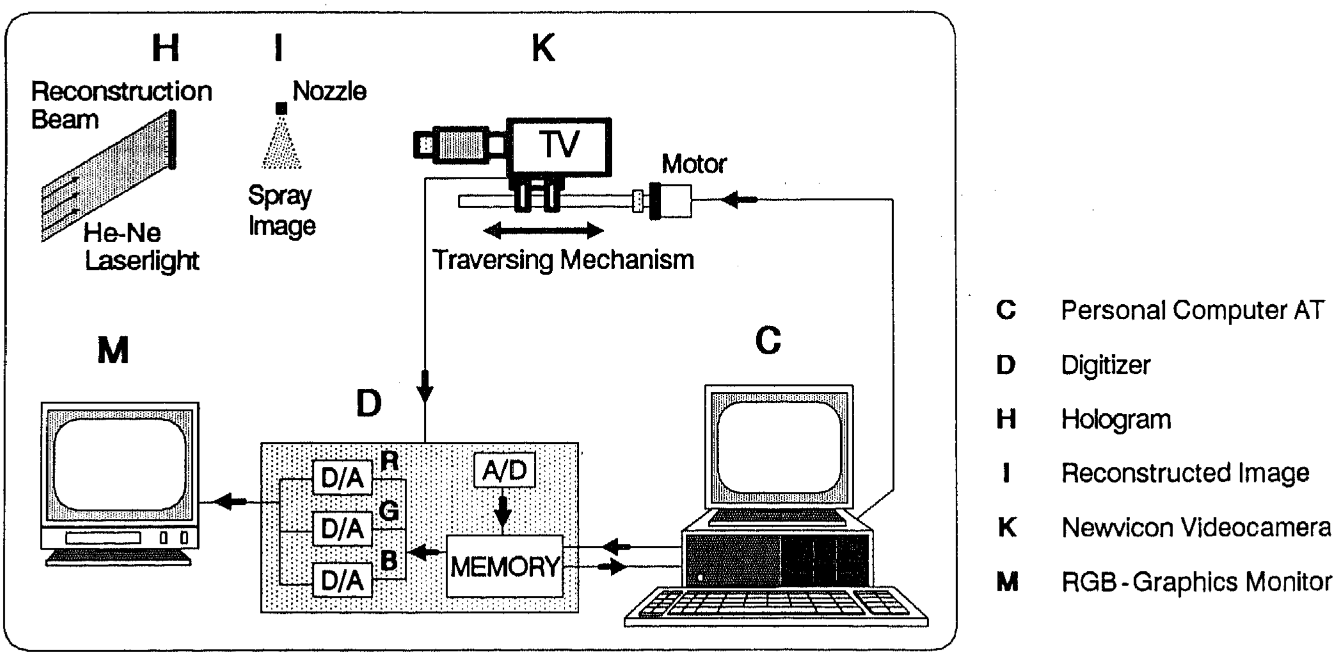

Fig.4. Digital image processing system

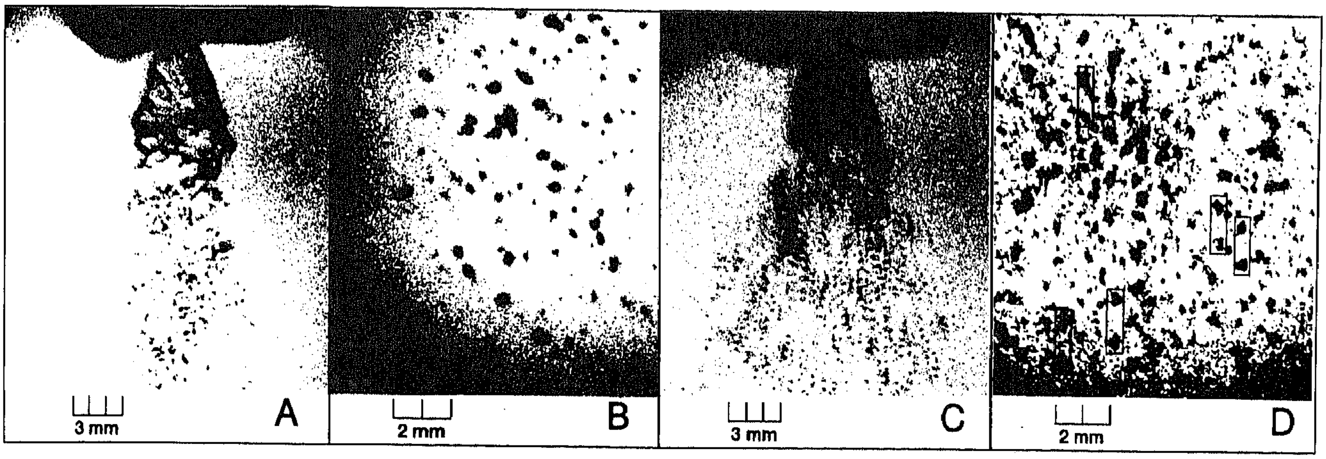

Fig.5. Typical pictures from single (A, B) and double (D, C) pulsed holographic reconstructions. A and C: Spray cone near the nozzle, B and D: enlargement of the droplet zone. The rectangles in D help to identify the two successive positions of droplets.

video pictures, it is necessary to adjust, as accurately as possible, the optical distance between the picture plane (focal plane) being scanned and the camera sensor, so that each picture can be correlated with a value of the depth coordinate **Y** (normal to the picture plane). This can be better accomplished by carrying out the process of focussing by moving the camera itself instead of adjusting its objective, and controlling the movement of the camera by the computer. For this realization, it was also necessary to provide a very good alignment between the optical axis of the camera lens system and the direction (depth coordinate **Y**) of the reconstructed object beam of the hologram. By forcing the optical axis of the camera to coincide with the **Y**-coordinate, lateral displacements of a pixel with coordinates **X**, **Z** on the camera sensor do not occur while the camera moves along the **Y**-coordinate. Consequently the droplets can be identified with an excellent repetibility.

In order to control the position of the camera and to measure the values of the **Y**-coordinate, the camera was mounted on a traversing mechanism, as indicated schematically in Fig.5. It consists of a precision, free from play, screw spindle/sleeve drive (ϕ 12 mm x 2mm pitch) coupled to a stepping motor (1000 steps/cycle). Together, they provide a linear resolution of 2 μm and permit the repositioning of the camera within a relative error of 10 μm in a distance of 200 mm. The movement of the stepping motor – representing the position of the video camera – is monitored by the computer through an RS-232 port. Fig.6 shows the control circuit to drive the stepping motor. The traversing mechanism itself is supported by a table with 5 degrees of freedom to facilitate the alignment.

Criterion for Automatic Focussing

In scanning holographic images of spray droplets with a video camera, single droplets have to be selected from the 2-D image in the camera sensor while the camera is moved stepwise through the reconstructed holographic image. For a sequence of video pictures of the same droplet imaged at different, but very narrow, focal distances, the best focussed picture has to be identified. When this succeeds, the corresponding droplet can be selected. After that, the droplet is measured and classified. In order to apply systematically this selection criterion to all droplets in the holographic image, an automatic focussing criterion was developed.

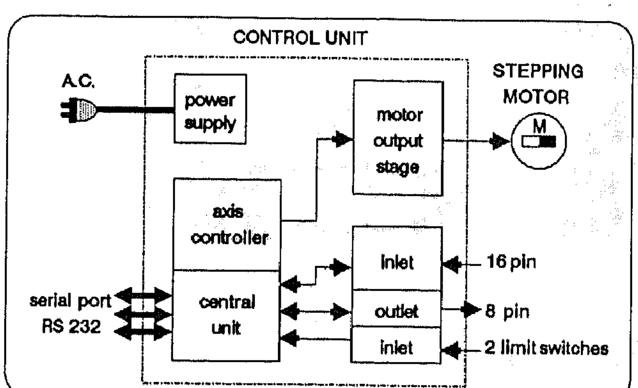

Fig.6. Control Circuit of the Stepping Motor

Two algorithms based upon grey-value gradients and grey value distributions were implemented as a focussing criterion. The first one is the Sobel-operator which is normally used as an edge detector (i.e. sharp edges have a bigger grey-value gradient than blurred edges). The values of the gradient (0 – 255) are used by the second algorithm (binarization) to discriminate all the objects having contours with gradient value smaller than 255. This ensures that only strictly sharp focussed objects (spray droplets) will be taken into account for later processing. Figs.7A to F, illustrate how sharp focussed images are selected. In A and B, grey-value histograms of a line drawn across the interface object-background of the same object (a glass pearl of 2.36 mm in diameter) at two different focal planes are presented. Strong differences in the shape of the histograms between A, in-focus, and B, 1 mm out-of-focus can be observed. C and D show the correspondent grey value gradients and E and F present the resulting pictures after applying the second algorithm. Those parts being out of focus disappear completely.

EVALUATION ROUTINES

The images to be processed are of the same kind as the photographs presented in Fig.5. They contain a collection of spots of different grey-values, ranging from 0 = black to 255 = white, which represent the spray droplets, and a given fine grain pattern forming a noisy background (speckle noise). This speckle noise is produced by the diffuse, coherent illumination used to record the hologram.

Although single and double pulsed holograms are of the same nature and their evaluation is similar, we decided to configurate two different evaluation routines. They are: the routine EINZEL, which evaluates single pulsed holographic images for which accurate measurements of the drop size are of essential importance, and the routine DOPPEL, which evaluates the images obtained from double pulsed holograms. For this last case, the size of the droplets does not need to be evaluated again. Better, the routine DOPPEL is dedicated to identify spot couples which are originated by droplets imaged at two successive positions. The distance between these successive positions represents the droplet velocities.

The Routine EINZEL

The processing of images obtained from single pulsed holograms involves: the separation of the spots from the background, identification of the sharp focussed droplets, measuring their projected areas, and the evaluation of

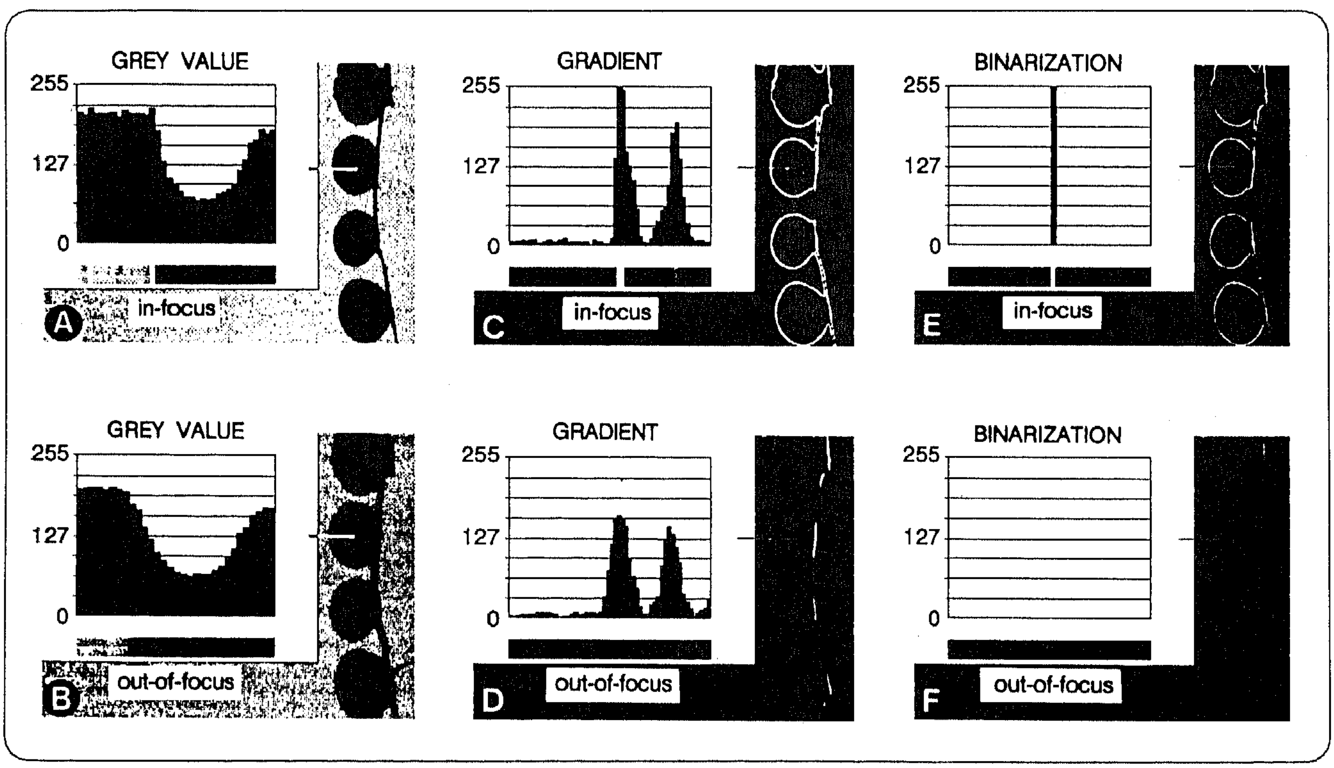

Fig.7. Focussing criterion of video pictures taken from a holographic reconstruction.
Object: glass pearls (ϕ 2.32 mm) adhered to a wire (ϕ 82 μm).
A, B: *grey value histograms of the object in-focus and out-of-focus respectively.* **C, D**: *the correspondent grey value gradients,* **E**: *the selected images and* **F**: *unsharp focussed images disappear.*

their equivalent diameters and their center points with respect to a reference frame. All these operations, from the image capture by the video camera to the final result, are carried out by the program EINZEL. It consists in a series of digital filters and gradient operators selected from standard image processing libraries and our own algorithms developed for measuring, calibration and data handling.

The application of the focussing criterion described earlier constitutes the kernel of the program. A brief description of its principal features can be summarized as follows:

1. Initially, the camera is situated in the middle of the traversing mechanism, and its objective is adjusted with the help of a calibration hologram, so that the focal distance coincides with the center of the holographic image to be evaluated (the origin of the depth-coordinate **Y** is set here). Then, the camera is moved away from the holographic image until it disappears completely. Here the initial point $\mathbf{Y}_i$ of the image processing is set. From this point, the camera will be driven stepwise towards the hologram, so that the focal plane, corresponding to the focal distance of the camera objective, will be moved through the 3-D holographic image.

2. An image (**A**) taken by the video camera is stored in the frame memory of the digitizer and the grey-value of the noisy underground is evaluated. By a simple adjustment of the gain and the offset of the image contrast, the grey-value scale is shifted so that the noise is filtered out or reduced to a minimum, without modifying the grey value gradients of the image.

3. The image **A** is smoothed using a median filter and the resulting image is named **B**. After that, the Sobel-operator is applied to enhance the spot contours in **B**. The darker the spot (drop), the bigger the gradient at the contour, which is represented again in grey-values. All parts of this last picture containing grey-values from 2 up to 253 are filtered out applying a contrast enhancement operation (binarization). The resulting image is named **C**.

4. The images **B** and **C** are superimposed using the boolean operation AND. Image parts in **C** produced accidentally during the processing are filtered out. This automatically assures the authenticity of the information being processed. The resulting image is named **D**. The closed contoures in **D** are filled up with a given color which can be easily identified by the measuring algorithm.

5. The equivalent diameters and centers of those spots (droplets) possessing a sphericity bigger than 0.4 are evaluated and stored for later data processing. And finally, the videocamera is moved a step of 0.5 mm towards the hologram and the complete routine is repeated until the whole depth of the holographic image is scanned.

Examples of representative stages of the image processing are presented in form of photographs in Fig.8. Here, the upper row shows the spray near the nozzle (liquid sheet and break-up zone). Measurements of the liquid sheet geometry are important for predicting the final form of the spray. The lower row presents the droplet zone 3.5 mm downwards from the nozzle. Here, the little window helps to obtain a better orientation between the stages 4 and 5. The black areas in the photograph 5 were measured by directly counting the amount of pixels per black area using the technique of the four "neighbours". The equivalent diameters and centers were then calculated and their **X**, **Y**, **Z** coordinates transformed into cylindrical **r**, **z** coordinates as defined in Fig.3.

The Routine DOPPEL

From double pulsed holograms one obtains the information about velocity and trajectory 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 times $\mathbf{t}$ and $\mathbf{t} + \Delta\mathbf{t}$, where $\Delta\mathbf{t}$ is the intervall time between the two exposures used to take the hologram. $\Delta\mathbf{t}$ can be adjusted by the ruby-laser electronics between 1 – 800 μs.

In order to evaluate the reconstructed images, the routine DOPPEL was developed. It consists in a series of subroutines similar to those used to build up the program EINZEL. The difference between both routines lies in the fact, that for the computation of the drop velocities, the correct identification of the center point of the drop images becomes more important than the measurement of the drop sizes. That means, that the application of the complicated measuring algorithms used by the program EINZEL is no more necessary. In the routine DOPPEL those algorithms were substituted with other simpler but more rapid algorithms. For example, the drop images are first expanded by using an unsharp mask, allowing a rapid identification of both spot partners of a couple when they lie in different focal planes. Furthermore, the operations of contouring and color filling were substituted with a quick threshold operation. Summarizing, the task of the program DOPPEL consists in identifying the spot couples from the pictures taken by the video camera while it scans the holographic image, in measuring the distance between the center points of the two successive droplet images, and in computing the droplet trajectories related to the space coordinates in the injection volume.

Representative stages of the image processing are presented in form of photographs in Fig.9. In this figure, (1) represents the source image, (2) the unsharp mask, (3) the image after noise filtering, and (4) the identification of spot couples and evaluation of the image.

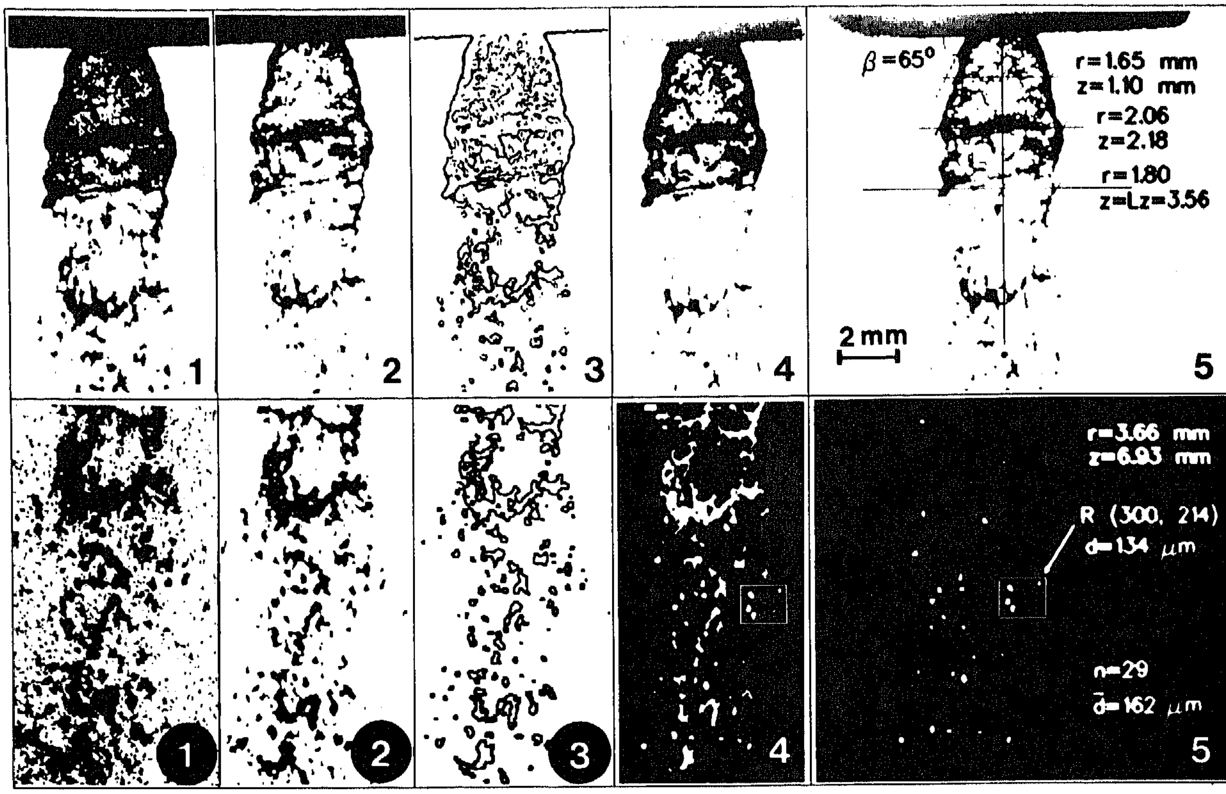

Fig.8. Representative steps of the image processing of a single pulsed hologram of the R113 spray. 1) Original image, 2) smoothing and noise filtering, 3) gradient and binarization, 4) identification of the sharp focussed droplets and 5) final evaluation. R is a reference drop with screen coordinates indicated between parenthesis and real coordinates r,z showed in the upper right corner.

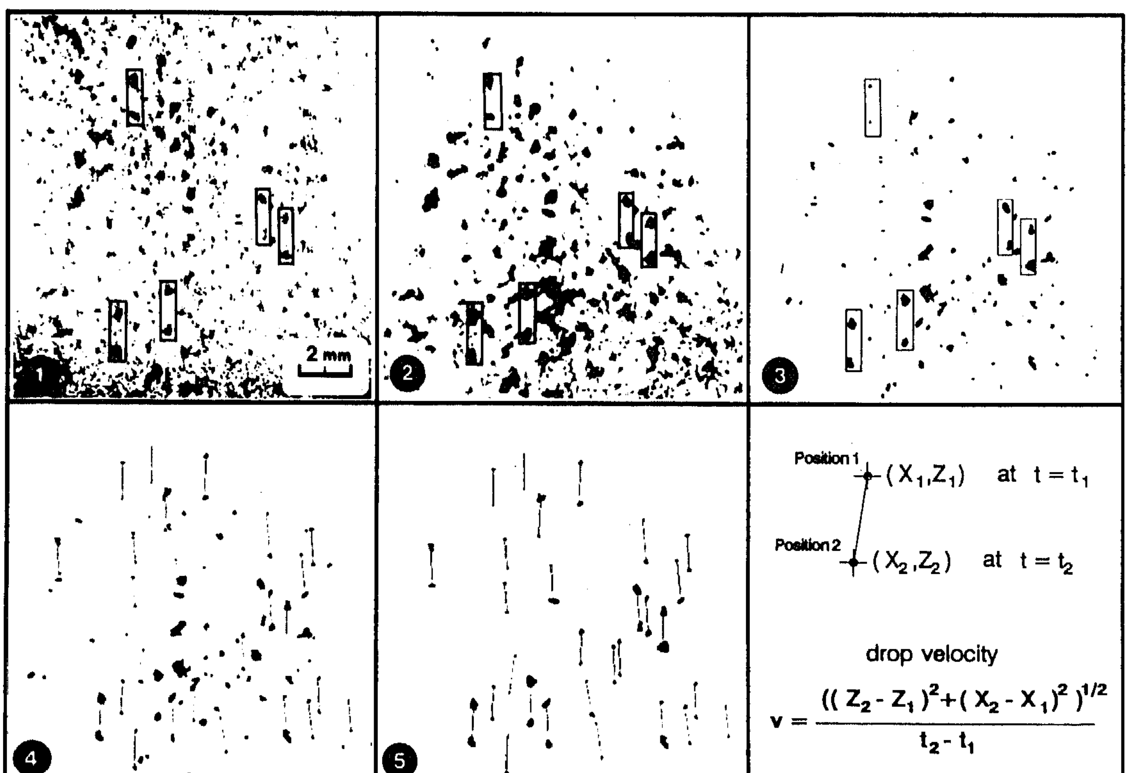

Fig.9. Representative steps of the image processing of a double pulsed hologram of the R113 spray. 1) Original image, 2) dilatation, 3) thresholding, 4) identification of the particle couples, and 5) final evaluation. The middle point of the screen has the real coordinates $r = 14.70$ mm, and $z = 25.19$ mm; 29 particle couples were found from which a mean velocity $\mathbf{v} = 2.6$ m/s was obtained.

In order to find the spot couples, the subroutine VEL was developed. It consists of two modules: a frequency analyser and measuring algorithm. The first one analyses if the spots contained in a processed image (e.g. picture 3 of Fig.9) can be ordered in couples. For this realization, the algorithm computes the center points of the spots and the distances between partners of all possible combinations of spot couples without regard to order in the spot conglomeration. The algorithm continues with a frequency analysis of the computed distances and directions. The distance and direction corresponding to the highest value of the frequency are interpreted as the mean velocity vector. This analysis is performed only one time per hologram. The algorithm of the second module uses the information of the first one to search the authentic spot couples. It searches those spots which are separated by a distance corresponding to the mean velocity vector, within a variation of $\pm$ 15° in direction and $\pm$ 20% in magnitude. The complete evaluation of a double pulsed hologram is carried out similarly as described for the case of single pulsed holograms.

RESULTS

As an example of the applicability of the discussed evaluation technique, results of the evaluation of 30 holograms, 15 single and 15 double pulsed holograms respectively, are presented in Figs.10 to 11. These results are part of a study dedicated to the characterization of sprays when liquid is injected into a condensable environment at high reduced pressures ($p_r = p/p_{crit}$). In this case, the holograms correspond to the situation in which subcooled liquid refrigerant R113 (Trifluorotrichloroethane) at 298 K is injected into an atmosphere formed by its own saturated vapor. The experiments were systematically carried out at stationary conditions in the thermally insulated autoclave described earlier where the vapor atmosphere could be prepared and kept at constant pressures of 0.15, 0.20, and 0.25 MPa. For each vapor pressure, five experiments were carried out at liquid mass flow rates of 0.8, 1.37, 2.0, 2.72, and 3.86 g/s. A pressure-swirl nozzle of 0.6 mm bore diameter was used as an atomizer.

The diagrams **A** and **B** of Fig.10 summarize, in form of arithmetic mean values of drop diameters and velocities, a great amount of measuring data (position, size and velocity of about 100 000 droplets were stored). The pressure p_v of the vapor environment is plotted as a parameter. The diagram **A** shows an asymtotical decrease of the mean drop diameter when the liquid mass flow rate is increased. According to *Frazer & Eisenklam, (1956)*, the increase in the inertial forces, which depend on the flow rate, have a desintegrating effect upon the liquid sheet of the spray near the nozzle. This leads to the production of droplets with a smaller diameter. From this figure, it is not possible to distinguish in which manner the variation of the vapor pressure, at least in the tested range, affects the mean drop diameter. It becomes apparent, that for fully developed hollowed cone sprays injected into pure saturated vapor, there is a characteristic mean drop size for each initial velocity independent of the vapor pressure. The diagram **B** reveals that the mean drop velocity increases almost linearly by increasing the liquid mass flow rate. In this case, the effect of varying the environmental pressure is clear. The mean drop velocity diminishes when the vapor pressure increases. The reason is, that when the saturation pressure of the vapor increases, its density and its viscosity increase, too. This leads to a higher resistance of the vapor against the movement of the droplets.

As commented above, the measurement of the liquid sheet of the spray is very important for the spray characterization. The present evaluation method is really an ideal tool to perform that measurement. From processed images of the nature of picture 4 in Fig.8, it is very easy to measure the liquid sheet. The measuring algorithms to carry out this task are not described in this paper, but their configuration is very simpler compared with the evaluation routines discussed here.

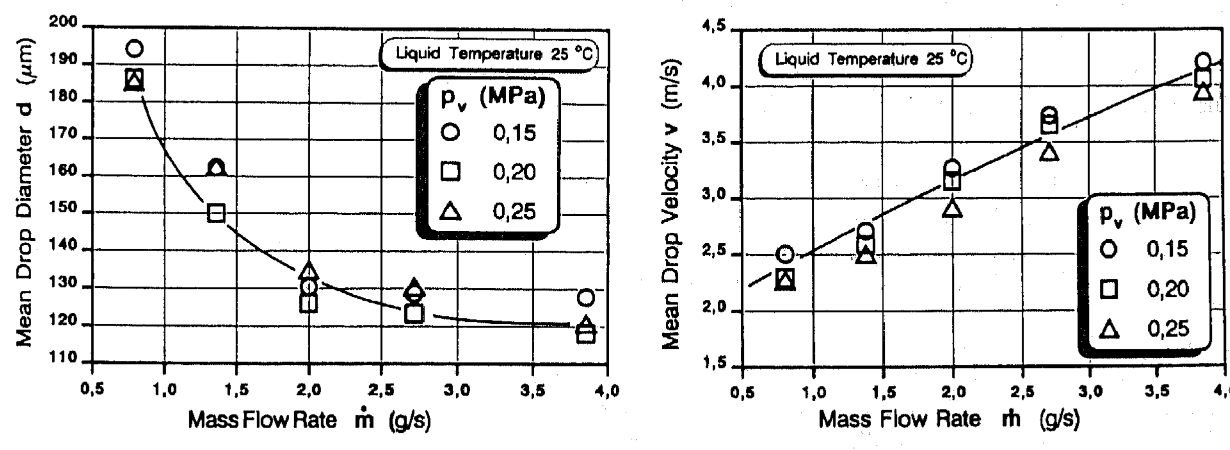

Fig.10. Mass mass flow rate ṁ *vs. A), mean drop size* d *and B), mean drop velocity* v*, respectively, of the R113-spray injected into its own saturated vapor.*

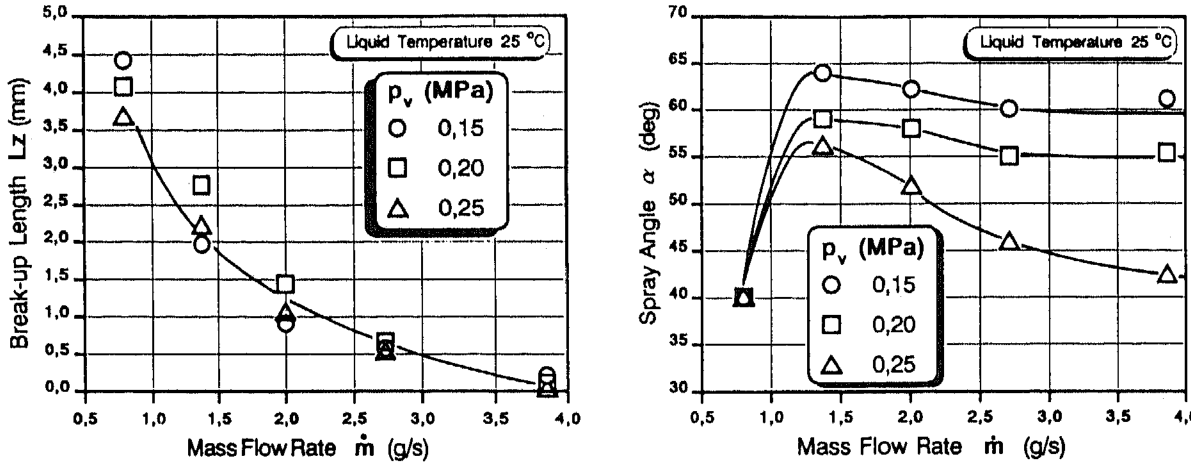

Fig.11. Mass flow rate $\dot{m}$ *vs. A), break-up length* Lz *and B), spray angle* α*, respectively, of the R113-spray injected into its own saturated vapor.*

The liquid sheet geometry can be represented by its break-up length Lz and its corresponding angle α at this length. The diagrams **A** and **B** of Fig.11 present the measurements of Lz and α, respectively, as functions of the mass flow rate $\dot{m}$. The pressure p_v of the vapor environment is plotted again as a parameter. The diagram **A** shows the typical decrease of the break-up length when the mass flow rate is increased. It is interesting to observe the similarity of this plot to that of the drop size vs. mass flow rate in Fig.10, which confirms one more time the observations of *Frazer & Eisenklam, (1956)*. The diagram **B** in Fig.11 illustrates the strong influence of the vapor pressure p_v upon the spray angle α. At higher vapor pressures, the resultant force in the radial direction, responsible for the formation of the hollowed cone, diminishes because of the higher resistance of the vapor agaist the liquid flow. From the observation of Figs.10 and 11, we can conclude that the vapor pressure has only a weak influence upon the drop size, but it is paramountly with regard to the droplet distribution in the injection volume.

Uncertainties

The main source of uncertainty of the measurement method lies in the pixel representation of circular objects (droplets), specially 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 $\pm 3\%$ 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 8 pixels (ϕ 94 μm) and the biggest ones 55 pixels (ϕ 256 μm). For larger objects or structures, the error diminishes under 1%. The reduction in the uncertainty of this hologram evaluation method as compared with other evaluation methods reported earlier by the authors (*Chávez & Mayinger (1988)*), represents about one order of magnitude (earlier $\approx \pm 17\%$, this work $\pm 3\%$).

CONCLUSION

The use of personal computers in the evaluation of pulsed laser holograms of particle fields constitutes a very important tool. It permits the immediate analysis of the holograms in the same optical laboratory. This will surely contribute to engage more researchers to take more frequent advantage of the excellent properties of the holographic techniques in the study of dispersed flows.

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