EVALUATION OF PULSED LASER HOLOGRAMS OF SPRAY DROPLETS BY APPLYING DIGITAL IMAGE PROCESSING

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ABSTRACT

The evaluation of pulsed laser holograms has been improved substantially by using digital image processing. Here, two computer aided procedures to evaluate single and double pulsed laser holograms of spray droplets are presented. By using these techniques implemented on a personal computer, it is possible to apply more efficient droplet focussing and classifying criteria throughout the whole evaluation process. The time dedicated to the evaluation is drastically reduced and the accuracy in drop sizing is improved by about one order of magnitude compared with other hologram evaluation methods.

1. INTRODUCTION

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. As opposed to other optical methods based upon light scattering analysis which provide time resolved measurements in a point of the control volume, the pulsed laser holography provides one or more three dimensional scenes taken at a very short exposure time ($\sim$ 30 ns) of the whole volume of interest. The recorded holograms can be reconstructed with the help of a continuous laser beam and analysed at any time. The resulting reconstructed images are very clear for particle sizes within the range of of $d > 10\lambda$ where d is the drop diameter and λ the wavelength of the laser light used to record the hologram, so that the particles can be observed directly or with the help of a microscope as in a photograph. 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)*.

The main problem appearing in the application of pulsed laser holography consists in evaluating the large amount of information contained in the holograms. One single hologram can contain information about position, size, and velocity of many thousands of particles. Comprehensive studies of the characteristics of the dispersed phase and its interactions with the gaseous environment necessarily require the help of computer aided particle counting and measuring methods, as proposed, for example, by *Schäfer & Umhauer (1987)*.

The evaluation of holographic reconstructions of particle fields consists in scanning the three dimensional image with a videocamera, 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 contol 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.

This paper presents two computer aided procedures (AREA and VEL) 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 this procedures, the operator is released from the stressed 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.

The holograms, obtained by using a pulsed ruby laser as a light source, contain the 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-swirl nozzle of 0.6 mm in bore diameter, into an environment formed by its own saturated vapor. A schematic picture of the spray flow is shown in Fig.1.

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

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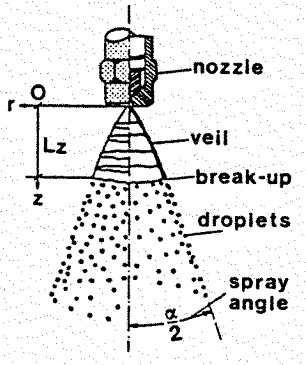

Fig.1 Scheme of the spray flow.

series of 30 pulsed holograms of the 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.

2. SCANNING OF HOLOGRAPHIC RECONSTRUCTIONS

The pictures to be processed are obtained from single or double pulsed off-axis holograms. Off-axis holograms are recorded with help of a reference beam, which arrives at the holographic plate under a different angle of incidence than the object beam (see e.g. Chávez & Mayinger; 1988). The holograms represent a three-dimensional (3-D) image corresponding to a "frozen" scene of the spray, as shown in the schematic of Fig.1. 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.2.

2.1 The Digital Image Processing System

The components of the digital image processing system are shown in the flow diagram of Fig.3. 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**.

Fig.2 Photographs from the reconstruction of a single pulsed hologram. A, the spray near the nozzle, and B, enlargement of the droplet zone.

2.2 The Scanning Technique

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 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 lense 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 shown schematically in Fig.3. 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 an 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. The traversing

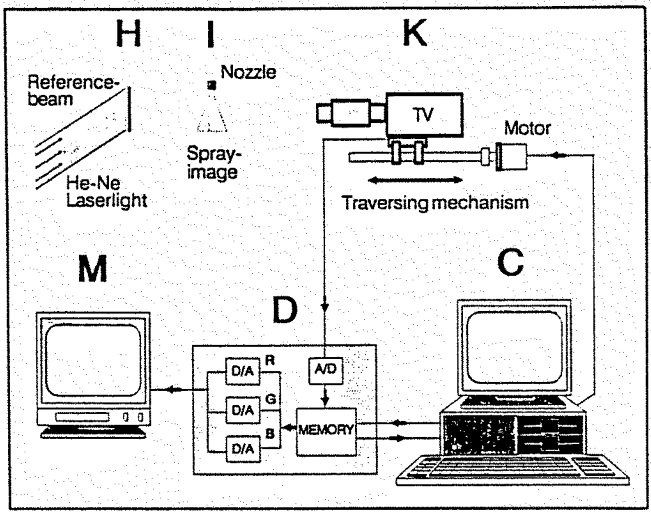

Fig.3 The image processing system. C, personal computer, D, digitizer, H, hologram, I, reconstructed image, K, video camera, and M, graphics monitor.

mechanism itself is supported by a table with 5 degrees of freedom to facilitate the alignment.

3. FOCUSSING CRITERION

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 this selection criterion systematically to all droplets in the holographic image, the help of automatic focussing algorithms is necessary. *Haussmann (1978)* and *Ligthart & Groen (1982)* discussed the capabilities of more of the known focussing algorithms. Some of them are now commercially used in autofocus photographic cameras.

In this work, 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.4A 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.

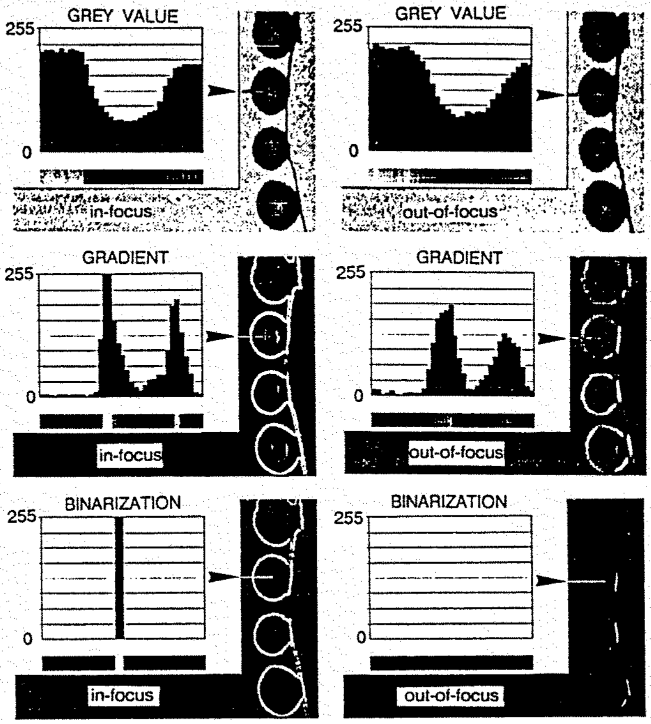

Fig.4 Focussing criterion of video pictures taken from a holographic reconstruction. Object: glas pearls (ϕ 2.32 mm) adhered to a wire (ϕ 82 μm). **A, B**: *grey value histograms of the object in-focus and out-of-focus respectively.* **C, D**: *the correspondent grey value gradients,* **E**: *the selected images and* **F**: *unsharp focussed images desappear.*

4. EVALUATION ROUTINES

The images to be processed are of the same kind as the photographs presented in Fig.2. They contain a collection of spots of different grey-values, ranging from 0 = black to 255 = white, representing 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.

4.1 Single Pulsed Holograms

The image processing of images obtained from a single pulsed hologram involves: the separation of the spots from the background, identification of the sharp focussed droplets, measuring their projected areas, and the evaluation of 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 program works as follows:

1. Initial position of the video camera. 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 Y-coordinate is set here). Then, the camera is moved away from the holographic image until it disappears completely. Here the initial point 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. Image capturing. An image (A) taken by the video camera is stored in the frame memory of the digitizer.

3. Analysis and noise filtering. The grey-value of the noisy background is evaluated, and 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.

4. Smoothing. The image is smoothed using a median filter. The resulting image is named B.

5. Contouring. By applying a grey value gradient operation (Sobel), the contours of the drops are obtained. The darker the drop (spot), the bigger the gradient at the contour, which is represented again in grey-values.

6. Binarization. All parts of the picture containing grey-values from 2 up to 253 are filtered out applying a contrast enhancement operation. The resulting image is named C.

7. Superposition and color filling. 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.

8. Measurement. Equivalent diameters and centers of those spots (droplets) possessing a sphericity bigger than 0.4 are evaluated and stored for later data processing.

9. New position of the video camera and routine repetition. The camera 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 swept.

Examples of representative stages of the image processing are presented in form of photographs in Fig.5. 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

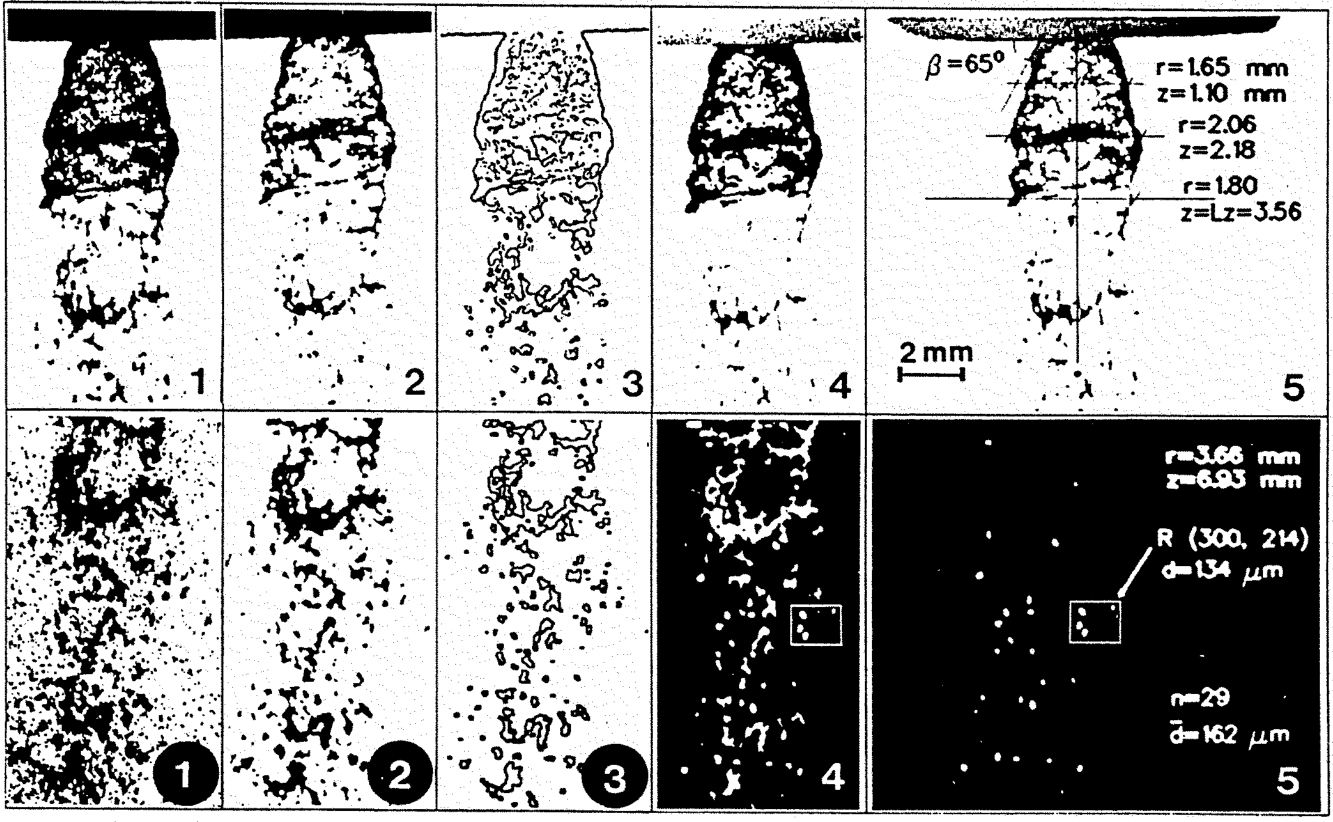

Fig.5 Representative steps of the image processing of a single pulsed hologram of the R113 spray. 1) Original image, 2) smoothing and noise filtering, 3) gradient and binarization, 4) identification of the sharp focussed droplets and 5) final evaluation. R is a reference drop with screen coordinates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

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.1.

4.2 Double Pulsed Holograms

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 t and $t + \Delta t$, where Δt is the intervall time between the two exposures used to take the hologram. Δt 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. Futhermore, 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.6. 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. In order to find the spot couples, the algorithm VEL was developed. It bases upon the assumption that the velocity field possesses axial symmetry, and that the mean velocity vector possesses a preferential direction and magnitude. Assuming this, the algorithm searches those spots which are separated by a distance corresponding to the mean velocity vector, within a variation of ± 15°in direction and ± 20% in magnitude. The algorithm VEL is integrated in the routine DOPPEL as a subroutine. The complete evaluation of the double pulsed hologram is carried out similarly as described for the case of single pulsed holograms.

5. 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.7 and 8. 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 of the substance Trifluorotrichloroethane (refrigerant R113) at 298 K is injected into an atmosphere formed by its own saturated vapor. The experiments were systematically carried out at stationary conditions in a thermally insulated autoclave 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. A description of the experimental facility has been presented in Chávez & Mayinger (1988).

The diagrams of Figs.7 and 8 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). An extensive anal-

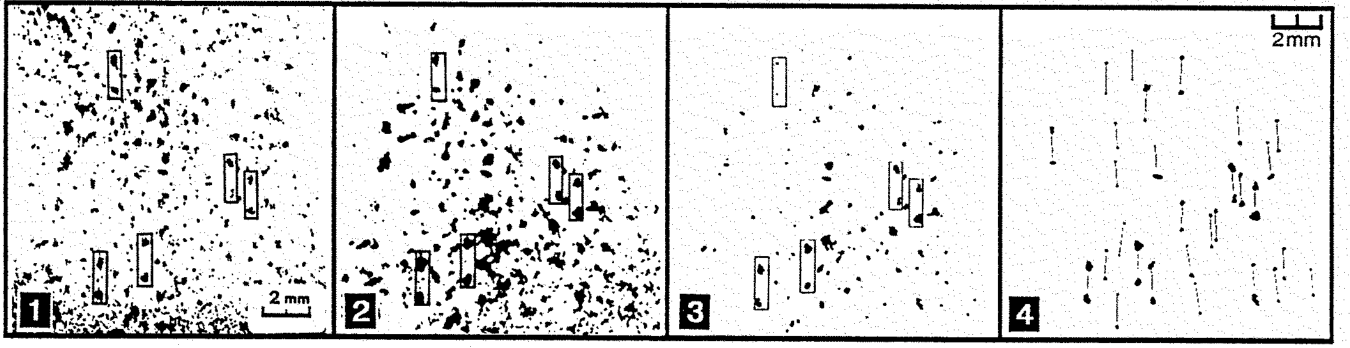

Fig.6 Representative steps of the image processing of a double pulsed hologram of the R113 spray. 1) Original image, 2) dilatation, 3) thresholding, and 4) identification of the particle couples and final evaluation. The middle point of the screen has the real coordinates r = 14.70 mm, and z = 25.19 mm; 29 particle couples were fund from which a mean velocity v = 2.6 m/s was obtained.

ysis of the data is obviously not possible in this paper, therefore it is reserved for a further opportunity.

The diagram in Fig.7 shows an asymtotical decrease of the mean drop diameter when the liquid mass flow rate is increased. According to *Frazer & Eisenklam, (1953)*, the increase in the inertial forces, which depend on the the flow rate, have a desintegrating effect upon the liquid sheet of the spray near the nozzle, which leads to the production of droplets with a smaller diameter. Measurements of the liquid sheet are very important for the spray characterization. Obviously, the liquid sheet can also be mesured with the present measurement method; an illustrative example is included in Fig.5.

The pressure p_v of the vapor environment is plotted as a parameter in Fig.7. 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 in Fig.8 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.

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 ±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 ≈ ±17%, this work ±3%).

6. 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.

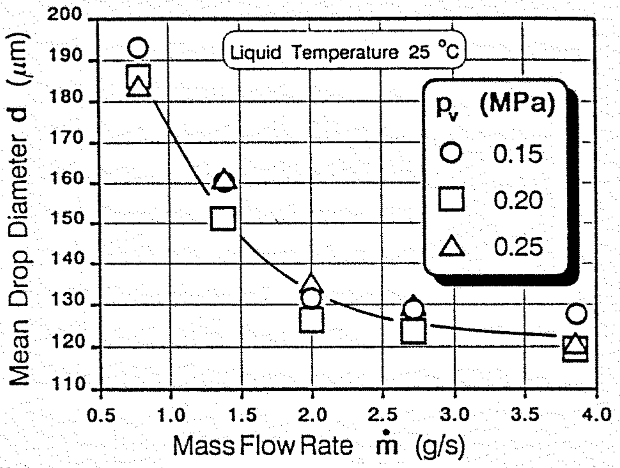

Fig.7 Mass mass flow rate ṁ vs. mean drop size d *of the R113-spray injected into its own saturated vapor.*

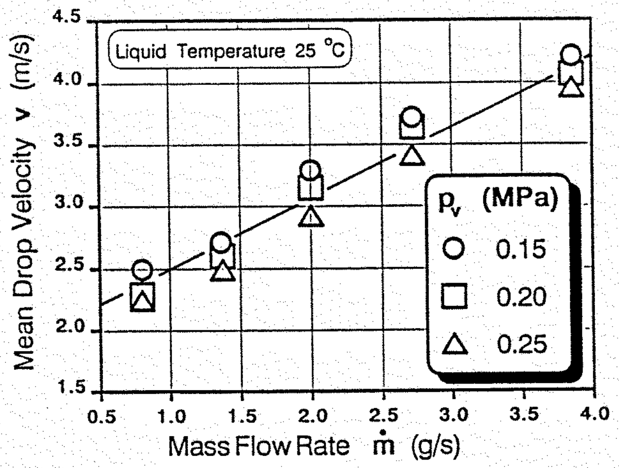

Fig.8 Mass mass flow rate ṁ vs. mean drop velocity v *of the R113-spray injected into its own saturated vapor.*

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