Evaluation of the Pulsed Laser Holography for the Characterization of Sprays and Direct Measurement of Drop Size and Velocity Distributions

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1. INTRODUCTION

The knowledge about interactions between sprays and their partially condensable environments is important for correct design of industrial processes and for better understanding of dispersed fluid flow phenomena.

In the last few years, the perfection of the laser technique made the application of more powerful, non-intrusive methods possible to study dispersed flows. Two major areas have been developed: on one side the LDA-sizers, which base on the analysis of LDA signals, as is decribed in the studies of *Durst & Eliasson (1975), Farmer (1980), and Bachalo (1986)*; on the other side the pulsed laser holography, which base on the Gabor-Holography, as illustrated in the reviews of *Thompson (1974)* and *Trollinger (1975)*. These two groups of measurement methods seem to be the most appropriate to provide data for the range of drop diameters $10\lambda < d < 1$ mm, where λ is the wavelength of the laser light.

The purpose of this paper is to examine the possibilities of the pulsed-laser holography for direct measurement of size and velocity distributions of spray droplets, and for the characterization of the spray. With two examples, a) injection of water into atmospheric air, and b) injection of subcooled refrigerant R113 into its own saturated vapour, the applicability of the pulsed laser holography to measure not only the size but also the velocities of the drops is demonstrated.

2. HOLOGRAPHIC SYSTEM

2.1 Arrangement for the recording of the holograms

The layout of the holographic system with the autoclave in which the spray is produced is shown in Fig.1. An off-axis arrangement using a high-power pulsed ruby laser was employed. The laser produces light of a wavelength of 694.3 nm, with an output energy of 1 J and a pulse width of 30 ns. It can also be operated in double-pulse modus with pulses of 0.5 J at intervals from 1 to 800 μs. The collimated object beam is led into the experimental chamber through a diffusor D to provide a uniform illumination of the object O and is transmitted through the spray. The imaging lenses IL were placed between the spray and the holographic plate (Agfa 8E75 HD), in order to produce a conjugate image of the spray close to the holographic plate. Thus, the necessity of the hologram to achieve a high resolution was reduced. The position of the mirror M was adjusted so that the optical path difference between the reference and the object beam path was kept shorter than the laser coherence length (~ 20 cm).
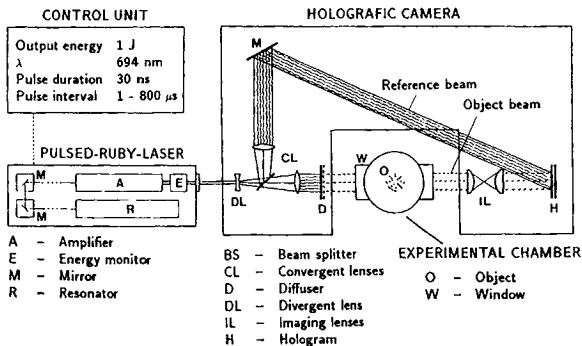
Fig.1 Holographic arrangement

In the present study, usual single pulsed laser holography (where a single exposure was made with one firing of the ruby laser) was carried out to measure the drop sizes and to observe the spray form. Next, double-pulsed laser holography (where a double exposure was made with two firings at a pulse interval of 200 μs of the ruby laser) was employed to achieve the droplet velocities.

2.2 Reconstruction and Evaluation of the Holograms

The reconstructed image of the liquid spray was obtained by illuminating the developed holographic plates – holograms – with a continuous Helium-Neon (He-Ne) laser beam which replaced the reference beam. Figure 2 shows the optical arrangement for taking photographs of the virtual image of the reconstructed hologram. By turning the plate 180°, a real image is produced which can be photographed directly with microscope objectives.

The holograms were evaluated by a manual method. First, a series of photographs was taken from each hologram in which the focussing lenght was varied stepwise by
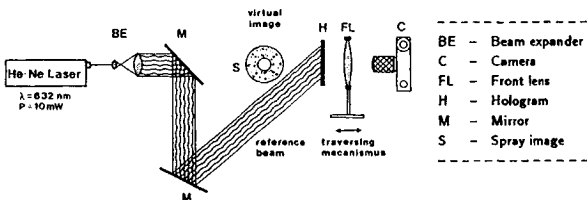

Fig.2 Arrangement for the reconstruction of the holograms

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adjusting the camera lenses, sweeping the full depth of the holographic image. In this manner the three dimensional information of the hologram was converted into a set of two dimensional slides (photographs) containing the part of the hologram information corresponding to the focal plane at which the photograph was recorded. The focussing depth of the photographs was kept as short as possible using a 400 mm teleobjective and a 500 mm front-lens which was moved to shift from a focal plane to another. The photographs could then be easier evaluated. The film negatives were projected onto a translucent screen measuring 130 cm x 100 cm using a common slide projector. The projected images could then be directly measured with a calibrated magnifier. Total magnifications up to 100 : 1 were achieved. To assure correct measurements, only very well focussed droplets, selected by human criterion, were taken into account. A holographic image of a tungsten wire of 100 μm diameter was used as a calibration scale.

3. EXPERIMENTS

3.1 Example a.: Water Spray in Atmospheric Air

For this case, the experimental chamber in Fig.1 was removed and only the water atomizer, a hollow-cone type swirl nozzle (Lechler & Co.) of 0.7 mm in bore diameter was installed. Tap water was injected at a constant flow rate of 116 cm^3/min into atmospheric air. First a thin veil-like liquid wall was formed which, after a given distance Lz (break-up length) from the nozzle, broke up into a fine droplet swarm as shown in the schematic diagram of Fig.3. After a few seconds, the spray flow reached the steady state. At these conditions, two holograms were recorded. A single-pulsed hologram to measure the break-up length, the spray angle and the drop sizes, and a double-pulsed one to evaluate the drop velocities. The double-pulsed holograms became clearer for pulse intervals of 200 μs at which the droplet pairs, meaning the same droplet corresponding to the two exposures, could be identified and the distance between them measured. The results are shown in Table 1, where r and z are the coordinates defined in Fig.3.

3.2 Example b.: Subcooled Refrigerant R113 in its own Saturated Vapour

A thermally insulated, cylindric vessel, designed for pressures up to 2 MPa, was used as experimental chamber (Fig.4). Its interior measures 206 mm in diameter and 650 mm in height. Two quartz glass windows of 100 mm in diameter were installed in the cylindrical wall for optical access. The spray was injected from the top of the vessel through the fine hollow cone nozzle described in section 3.1. The nozzle was positioned concentrically with respect to the cylindrical wall and can be moved
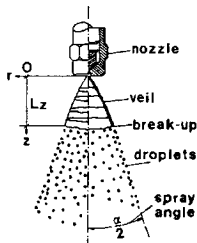

Fig.3 Spray definition scheme

Table 1. Results of Example a
Water spray ($\dot{m}$ = 116 g/min)

r [mm]	z [mm]	$\bar{d}$ [µm]	d_{max} [µm]	d_{min} [µm]	$\bar{u}$ [m/s]	Lz [mm]	α
6.95	9.50	190	269	110		9.5	72
6.96	9.66	150	220	74	2.05		
8.10	14.50	220	340	150	2.05		
8.45	19.40	200	330	65	2.05		
12.34	32.20	220	280	105	2.05		
15.60	43.70	210	300	95	2.05		

axially to permit the observation of any section of the spray. The lower third of the autoclave was filled with part of the liquid refrigerant R113 which was heated by the electrical heating elements (1.2 kW), installed in the lower plenum, to produce the saturated vapour environment in the upper two thirds of the vessel. A funnel was placed between the liquid and the spray. It collected the spray droplets and led them to the outlet. The R113 vapour environment was maintained at constant pressure of 0.1 MPa (T_s = 47 °C). The liquid, supplied by a pressurized R113-reservoir, was injected at a temperature of 25 °C. The mass flow rate was varied from 32.5 up to 231.87 g/min at the intervals shown in the table of results (Table 2). For each fow rate ṁ, two holograms were recorded as described in section 3.1 to obtain the information of the spray, in this case flowing through a condensable environment. Typical photographs of reconstructed singe-pulsed holograms are presented in Fig.5. The results summarized in Table 2 are illustrated in the diagrams of Fig.6. The droplet size, droplet velocity and break-up length depend strongly upon the mass flow rate.
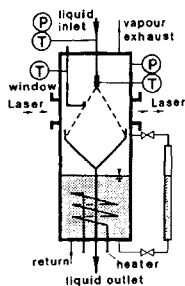

Fig.4 Experimental chamber

Table 2.   Results of Example b
Spray of the Refrigerant R113

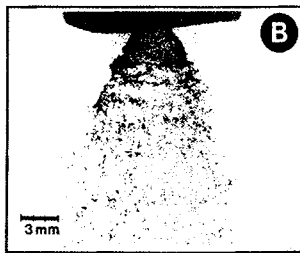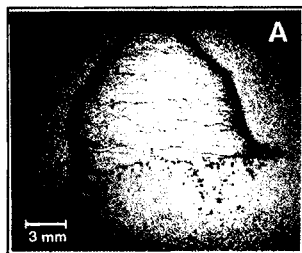| ṁ (g/min)	r (mm)	z (mm)	d (μm)	d_{max} (μm)	d_{min} (μm)	ū (m/s)	l_z (mm)	α
32.50	0.50	3.48	340	450	220		3.48	25.6
	1.14	5.70	300	540	220	0.70		
	2.28	11.40	370	570	170	0.70		
64.44	2.16	5.70	310	340	220		5.70	30.8
	2.26	11.40	370	450	310	1.66		
	3.64	17.10	370	420	310	1.66		
82.28	3.10	5.30	290	340	205		5.30	66.0
	6.85	11.40	250	280	230	2.50		
	14.20	17.10	290	350	250	2.50		
101.86	3.02	5.13	230	235	230		5.30	66.0
	6.30	11.70	240	285	190	3.35		
	17.80	17.10	269	310	199	3.35		
141.66	4.10	3.75	240	290	182		3.75	71.6
	8.21	11.40	130	140	110	3.75		
	11.17	17.10	140	190	90	3.75		
231.87	3.30	2.40	150	190	110		2.40	72.0
	7.52	11.40	100	140	50	5.02		
	10.90	17.10	120	140	90	5.02		

Fig.5   Typical photographs of reconstructed single-pulsed holograms: A, water spray in atmospheric air (ṁ = 116 g/min) and B, R113 spray in its own saturated vapour (ṁ = 101.86 g/min ; p_v = 0.1 MPa).
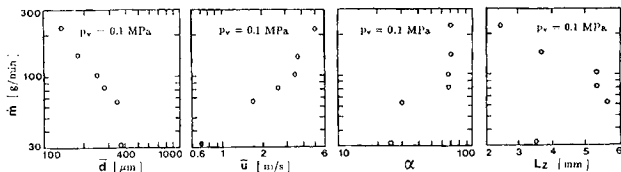
Fig.6 Mean drop diameter, mean drop velocity, spray angle and break-up length vs. the mass flow rate.

3.3 Discussion of the Results

The measurements of the break-up length from both examples a and b were compared with known spray correlations (*Lee & Tankin; 1984a and 1984b*) for water-air (a) and water-steam (b) respectively. While for the case a, a good agreement was observed, the comparison for the case b revealed great discrepancies, as can be seen in Fig.7. It becomes apparent that R113-sprays can not be directly described with these kind of correlations. A plausible explanation of this behavioural discrepancies takes root in the strong differences in the physical properties (liquid density, surface tension and liquid viscosity) of water and refrigerant R113. In spite of this it seems promising that, with sufficient R113-spray data, it will not be very difficult to extend actual spray correlations – or to provide new, more general correlations – in future research, in order to predict the behaviour of generalized sprays.

3.4 Uncertanty Sources

The human criterion in our hologram's evaluation method, especially to decide whether a droplet appears sharp enought in the photographs, is a dominant factor in the estimation of the uncertainties of the results. In order to take into account this error source, three persons evaluated separately the film negatives corresponding to all the holograms reported here and their measurements were compared together. Deviations up to 16% were achieved. Errors due to other sources were one order of magnitude smaller.
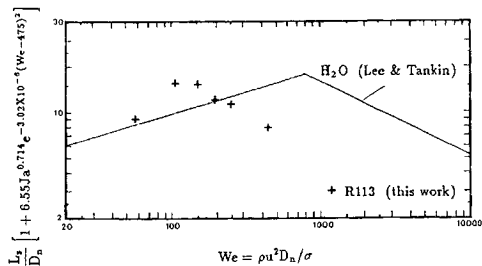

Fig.7 Break-up length Lz as a function of Weber and Jakob numbers

4. CONCLUSIONS

– Off-axis holographic arrangements for the pulsed laser holography provided very clear single-pulsed holograms that could be easily evaluated for drop sizes $d > 10\lambda$.

– Information about velocity distributions could be quite easily obtained from double-pulsed holograms that, combined with the information gained from single-pulsed holograms, allowed the complete evaluation of the spray and droplet parameters.

ACKNOWLEDGEMENTS

NOMENCLATURE

D_n	nozzle diameter	[mm]	r	radial coordinate	[mm]
Cp	specific heat	[kJ/kg K]	ū	mean droplet velocity	[m/s]
Ls	break-up length	[mm]	z	axial coordinate	[–]
Ja	Jakob number	[–]	α	spray angle	[–]
	Ja = Cp (Ts - T)/h		λ	wavelength of laser light	[nm]
O	origin of coordinates	[–]	ρ	density	[kg/m³]
T	temperature	[°C]	μ	viscosity	[Pa s]
We	Weber number	[–]	σ	surface tension	[N/m]
	We = $\rho u^2 D_n / \sigma$				
d	droplet diameter	[μm]		subindices:	
d̄	mean droplet diameter	[μm]		max – maximum	
h	heat of vaporization	[kJ/kg]		l – liquid	
ṁ	liquid mass flow rate	[g/min]		min – minimum	
p	pressure	[MPa]		s – saturation	
u	droplet velocity	[m/s]		v – vapour	

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