Digital Holography for micro-droplet diagnostics

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Abstract The performance of two digital holographic techniques (digital in-line holography and Digital Image Plane Holography) is compared in the study of the droplets generated by a micro-dispensing device. This device provides droplets whose diameter can be changed by varying the pressure applied to the reservoir containing the substance to be atomized.

Digital in-line holograms of the droplets were recorded at four different pressures (10, 15, 20 and 25 psi). The obtained size distribution is quite similar for the four pressures. Although is true that the mean droplet diameter increases with the pressure, also increases the dispersion in the measured values. While for P= 10 and 15 psi the droplet sizes are quite uniform (mean diameter = 159,63 ± 17.1 μm and 163.24±21.8 μm respectively) for the higher pressures the dispersion is three times bigger. The mean diameter measured for 20 psi is 174.2 ± 56.03 μm and for 25 psi is 155,42 ± 34.4 μm.

The droplets generated at pressures of 10 and 20 psi were also analyzed with Digital Image Plane Holography. As expected, we found basically the same results as when in-line holography was applied. The mean diameter increases as the pressures increases and so does the dispersion. In this case the average droplet size is 176.78 ± 21.9 μm and 184.71±40.56 μm for 10 and 20 psi respectively.

The results obtained with both techniques agree reasonably well. Digital in-line holography can be a very good option for particle characterization in systems with low particle density and relatively big sizes. The great attractiveness of the in-line holographic set-up is that it requires minimum optical equipment and laser coherence length. On the other hand Digital Image Plane Holography need a slightly complicated optical set-up but it can be easily adapted for any droplet size by choosing the appropriated magnification on each case. Also, it can be used when the particle density is high, as individual particles in the illuminated plane can be easily isolated.

1. Introduction

Digital holography (Kreis and Jüptner (1997) is a promising technique for fluid diagnostics due to its great versatility. On one hand it allows the measurement of the 3D-3C velocity field in a fluid volume. On the other hand, its application in two-phase flows is increasing as not only the velocity but also the size and shape of the particles in the disperse phase can be measured.

Digital holography shares with optical holography the recording process, i. e., the light scattered by the object (tracers in a flow, droplets, bubbles,...) interferes with a reference beam in a photosensitive device (a CCD sensor in digital holography). Therefore, both the amplitude and the phase of the object wave are captured. However, in digital holography, the hologram is mathematically reconstructed, avoiding the chemical processing needed for developing the holographic plate.

Two main inconveniences remain when digital holography is applied. First, the low spatial resolution of the CCD cameras does not allow the recording of high spatial frequencies and forces the use of small angles between the object and the reference beam. One immediate consequence is that the virtual and real images are not fully separated when the hologram is reconstructed. Secondly, the recording of a whole fluid volume requires a low particle density as the defocused particle images will add noise when a plane is analysed.

Recently, digital holography has started to be used with different optical configurations as a velocimetry technique (Meng et al.(2004), Lobera et al. (2004) and for particle diagnostics (von Ellenrieder and Soria (2003), Palero et al.(2005), Pu et al. (2005)).

Meng et al (2004) and von Ellenrieder and Soria (2003) apply in their works the in-line holographic set-up. In this case a fluid volume is illuminated with a coherent collimated beam. Light diffracted by the particles in the flow forms the object beam, while the undiffracted light forms the reference beam. The great attractiveness of the in-line holographic set-up is that it requires minimum optical equipment and laser coherence length. However it presents some drawbacks, being the more relevant in our case that the size of the reconstructed image in the direction of the optical axis is several times bigger than the real size, making difficult to determine the position of the particle.

Digital Image Plane Holography (DIPH) is a holographic technique where a plane of the fluid is illuminated with a laser sheet and imaged onto a CCD sensor like in PIV. The difference with PIV is that the image of the fluid plane (object beam) interferes with a reference beam in the CCD sensor, making a so-called image hologram. As a plane and not a volume is recorded, the problem with the large depth of focus disappears. Besides the illumination light is used in a more efficient way. Another advantage is that using DIPH the particle concentration is not limited, it can be as in PIV. DIPH has been used for the measurement of the complete velocity field in a convective flow (Lobera et al (2004)) and for particle diagnostic (Palero et al. (2005)). This last approach is what we are going to use here. It is well known that if a fluid plane is illuminated with a laser sheet, each of the transparent droplets immersed in the laser sheet will scatter light that is refracted and reflected thus yielding either a fringe pattern (defocused particle image) or two distinctive spots (focused particle image). The fringe count or fringe frequency and the separation between the two spots provide the droplet size (Glover et al. (1995), Burke et al. (2002)).

These two holographic techniques are applied in the present work to the study of the droplets generated by a micro dispenser device that can be operated at different conditions. Micro dispensers are widely used in medical and pharmacological applications as drug dispensers. They provide micro droplets whose diameter can be easily controlled by changing the pressure applied to the reservoir containing the substance to be atomized. The fluid volume will depend on the pressure as well, increasing as the pressure increases. The micro dispenser used here is a Lee Micro-Dispensing VHS system. The most important parts are a high-speed micro-dispensing valve (that operates in the 0-120 psi range), and a nozzle of 127 μm in diameter. The valve controls the liquid flow and must be connected to a pressurized reservoir.

2. Digital in-line holography

A schematic of the experimental set-up used for the in-line digital holography is shown in figure 1. A Nd:YAG pulsed laser (λ = 532 nm, 100 mJ per pulse) has been used as a light source. A set of neutral density filters ensured that the CCD sensor was not damaged by an excess of energy. Two spherical lenses (L_1, f_1=-30 mm, L_2, f_2=100 mm) created a collimated beam of 3.5 cm in diameter. The pattern resulted of the interference between the droplets (object) and the collimated (reference) beam directly illuminates the CCD sensor of a digital camera, which is at 90 mm from the plane were the nozzle tip was located. The CCD array contains 1280 x 1024 pixels, each of them with a nominal size of 6.7 μm x 6.7 μm. The area covered by the CCD sensor was 8.6 x 6.97 mm^2.

Holograms of the droplets were recorded while the micro-dispenser was operating. The holograms were reconstructed using a method developed by Onural and Scott (1987). The computer code used in this work is a direct implementation of the mathematical reconstruction algorithm developed by these authors and has been adapted here for the analysis of sprays by von Ellenrider and Soria (2003). This method utilizes an iterative filter that limits the twin-image effect, common to all in-line holograms. The particle image can be reconstructed at any plane by varying the non dimensional parameter $\alpha = (NX^2/\lambda d)^{1/2}$, where N is the number of pixels across the entire hologram, X is the pixel size, λ is the wavelength of the recording illumination and d is the distance between the CCD sensor (recording plane) and the position of the original object. The algorithm uses the Fast Fourier Transform, which is optimized for data of size $2^n x 2^n$. However the holograms were not cropped down to 1024 $pixel^2$ because the droplets rarely were at the center of the image. Increasing the size of the images up to 2048 $pixel^2$ was another option but the time for calculation was bigger than when the images were filled up to 1280 $pixel^2$ with zeros. Then, in this case N = 1280.

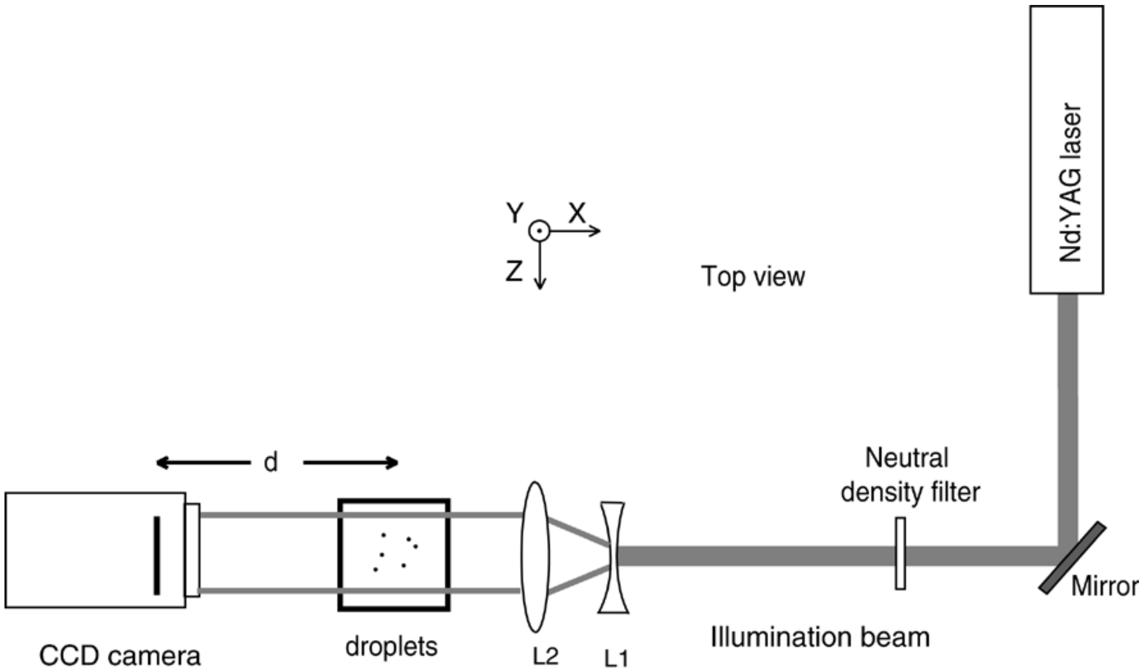
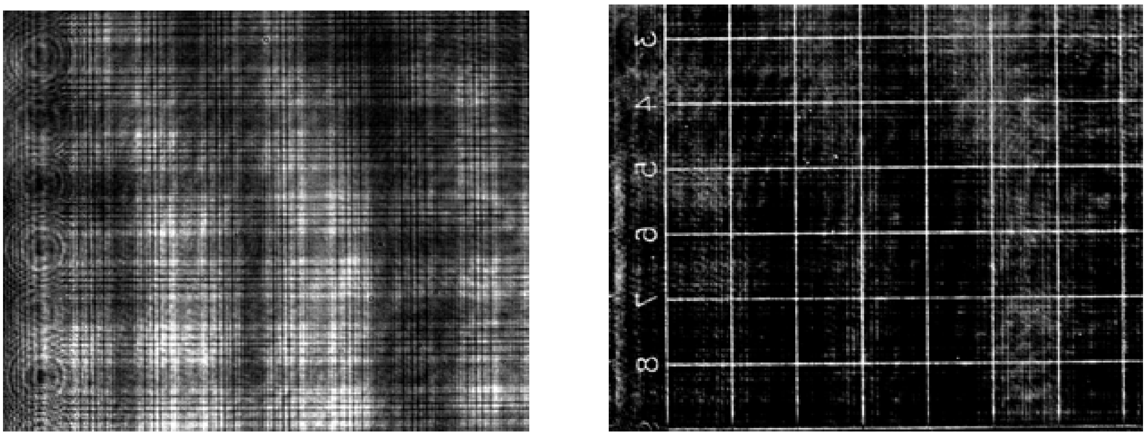


Fig. 1 Digital in-line holography set-up. L1 divergent lens, L2 convergent lens, d distance between the CCD sensor and the position of the droplets

As a way to test the performance of the reconstruction algorithm a transparent square grid (10 mm x 10 mm) was used for calibration. In figure 2 the hologram of the grid is shown. The grid was located below the nozzle tip. The best-focused reconstructed image was found for α = 1.07, which corresponds to a distance of 94 mm from the CCD sensor.



(a) (b)

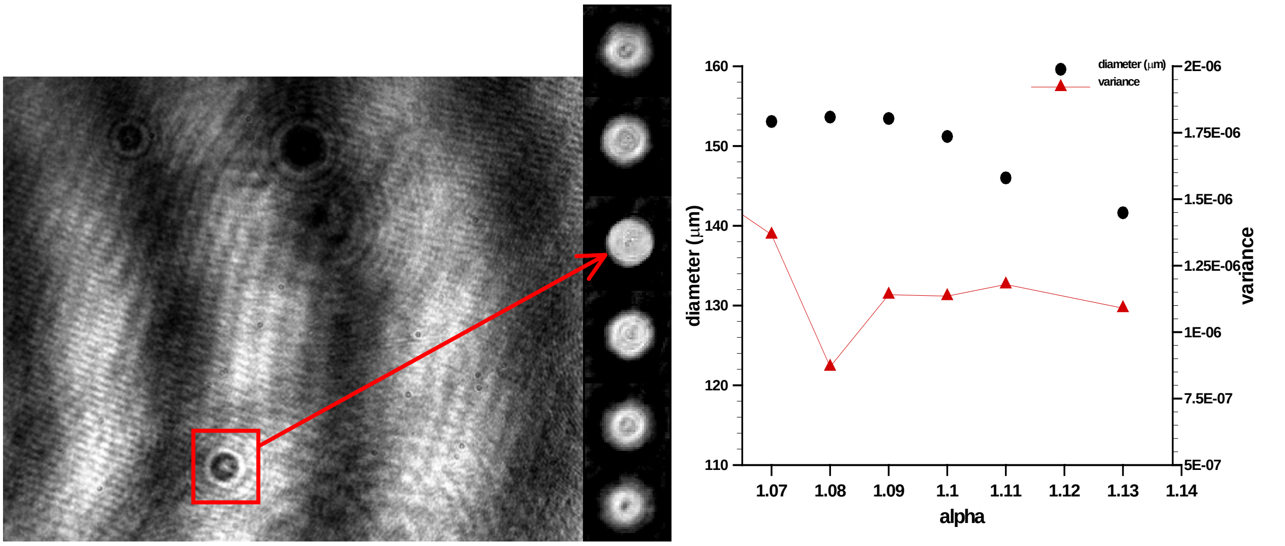
Fig 2 a) Digital in-line hologram of a grid of 1 mm^2 spacing; b) reconstructed image of the grid.

A further improvement done for the present work was the complete automation of the reconstruction process. Knowing the position where the grid is focused is a good help to estimate the droplet position. However, the droplet trajectory will not always be perfectly vertical. Furthermore, due to the small aperture the reconstructed particle image is not longer a sphere but is elongated in the direction of the optical axis of the system. Therefore some criterion is needed for determining the exact location of each droplet. We have used the PECA method developed by Pan and Meng (2003). These authors demonstrated that in the plane where the droplet is located, the variance of the imaginary part of the reconstructed real image has to be a minimum.

Then the holograms are reconstructed following these steps:

- For each hologram a series of reconstructed images are obtained by varying the parameter α.
- Each image is strongly binarized and filtered in order to remove the high frequency noise.
- 2-D structures with connected pixels are identified like possible droplets in the hologram. The area and eccentricity of these structures are used like criteria for deciding whether they are droplets or not.
- Once a structure is identified as a droplet the original reconstructed image is used for calculating the variance of the imaginary part of the reconstructed particle. Then the image is binarized again and the final area and diameter are calculated.
- Once all the planes have been reconstructed for a single hologram, the variance is minimized in order to find the correct droplet position.

Figure 3 illustrates the procedure described above. A hologram (fig 3 (a)) recorded with a pressure of 10 psi, is reconstructed at several positions, by changing α. In figure 3 (b) only the reconstructed portion corresponding to the diffraction pattern marked in red is shown. The droplet has been reconstructed at alpha (from top to bottom) = 1.06, 1.07, 1.08, 1.09, 1.11 and 1.12, which represent a change in the axial distance d of 10 mm. The droplet location is indicated by the minimum in the variance of the imaginary part of the reconstructed real image (figure 3 (c)) and corresponds to a distance of 92.6 mm (α = 1.08) from the CCD sensor. A more accurate position can be determined, decreasing the interval of variation in α. The hologram is reconstructed again around the position where the minimum has been found changing α in 0.001 (figure 4).



(a) (b) (c)

Fig 3 a) Digital in-line hologram; b) reconstructed particle for alpha ranging from 1.06 up to 1.12, Δα= 0.01; c) droplet diameter (µm) and variance of the imaginary part of the reconstructed image as a function of alpha

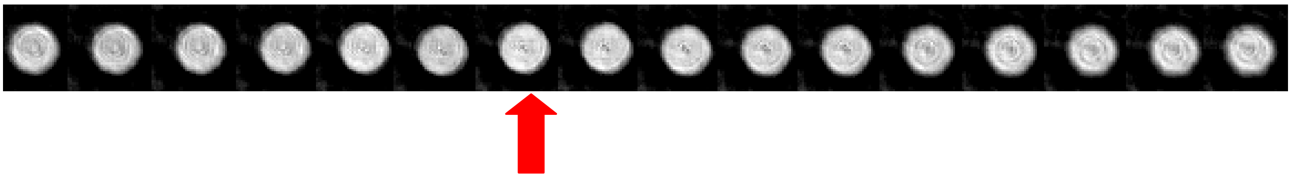


Fig 4 Particle reconstructed with α varying from 1.075 up to 1.09 (Δα= 0.001). The best focused image (pointed with the red arrow) is obtained for α = 1.081 (d= 92.43mm).

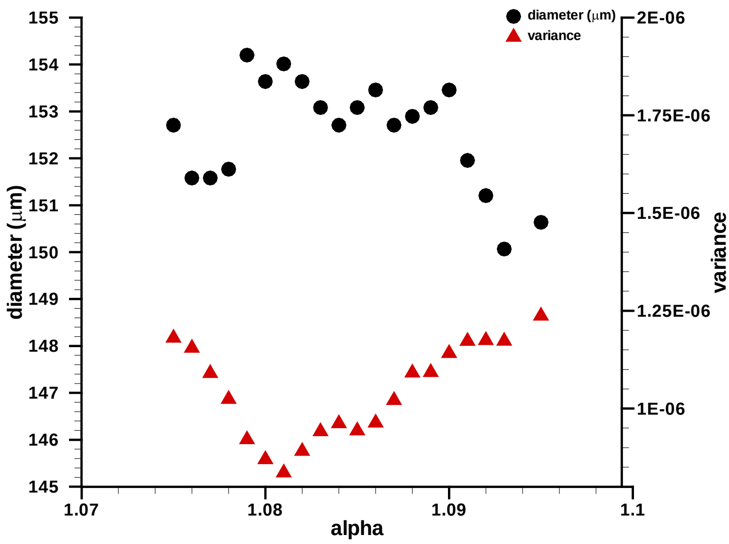
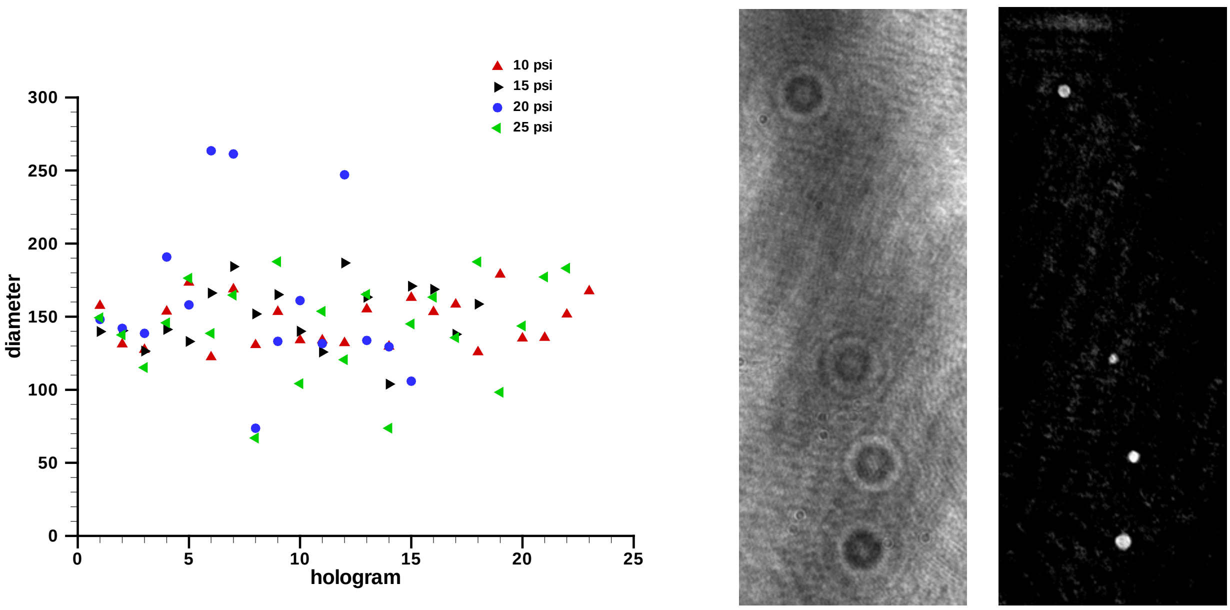


Fig 5 Particle diameter (µm) and variance of the imaginary part of the reconstructed image as a function of α

This droplet has been chosen as a representative sample of the general results obtained for all the droplets. This is valid as well for what is described in the following, being the figures presented a global estimation. It can be noticed that the particle diameter is almost constant when alpha changes from 1.075 to 1.09 (figure 5), which means a variation in the distance d of 3 mm. It has been found that the variation is less than 1% (in this case is 0.03%). The variation in the measured diameter increases when the particle is analyzed over a bigger range of d (10 mm), being the maximum difference about 7% (6.6% for this droplet).

In order to investigate the relation between the droplet diameter and the pressure in the reservoir, four pressures were tested: 10, 15, 20 and 25 psi. At each condition 25 holograms with droplets were recorded and analyzed. According to the manual, droplet size can be easily changed by changing the pressure. It is also indicated that droplets sizes will strongly depend on fluid viscosity and the fluid cleanness. In any case, it was expected to find some significant difference in the droplet sizes as the pressure increased but as it can be seen in figure 6 the size distribution is quite similar for the four pressures. Although is true that the mean droplet diameter increases with the pressure, also increases the dispersion in the measured values. While for P= 10 and 15 psi the droplet sizes are quite uniform (mean diameter = 159,63 ± 17.1 μm and 163.24 ± 21.8 μm respectively) for the higher pressures the dispersion is three times bigger. The mean diameter measured for 20 psi is 174.2 ± 56.03 μm and for 25 psi, 155,42 ± 34.4 μm. A possible explanation is that, although the volume dispensed is bigger with the increase in the pressure, smaller droplets are produced initially. When the droplets are falling down they can collide and agglomerate giving as a result bigger droplets. However it is difficult to reach any conclusion as the number of holograms is not enough for doing statistics. In figure 6 (b) is also shown a hologram recorded at a pressure of 25 psi where the broad size distribution can be seen.



(a) (b)

Fig 6 a) Droplet diameter (μm) distribution for the four pressures tested; b) example of a hologram and its reconstruction, recorded with a pressure of 25 psi

Assuming that the reconstruction algorithm does not introduce any error (this point will be studied in the near future) let us analyze the possible sources of error in the measured diameters. The most important cause seems to be the accurate location of the droplet position, which can introduce a variation in the droplet size of a 7%. But once the location is fixed and this can be done with accuracy, another source of error to consider is the binarization of the image. There is not any clear criterion that establish which is the end of the particle so the correct choice of the particle boundary has to be done very carefully. We have been found that a not-too-bad binarization (eliminating a couple of pixels in the edge of the droplet image) can change the droplet size in a 10%.

3. Digital image-plane holography

DIPH has its origin in the spatial phase shifting-digital speckle pattern interferometry (SPS-DSPI), a technique widely used in solid mechanics, but reported quite recently as a velocimetry technique (Lobera et al (2003)).

A fluid plane is illuminated with a laser sheet and a lens is used to image the object onto the CCD sensor, where interferes with a reference beam. Specific of this DPIH set-up is the divergent reference beam that has to be placed in a very precise position respect to the object beam. The reference beam has to originate in the same plane and at a suitable distance from the lens aperture. Then we are recording a lensless Fourier hologram of the lens aperture. Because of the small angles allowed by the low spatial resolution of CCD sensors, the reference and the object beams are combined by means of a beam splitter placed between the lens and the CCD camera sensor.

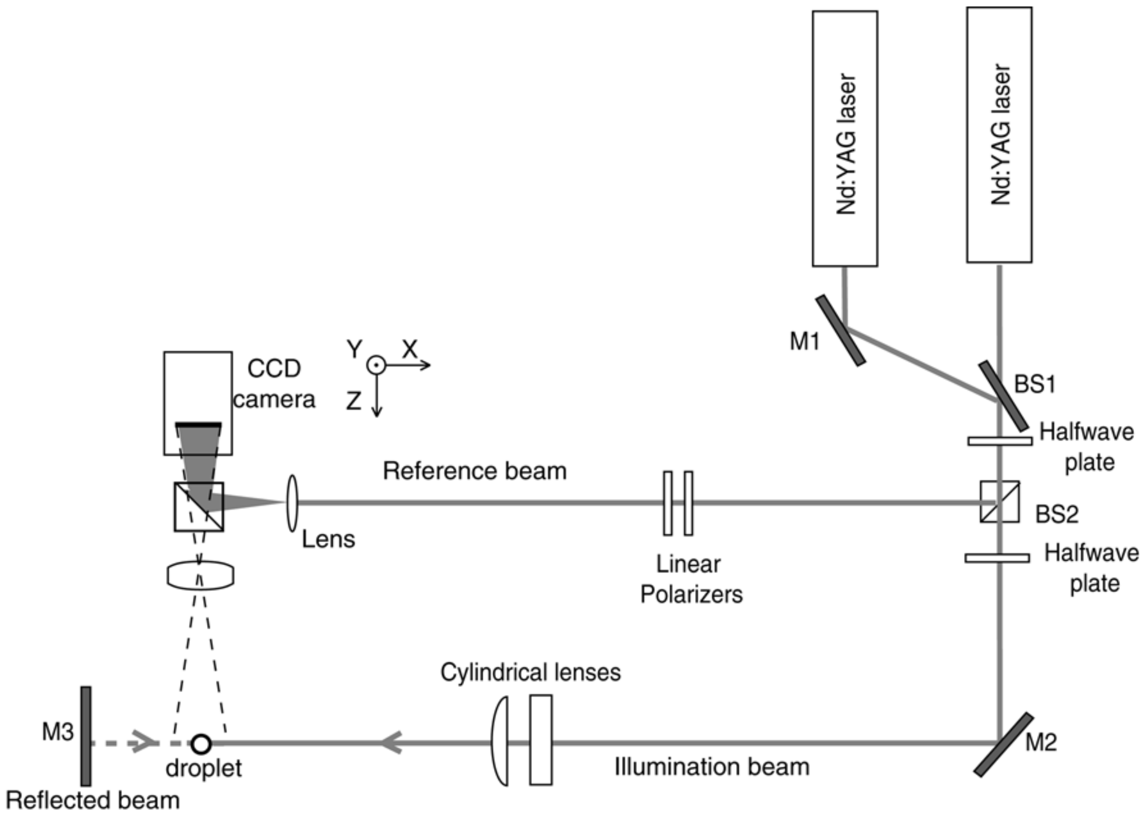
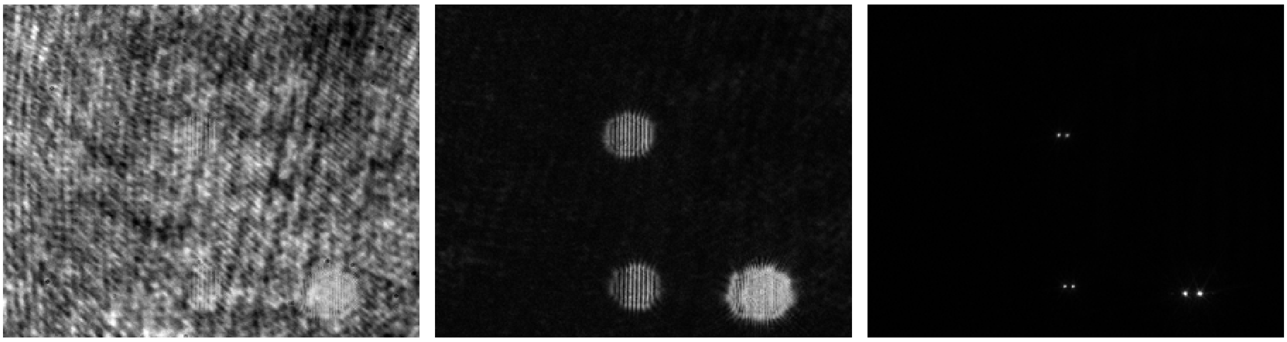


Fig 7 Experimental set-up for Digital image plane holography (top-view).

Figure 7 shows the set-up used for digital image plane holography. Now, the laser beam is separated into an object and a reference beam. The reference beam is a diverging wave, formed with a microscope objective located at the same distance from the CCD sensor than the distance between the camera lens and the CCD sensor. The object beam is shaped into a sheet with two cylindrical lenses. A lens with f'= 85 mm and working with N.A =8 was used to form the image of the droplets onto the CCD sensor. The magnification was set at 1.7.

The droplets are illuminated with two laser sheets travelling in opposite directions, the so-called illuminated and reflected beams in figure 8. The reflected beam is created with the mirror M3. As the droplets are illuminated with two beams, we will obtain two bright spots on each focused droplet image. The distance between these spots is related with the droplet size in a very easy way (Palero et al. (2005)). When the image is defocused the light coming from this spots interferes giving rise to a fringe pattern which frequency is related with the distance between the spots and, therefore, with the particle diameter. These spots will have the same intensity as they are coming from the first reflection of each laser sheet on the droplet surface, so the fringe contrast will be optimum. In these experiments the holograms of these fringe patterns, i.e., the defocused images of the droplets, are recorded.

An example of the typical holograms recorded with DIPH is shown in figure 8 (a). The non-uniform background is the reference beam. In figure 8 (b) the reference beam has been subtracted and the fringe patterns corresponding to three droplets are now evident. This image is similar to the images obtaining when the ILIDS technique is used (Glover et al (1995)). However, an important characteristic of the digital holography, is that *any plane* can be reconstructed, not necessarily the recorded plane. Therefore, we will be able to reconstruct the droplet images in the best focused plane where we can isolate them easily (figure 8 (c)).

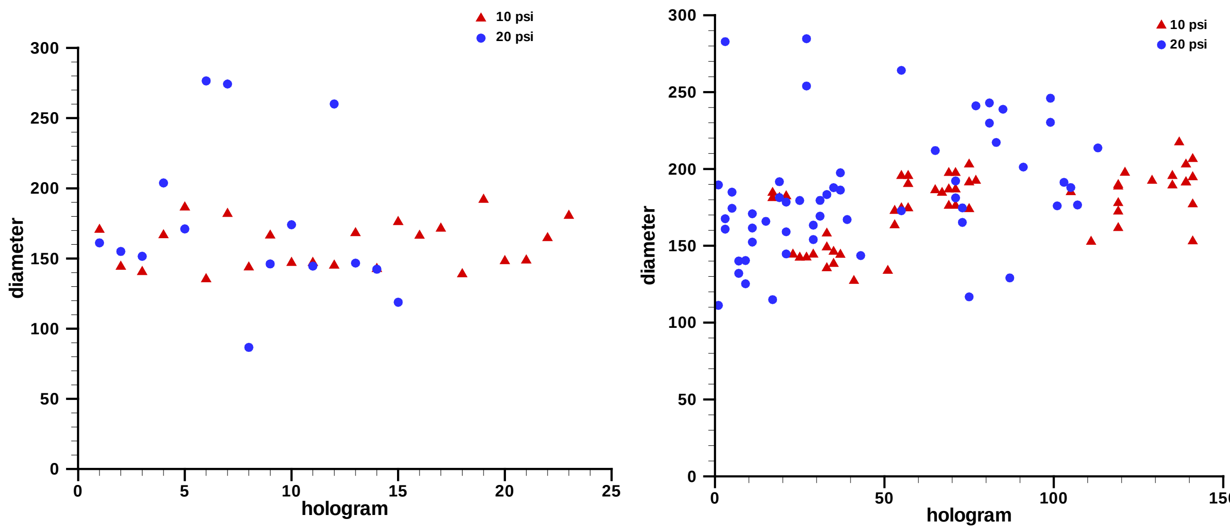


(a) (b) (c)

Fig 8 a) Digital image plane hologram; the background is the reference beam; b) hologram where the reference beam has been removed; the defocused image of the droplets can be seen; c) reconstructed image at the best focused plane.

The reconstruction process is described in detail in Palero et al (2005). For the present work, the reconstruction has been also completely automated. The procedure is quite similar to the one described for the reconstruction of the in-line holograms. Once the hologram is reconstructed in the best focused plane (image plane) the images are binarized. Then, 2-D structures were identified by pixel connection. The droplets were selected among the structures found using three different criteria (area, eccentricity and orientation). Then the droplet image is isolated and propagated to the recorded plane (defocused image) where the frequency of the fringe pattern is calculated.

Droplets obtained at 10 and 20 psi were analyzed applying DIPH. As expected, we found basically the same results as when digital in-line holography was applied. The mean diameter increases as the pressure increases and so does the dispersion (figure 9). In this case the average droplet size is 176.78 ± 21.9 μm and 184.71±40.56 μm for 10 and 20 psi respectively.



(a) (b)

Fig 9 Droplet diameter (μm) distribution 10 and 20 psi obtained a) with digital in-line holography b) with digital image plane holography

4. Concluding remarks

The performance of digital in-line holography and Digital Image Plane Holography has been analyzed when both techniques were applied for the study of the droplets generated by a micro-dispensing device. The results obtained with both techniques agree reasonably well, as they provide similar measured diameters and the same size distributions when the operating conditions of the micro-dispenser change. It has been found that although the mean droplet diameter increases with the pressure, also increases the dispersion in the measured values.

Digital in-line holography can be a very good option for particle characterization in systems with low particle density and relatively big sizes. The great attractiveness of the in-line holographic set-up is that it requires minimum optical equipment and laser coherence length. On the other hand Digital Image Plane Holography need a slightly complicated optical set-up but it can be easily adapted for any droplet size by choosing the appropriated magnification on each case. Also, it can be used in cases where the particle density is high, as individual particles in the illuminated plane can be easily isolated.

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