Digital Image Processing for the Evaluation of Pulsed Laser Holograms of Spray Droplets

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INTRODUCTION

The injection of liquid materials into gaseous environments plays an important role in a large number of industrial processes. For many of these it is also important to know those parameters related with the liquid injection, for example: the form of the liquid jet or spray, the size and velocity of the droplets and their spacial distributions. This allows, amongst others, the evaluation of the interactions (i.e. heat and mass transfer) between the liquid phase and its gaseous environment, not only resulting in better equipment design but also for the optimation and control of the process itself. Nevertheless, the measurement of the size and velocity of the droplets is not a trivial task. *Azzopardi* /1/, and *Hawighorst* /2/ describe in detail the more frequently used measurement methods in the last four decades.

The pulsed laser holography, based upon the Gabor holography, represents one of the more suitable non intrusive measurement methods for the study of the injection of liquids into transparent gaseous environments. With one single hologram taken in a very short time (~ 30 ns), it is possible to record – to freeze – the three dimensional (3-D) scene of what is happening in the control volume for later analysis. The method can be applied in the range of drop sizes of $d > 10\lambda$, where d is the drop diameter and λ the wavelength of the laser light used to record the hologram. The method of the pulsed laser holography is explained in detail by *Trollinger* /3/, and *Chávez & Mayinger* /4/.

In spite of the advantages of this measurement method, it is not so popular as it might be thought. The reason for this lies in the difficulty in evaluating the large amount of information contained in the holograms. For example, for a relatively small droplet concentration of 10 droplets per cubic centimeter, there are already 1000 droplets in only 0.1 liters of the control volume. Under these conditions, the counting and classification of the droplets by manual methods becomes a very time–consuming task while the amount of holograms increases. Attempts at improving this situation were undertaken by some researchers (i.e. *Haussmann & Lauterborn*, /5/) who developed procedures to evaluate holographic images with the help of computers, but until the middle of this decade, the computer-aided image evaluation was only possible in large computing centers and, in general, a very expensive alternative.

In this work, a computer aided method used to evaluate holograms of spray droplets implemented on a personal computer AT3 is presented. It bases upon techniques of the digital image processing. By applying this method, the time dedicated to the evaluation of the holograms was reduced drastically, and the error normally introduced by human decisions was also reduced by about one order of magnitude.

SCOPE OF THE WORK

The aim of this investigation is to adapt a procedure based upon digital image processing, for the automatic evaluation of pulsed laser holograms which contain information about size, position and velocity of spray droplets. In this case, the spray was produced by injecting subcooled liquid of the refrigerant R113 through a hole cone type swirl nozzle of 0.7 mm in diameter, into an environment formed by its own saturated vapor at a pressure of $p_v = 1$ bar at a constant mass flow rate and temperature of $\dot{m} = 49.4$ g/min and $T_l = 25$ °C respectively. A schematic picture of the spray flow is shown in Fig.1. There are two holograms to analyze: a single pulsed hologram (one scene of the spray is recorded in the holographic plate) from which the measurement of the size and position of the droplets is possible, and a double pulsed hologram (two successive scenes of the spray are recorded on one holographic plate at a pulse interval of 0.2 ms) used to evaluate the droplet velocities. In both cases, a high power pulsed ruby laser was used. It produces light of a wavelength of 694.3 nm, with an output energy of 1 J and a pulse width of 30 ns. Figure 2 shows photographs of the two holograms before being processed.

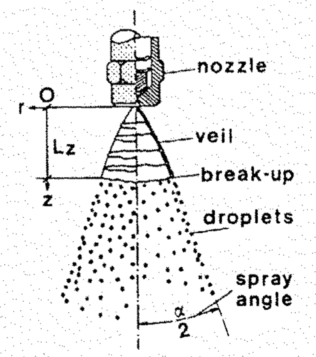

Fig.1 Scheme of the spray flow.

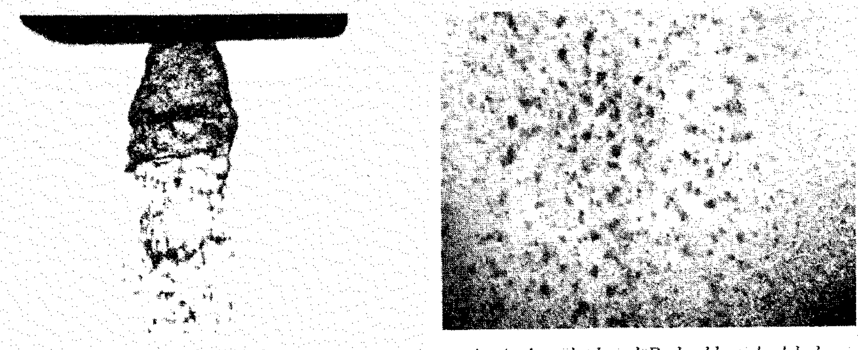

Fig.2 Typical photographs of hologram reconstructions. A, single pulsed and B, double pulsed hologram with pulse interval of 0.4 ms.
Object: Liquid refrigerant R113 injected into its own saturated vapor.

DIGITAL IMAGE PROCESSING SYSTEM

Components

The components of the digital image processing system are shown in the flow diagram of Fig.3. The optical information contained in the reconstructed holographic image **I** is transformed into an analogous electrical signal by the TV camera **K**, and transmitted to the digitizer **D**. Here, the signal is transformed again 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, to allow for fast communication. In order to visualize the information actually stored in the digitizer frame memory, the digitizer produces a continuous RGB (red, green, blue) output signal which can be observed in the graphics monitor **M**.

Positioning of the TV-camera

In order to scan 3-D holographic images with a TV-camera, it was necessary to provide a very good alignment of the optical axis of the camera lense system with the direction of the reconstructed object beam of the hologram. Only when this condition is satisfied, can the X and Y coordinates of the 2-D image on the camera sensor be related to the depth coordinate Z of the holographic image. This means, if the optical axis of the camera and Z- coordinate coincide, the X and Y coordinates on the camera sensor will not suffer lateral displacements while the camera moves along the Z-coordinate. This avoids the possibility of confusing the X-Y position of the same spot corresponding to two successive pictures at the positions Z and Z+ΔZ. To control the position of the camera and to measure the values of the

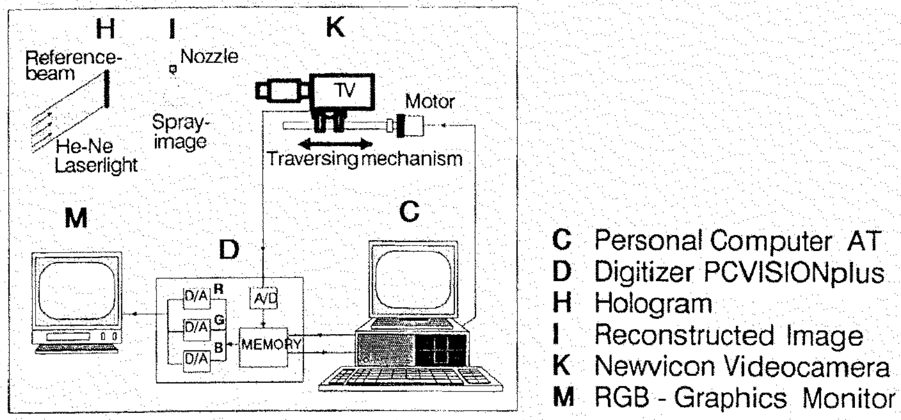

Fig.3 Flow diagram of the image processing system.

Z-coordinate, the camera was mounted on a traversing mechanism, as shown 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. The movement of the stepping motor – representing the position of the TV-camera – is monitored by the computer through an RS-232 port. The traversing mechanism itself is supported by a table with 5 degrees of freedom to facilitate the alignment.

Processing Routine

The images to be processed are of the same kind as the photographs in Fig.2. They contain a swarm of spots of different grey-values (in a scale from 0 = black to 255 = white) representing the spray droplets, and a given fine grain pattern which forms the noise-background. This speckle noise is produced by the diffuse, coherent illumination used to record the hologram. The image processing in the case of images obtained from a single pulsed hologram then involves: the separation of the spots from the background, identification of those drops corresponding to the vertical plane (focal plane) on which the video camera is focussed, and the evaluation of their equivalent diameters and their centers with respect to a reference frame.

The digital filters and gradient operators used in this procedure were selected from the *Itex* /6/ and *Image-Pro* /7/ libraries which, together with our own algorithms developed for measuring, storing and calibration, allowed us to configurate the following routine:

i. Initial position of the TV-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 Z-coordinate is set here). Then, the camera is moved away from the holographic image until it disappears completely. Here the initial point Z_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.
ii. Image capturing.– An image (Image A) taken by the TV-camera is stored in the frame memory of the digitizer.
iii. Analysis.– Evaluation of the grey-value of the noise-background.
iv. Noise filtering.– 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.
v. Smoothing.– The image is smoothed using a median filter. The resulting image is named Image B.
vi. 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.

vii. 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 Image C.

viii. Superposition.- Images B ana C are superposed using the boolean operation AND. This automatically assures the authenticity of the information being processed.

ix. Measurement.- Equivalent diameters and centers of those drops (spots) containing the information B+C are evaluated and stored.

x. New position of the TV-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 holographic image disappears completely.

In the case of a double pulsed holografic image, the measurement subroutine consists of the identification of those spot-couples corresponding to the same drop at the two exposures, evaluation of their centers and the distance between them. This distance is then related to the time interval between exposures in order to calculate the drop velocities.

FOCUSSING CRITERION

Focussing algorithms are of particular importance in scanning holographic images of particle fields with a TV-camera (*Haussmann*, /8/; *Ligthart & Groen*, /9/). Single objects have to be selected from the image on the camera sensor while the camera moves stepwise through the reconstructed holographic image.

In this study, two algorithms based upon grey-value gradients and grey value distributions were implemented as a focussing criterion (steps vi and vii of the processing routine). The first one is the Sobel- operator which is normally used as an edge detector - sharp edges have a bigger grey-value gradient than blurred edges - as illustrated in Fig.4. In this figure, 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 between the two cases (A, in-focus, and B, 2 mm out-of-focus) can be observed. The values of the gradient are again represented in grey-values from 0 to 255, and 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 (droplets) are taken into account for later processing.

EVALUATION OF THE HOLOGRAMS

Single pulsed hologram

Figure 5 illustrates some of the most representative steps of image processing applied to evaluate single pulsed holographic images. The first picture row shows the zone near the nozzle (liquid sheet and break-up zone), the second one presents the droplet zone 3.5 mm downwards from the nozzle. The black areas of picture 5 of the second row 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. Table 1 summarizes the results of the evaluation, where a total of 937 droplets covering a volume defined by $r \leq 13$ mm and $z \leq 43$ mm were measured.

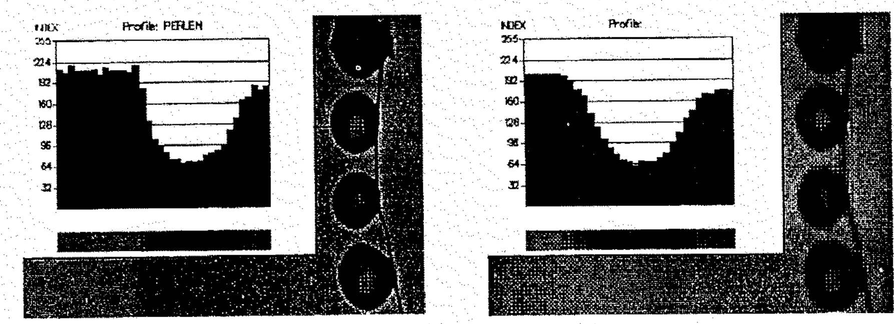

Fig.4 Use of the grey-value and grey-value gradient distributions as the focussing criteria.

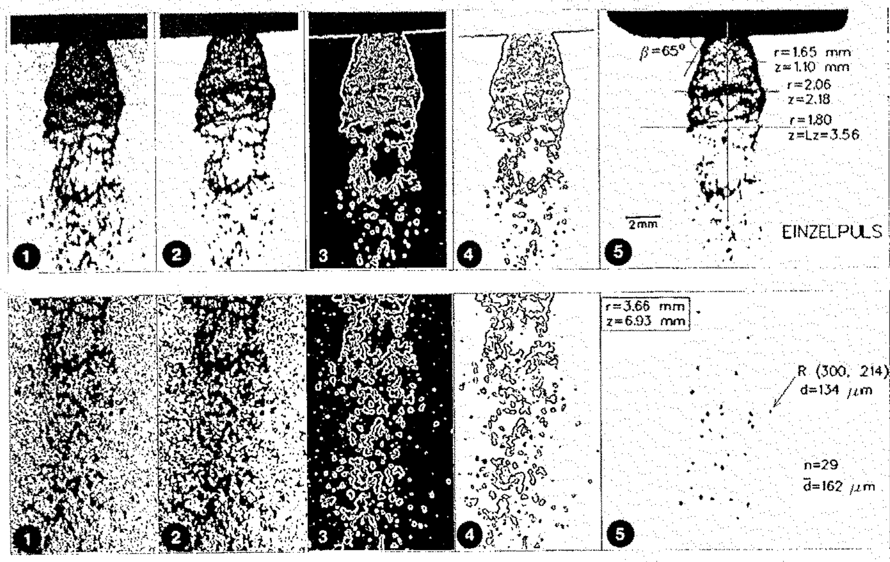

Fig.5 Processing of the images obtained from the single pulsed hologram.
1) Original image, 2) noise filtering, 3) contouring, 4) binarization, and 5) final evaluation.

Double pulsed hologram

In this case, the task of the image processing was to filter out the strong specle noise of the source images and to expand the area of the filtered spots for easier identification, as illustrated in Fig.6, where (1) represents the source image, (2) the filtered image and (3) the evaluated image. The droplet velocities can be measured from the filtered image (2). An algorithm was developed to find spot couples corresponding to two successive positions of the same droplets in two different times t and t+Δt respectively. 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 the first pixel containing the color of the spots, recognizes all the pixels contained in the spot and calculate its center. In order to find the corresponding couple, the algorithm builds the mean velocity vector at the center of the first spot, then varying the direction of the vector with an angle of $\pm$ 15°and its magnitude with $\pm$ 20%, defining a region where it searches the second spot. If there is at least one pixel in this region, it will be identified as the center of the second position of the droplet and the correspondent velocity is calculated. Elsewhere, the algorithm searches a new first spot and so on. Table 1 shows the results of the velocity measurement.

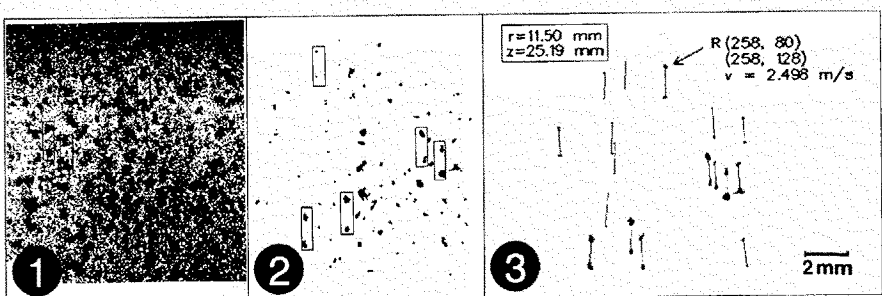

Fig.6 Procesing of the images obtained from the double pulsed hologram.
1) Original image, 2) filtered image, and 3) final evaluation.

UNCERTAINTY

A comparison between the results of this work and manual evaluations reported earlier (*Chávez A. & F. Mayinger*, /4/), reveales that the uncertainty in the measurement of the drop size can be reduced from 16% (manual) down to 3% (computer aided), due to the larger amount of droplets per cubic centimeter (factor 6) taken into account in the present evaluation. The error source of 3% results from the calibration uncertainties for droplet images containing less than 50 pixels and from the pixel representation of circular objects.

CONCLUSION

The use of personal computers in the evaluation of pulsed laser holograms of particle fields constitutes a very important tool, that will surely contribute in taking more frequent advantage of the excellent properties of the holographic techniques in the study of dispersed flows.

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Table 1. Results.

$p_v = 0.1$ MPa, $\dot{m} = 49.4$ g/min

r [mm]	z [mm]	$\bar{d}$ [µm]	d_{max} [µm]	d_{min} [µm]	$\bar{u}$ [m/s]	Lz [mm]	α
1.80	3.56	–	–	–	–	3.56	50
3.60	6.90	162	240	97	2.52		
5.60	11.60	174	304	117	2.50		
8.59	19.10	169	291	92	2.31		
11.50	25.30	177	309	91	2.36		
12.13	32.00	161	280	94	2.49		
12.88	38.10	169	312	105	2.50		
13.10	43.20	177	283	89	2.49		

$\bar{d}$ – mean drop diameter, $\bar{u}$ – mean drop velocity
Lz – break-up length of the liquid sheet, α – spray angle.

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