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A fluorescent laser-diffuser arrangement for uniform backlighting

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Abstract Laser-light diffusers are used in conjunction with pulsed lasers to generate bright, spatially uniform background illumination for imaging and particle sizing applications.The present paper describes a cost effective way of fabricating a fluorescent laser-light diffuser. The procedure to obtain a uniform background using laser illumination is explained. To characterize the diffuser, images are acquired using a CCD camera with the illumination provided using the diffuser and the variations of pixel intensity values along the centerline of the image are plotted. It is observed that the standard deviation of pixel intensity values is fairly small. Hence, these diffusers are suitable for experiments that need a uniform background.

Keywords Laser diffuser · Uniform Background · Particle/droplet sizing and analysis · Spray imaging

1 Introduction

Spray visualization techniques such as backlit/shadow imaging [1] and droplet sizing techniques such as particle / droplet image analysis (PDIA) [2], require images of the spray / droplets on a uniform background to be able to analyse the spray/droplets and determine the spray angle, spray penetration, droplet sizes, shapes, and velocities, etc. Fig. 1 shows one such shadow image where fuel droplets exiting a carburetor are visible against a diffuse, bright, uniform background. The preferred choices of light sources for such imaging are often pulsed lasers - these are often available in diagnostic labs and are used as light sources for various experiments, due to the short pulse duration (of the order of a few ns) which helps to 'freeze' the movement of a fast moving droplets in an image, and due to the high intensity of light available. Obtaining a uniform background from a laser beam, is however, a challenge. The uniform background which is essential for effective image processing, is generally obtained using commercial diffusers which have proprietary designs. One such diffuser contains a diverging lens, an opal diffuser, ground glass plates, and a variable number of fluorescent plates arranged in series. The illumination from such a diffuser is uniform. The normalized standard deviation of pixel intensity values of an image acquired with such lighting is around 0.025 for a small region of 100 pixels. While such diffusers provide the desirable uniform field, their cost is very high (of the order of \$2000 or higher).

Inspired by the work of Jermy [3] on developing an inexpensive method for PIV seeding and Pedocchi et al. [5] on creating fluorescent seeding particles, preliminary experiments were performed by Mali [4] to identify a method by which an inexpensive but efficient laser diffusing arrangement could be arrived at. Consequently, detailed studies were performed to fine tune the design as described in the following sections.

A rudimentary diffuser consists of a ground glass plate which helps to spread out or scatter the light from a source, uniformly. While this is satisfactory for normal light sources (such as LED lights or halogen lamps), the light from a laser is coherent and concentrated in a small region. The light has to be spread out for the intensity of the background to be uniform. This can be achieved by means of a diverging lens or a set of lenses. However, small variations in the roughness of the lens (on the scale of the wavelength of light) cause the phase of the waves at various locations to be different, and a speckle pattern appears due to constructive and destructive interference [6]. The presence of these speckles

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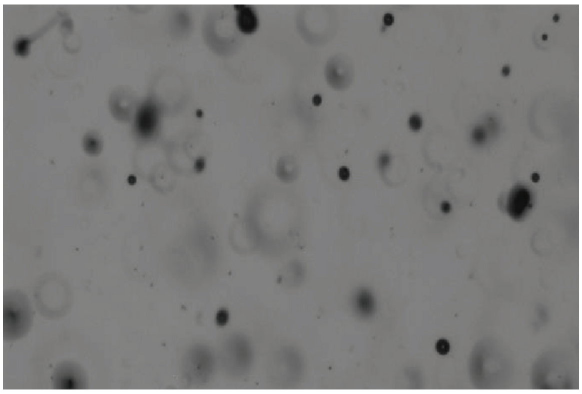

Fig. 1 Representative image of focused and defocused droplets of various sizes on a bright uniform background obtained with the present diffuser arrangement.

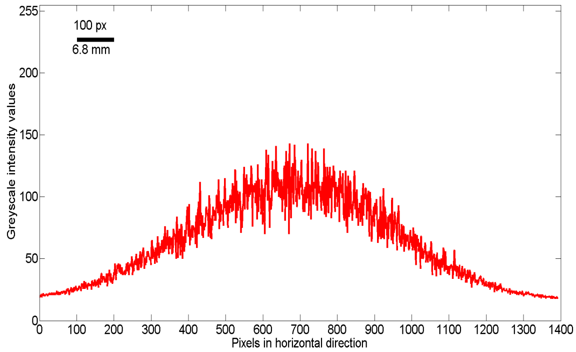

Fig. 2 Variation of light intensity along a line of an image acquired for a rudimentary diffuser arrangement and laser light source.

in the background makes it difficult to process the images as the images become noisy. This is observed in Fig. 2 which shows the variation of light intensity along the center line of an 8-bit image acquired with the background illumination provided by a pulsed laser, a diverging lens and a ground glass plate. The normalized standard deviation or coefficient of variance (standard deviation/mean) of the pixel intensity values for this image is 0.66, which is high. At the same time, the mean intensity value is 25 which is quite low for effective image processing. Due to a large number of speckles in the image, the variation in pixel-to-pixel intensity is large, as reflected by the high standard deviation.

Since the speckles are caused due to the incident laser light being coherent, one of the methods to eliminate the speckles is to ensure that the light leaving the diffuser arrangement is incoherent. This can be ensured effectively by fluorescence. Hence, commercial diffusers use custom built fluorescent plates. However, in the present design, the diffuser setup includes a cubic chamber filled with rhodamine B solution, with frosted or ground glass plates inserted inside the chamber. The rhodamine solution fluoresces when green laser light is incident on it, and the fluorescent light now forms the uniform background for the images. This setup when placed between the laser beam coming from a plano-concave lens and the CCD camera, produces a uniform background. The background illumination obtained using this arrangement was examined for chambers of varying widths and for different regions of interest. The designs are explained in detail for two regions of interest: 96.4 mm x 72 mm (which could be used for imaging a spray), and 1.7 mm x 1.3 mm (which could be used for drop sizing).

2 Design of the low-cost diffuser arrangement

Commercially available clear glass plates of 2.5 mm thickness were cut to a size of 15 cm x 15 cm, and bonded using silicone paste to make rectangular chambers of different depths along the path of the laser. In this study, chambers of depths 1 cm, 3 cm, 5 cm and 10 cm in the direction of propagation of the laser beam, were utilized. Only one of the chambers was used at a time. A known quantity of rhodamine B ($\geq$ 95% pure, supplier: Sigma) was mixed with distilled water and the solution was poured inside the chamber. Rhodamine B was chosen as it is a commonly used, inexpensive laser dye, which fluoresces when excited with radiation from frequency doubled Nd:YAG lasers. Other laser dyes with higher efficiencies such as rhodamine 6G would be expected to work satisfactorily as well. This chamber filled with the Rhodamine water solution constitutes the main part of the diffuser arrangement. Experiments were performed by varying the concentration of rhodamine dissolved in water. Commonly available food grade aluminium foil sheets were pasted externally on the two side plates of the chamber to prevent loss of light intensity. A fixed number of commercially available frosted glass plates were inserted inside the chamber, perpendicular to the direction of propagation of light, based on the depth of the chamber. These are used to promote interference and further diverge the beam to achieve a more uniform background. Two frosted plates were inserted (equally spaced apart) in the chamber having a depth of 10 cm and only one frosted plate was utilized at the centre of the chamber having a depth of 5 cm. The chambers of 1

Table 1 Bill of materials and cost of the diffuser arrangement

Part	Cost in USD
Plano-concave lens (Dia.: 12.5 mm, focal length: 20 mm)	65.00
Plain Glass	2.00
Frosted Glass	3.00
Rhodamine-B (1000 mg)	2.00
Aluminium foil	2.00
Distilled water (2L)	1.00
Total cost	**75.00**

cm and 3 cm depth were tested without frosted plates inside them. Another frosted glass plate was placed ahead of the chamber in most cases. A bill of materials used to construct the diffuser and approximate costs are mentioned in Table 1.

3 Experimental setup for testing the diffuser arrangement

The experimental setup for testing the diffuser arrangement includes a pulsed laser, a CCD camera and a spherical plano-concave lens (Source: Edmund optics) of 12.5 mm diameter with 20 mm focal length. A pulsed Nd-YAG Laser of 532 nm wavelength with a beam diameter of around 6 mm and a pulse duration of around 4 ns with a maximum energy of 180 mJ was used. The 14-bit CCD camera used has a resolution of 1392 x 1040 pixels and a minimum exposure time of 5 micro seconds. A larger exposure time of 500 μs was used to achieve synchronization with the laser pulses. The images were saved in an 8 bit format with allowed light intensity values of 0 to 255. The frosted glass plate and diffuser arrangement were placed in between the laser and camera. The design of the diffuser arrangement was modified based on the field of view required to be imaged, as discussed in the following section. The imaging lens of the camera was also changed accordingly.

Figure 3 shows a schematic of the experimental setup for testing the diffuser arrangement. The camera and the pulsed laser are aligned in a straight line, facing each other, at a fixed distance. The spherical lens is placed in between the laser and the diffuser chamber. The diffuser arrangement is placed at a distance c from the lens. One frosted plate of dimensions 15 x 15 cm is placed at a distance d ahead of the diffuser arrangement. The camera, fitted with a 50 mm Nikon lens, is focussed on a 'plane' at a distance b from the diffuser arrangement, and a distance a from the camera, giving a region of interest of around 9.6 cm x 7.2 cm. The laser beam is expanded by passing it through the spherical lens and it is further expanded and partially diffused by the frosted glass plate. The beam then passes through the diffuser arrangement where speckles are reduced. The light exiting the diffuser arrangement is captured by the camera. All the components of the experimental setup are arranged on an optical bread board.

4 Results and discussion

The distances between the various components (shown in the Fig. 3) were fixed as follows: the distance a was fixed as 63 cm (in order to obtain the required field of view), b (the distance between the diffuser and the spray or experiment which would generally be imaged) was fixed as 15 cm, and c was fixed as 52 cm. The distance c was chosen such the

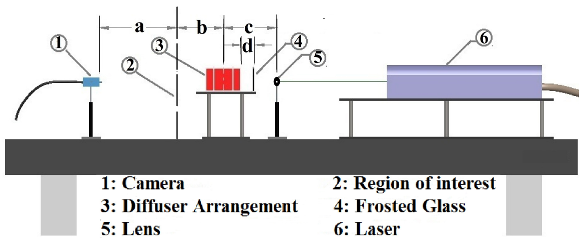

Fig. 3 Schematic of the experimental setup for the diffuser arrangement. The dye chamber is shown having one frosted glass plate ahead of it and two frosted glass plates inside it.

laser beam illuminates the entire diffuser arrangement as it diverges from the concave lens. The distance d between the diffuser arrangement and the frosted glass plate was varied as 2 cm, 5 cm, 10 cm, 15 cm, and 20 cm. This distance was varied in order to vary the divergence of the beam. Experiments were also performed with chambers having different depths (of 1 cm, 3 cm, 5 cm and 10 cm).

Experiments were initially performed by mixing 25 mg of rhodamine B with 2 litres of distilled water, and the solution was poured into the diffuser chamber. The laser beam was passed through the arrangement and images were captured by the camera. It was observed that the images contained a large number of speckles as much of the laser beam passed through the chamber due to low absorption. The concentration of rhodamine B was hence increased in steps of 25 mg upto a maximum of 150 mg (in 2 L). As the concentration increases, more of the laser light is absorbed by the liquid, and the fluorescence intensity increases, leading to a more uniform background. At even higher concentrations, quenching of the fluorescence could also occur, which in turn reduces the intensity of the background. Experiments were conducted with different concentrations and the images were processed to obtain the variation of intensities. A concentration of 75 mg in 2 litres of water was found to give a good intensity with few speckles. Hence, keeping this concentration fixed, images were captured for different distances d, for chambers of different sizes.

Figure 4 shows the variation of the normalized standard deviation of the pixel intensity values of the entire image with chamber depth, and with distance d, at a constant laser energy of 10.3 mJ per pulse. This value of laser energy (10.3 mJ) was chosen as it is the largest value which could be used without saturating portions of the image for the chambers with small depths. It is observed that for a constant chamber size (indicated by red filled bars), as the distance d increases (indicated by the hatched bars), the normalized standard deviation (denoted by green square symbols) reduces. Since the aim is to obtain a uniform background, the objective is to arrive at a configuration which has low standard deviation values. Hence, it is beneficial to maintain a larger value (of 20 cm) for the distance d.

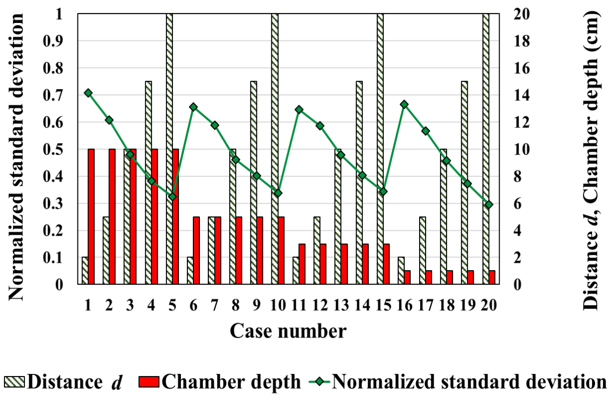

Fig. 4 Variation of the normalized standard deviation of pixel intensity values for images taken with different chamber depths, with varying distance *d*, at constant laser energy.

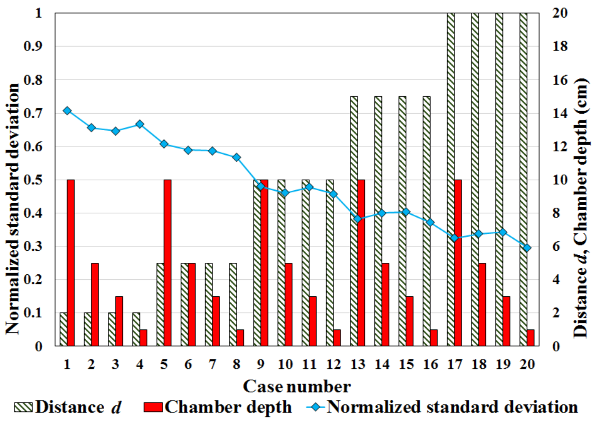

Fig. 5 Variation of the normalized standard deviation of pixel intensity values for images taken with different distances *d*, with chambers of different depths, at a constant laser energy.

Figure 5 shows the variation of the normalized standard deviation of the pixel intensity values of the entire image for distances *d*, for the different chambers, at a constant laser energy of 10.3 mJ per pulse. It is observed from Fig. 5 that, as the chamber size varies (indicated by red bars), for a constant distance *d* (indicated by the hatched bars), the variation in normalized standard deviation is small, i.e., the size of the chamber does not play an important role with respect to overall uniformity of the image in the range studied.

The value of normalized standard deviation has been discussed so far as the mean intensity in the images varies with the diffuser chamber depth and distance *d*. The normalized standard deviation values for the entire image take into account both local variations, as well as the global variation due to the Gaussian nature of the beam. Hence, it is also instructive to look at the normalized standard deviation of only small regions to evaluate the local fluctuations in intensity. Normalized standard deviation values for small regions (of 100 pixels near the centreline) were observed to be low (in the range of 0.02 to 0.05) with smaller values of 0.02 to 0.03 at larger values of the distance *d* at high laser powers. For comparison, a similar value for a typical case with a commerical diffuser was 0.025. Mean values of intensity were also observed to be high near the centreline of the images.

Images were also compared by keeping the distance *d* constant for the chambers of different sizes while varying the laser power. The value of laser power chosen in each case (for the varying power cases) was the highest value at which saturation of pixels of the camera was absent. Figure 6 shows the variation of the normalized standard deviation with distance *d* for chambers of different depths at variable laser energy (and also at a constant energy of 10.3 mJ/pulse). The blue circles in Figure 6 correspond to those at constant laser energy and were presented earlier in Figure 5. The black triangles represent values with varying laser energy. It is observed that images with lower (upto 0.05 lower) normalized standard deviation values can be obtained by increasing the laser energy, but the values are similar. Hence, varying the laser energy (or power) is not particularly beneficial as far as the normalized standard deviation is concerned.

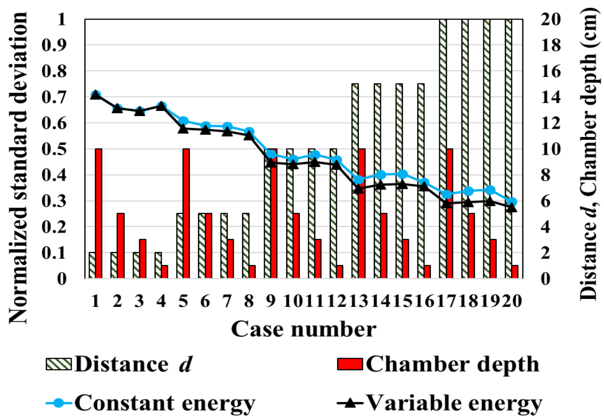

Fig. 6 Comparison of variation of the normalized standard deviation of pixel intensity values for images taken with varying distances *d*, with chambers of different depths, at constant and variable laser energies.

Mean values of intensities were also compared for both variable and constant energy cases, and are shown in Fig. 7. It is observed that, as expected, an image with higher mean intensity can be obtained with higher laser power. Unlike the normalized standard deviation for the full image which did not vary much with laser energy (as seen before from Figure 6), the mean intensity varies significantly. It is observed that brighter images (with potentially higher contrast) can be obtained by increasing the distance *d* while increasing the laser energy and choosing any of the chamber sizes.

The spatial variation in intensity is observed in Figure 8 which shows the variation of intensity along a horizontal line at the center of the image for *d* as 20 cm for the chambers

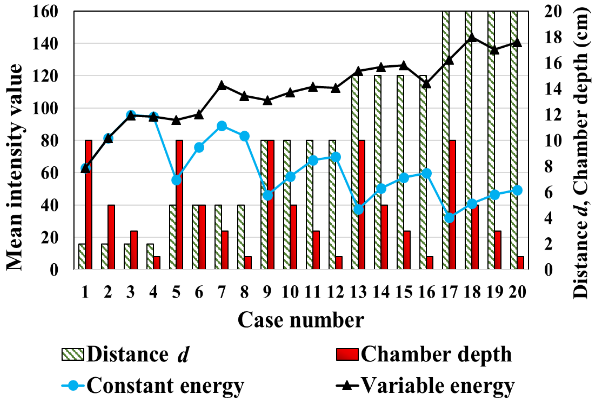

Fig. 7 Comparison of variation of the mean of pixel intensity values in the images taken with different distances d and with chambers of different depths, at constant and variable laser energy.

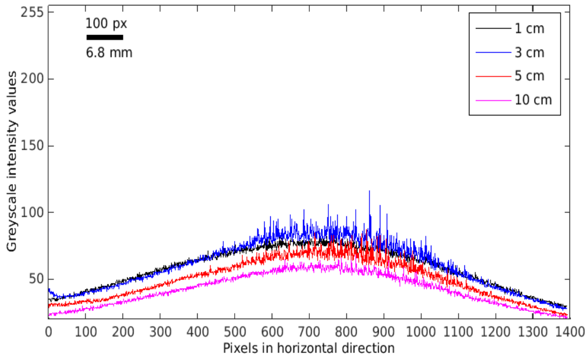

Fig. 8 Spatial variation of intensity along a horizontal line in the image for d as 20 cm, at a constant power of 10.3 mJ, for the chambers of different sizes (mentioned in the legend).

of different sizes (depths). It is observed that chambers with sizes of 1 cm and 3 cm produce more speckles and local variations in intensity while chambers with depths of 10 cm and 5 cm, have low local variations in intensity and would hence be satisfactory for imaging applications.

Figure 9 shows the spatial variation of intensity along a horizontal line in the image, for a chamber of depth 10 cm, by varying the distance d. The laser power was maintained at 10.3 mJ for all these cases. For the case of d as 20 cm, the variation in intensity is less compared to that in the other cases, and the variation is more in the case where the distance is 2 cm. As the distance between the frosted plate and the diffuser arrangement is increased, the beam diverges more and becomes more uniform, but the intensity reduces. The mean is high when the distance d is 2 cm and is lowest when d is 20 cm. Thus, if a smaller region needs to be illuminated, a smaller distance d (e.g. 2 cm) is preferable. If, however, the whole image needs to be illuminated, a d of 20 cm is preferable.

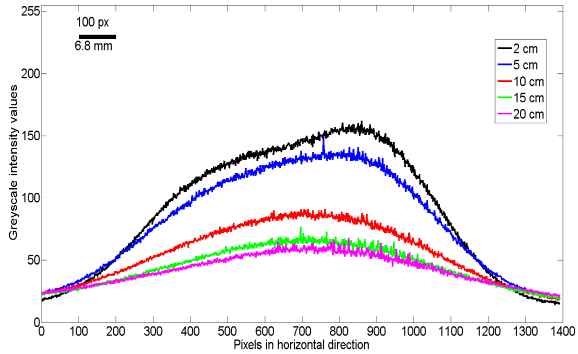

Fig. 9 Spatial variation of pixel intensity values along a horizontal line with a chamber of depth 10 cm for different values of distance d.

Effectiveness of the diffuser: Images taken without the diffuser arrangement have significantly more speckles when compared with the images taken with diffuser, with a normalized standard deviation of 0.65 vs. 0.20. For a smaller region of 72 mm x 47 mm, the normalized standard deviation values with the diffuser setup were as low as 0.17 with varying power and 0.21 with constant power. These compare very well with a value of 0.23 from a commercial diffuser. This highlights the effectiveness of the present diffuser in reducing speckles.

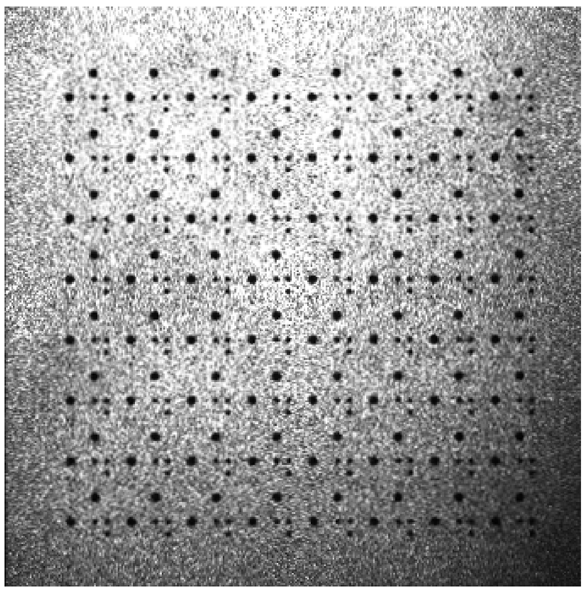

Fig. 10 Photographs of a target with dark filled circles taken with a CCD camera fitted with a 50 mm lens. The image is illuminated with the laser. Only the diverging lens and frosted glass plate are used to diffuse the light.

The effectiveness of using the dye solution is also visible from Figs. 10 and 11 which show images of a calibration target illuminated with the diffuser arrangement. In Fig. 10,

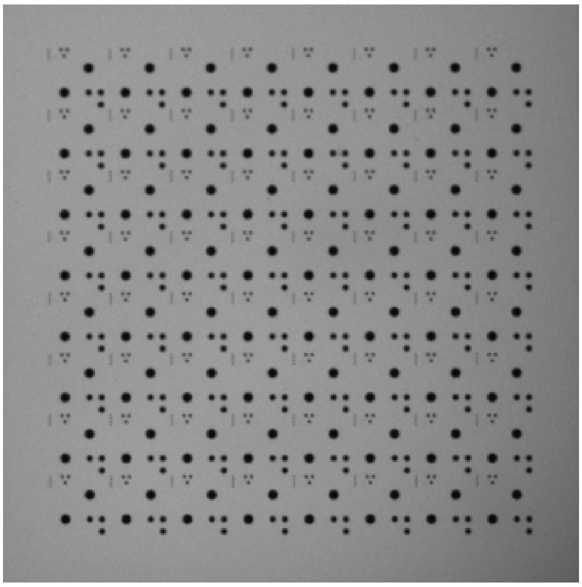

Fig. 11 Photographs of a target with dark filled circles taken with a CCD camera fitted with a 50 mm lens. The image is illuminated with the laser. The diverging lens, frosted glass plate, and dye solution are used to diffuse the light.

the dye chamber was emptied and used without the dye solution, while in Fig. 11, the dye solution was used. The images were taken with the 50 mm lens, at the same location and magnification. The calibration target imaged has repetitive patterns with circles of sizes 400, 250, 125, 63, and 20 μm on it. In Fig. 10, the background intensity is not uniform and the beam saturates some regions of the camera while other regions are dark. Single large black circles (of diameter 400 μm) are visible followed by groups of three circles (of diameter 250 μm). There are variations in intensity and bright and dark speckles are present in the image making the identification of any smaller circles difficult. In Fig.11, the more uniform intensity due to the dye solution reveals the presence of smaller groups of 125 μm circles as well, and the presence of 63 μm circles arranged in a vertical line is visible. Thus, the overall effect of using the dye solution is in making the background more uniform, thus improving the capability of resolving small structures.

Effect of temperature: The experiments described were all conducted at 24 °C. However, in general, the fluorescent intensity of rhodamine B varies with temperature. The average intensities of the images acquired by varying the temperature of the dye solution are plotted in Fig. 12. It is observed that the fluorescent intensity reduces with an increase in temperature, as also observed in literature [7]. In applications where the temperature of the solution changes, instead of using rhodamine B whose fluorescence intensity is temperature dependant, it would be preferable to use dyes such as rhodamine 110 whose fluorescent intensities are not sensitive to temperature changes.

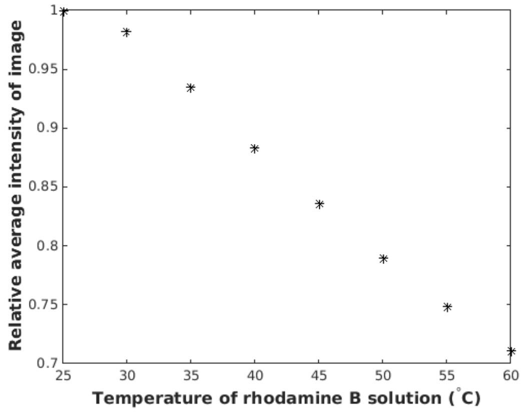

Fig. 12 Variation of the average intensity of images with temperature of the rhodamine B solution.

For a small field of view: Large regions of interest are required in general to visualize macroscopic spray structures and tip penetration, while small regions with a high light intensity are required for droplet sizing. To visualize a small region of interest, a Questar QM-100 long distance microscope (LDM) was coupled with the camera. The camera and the pulsed laser were aligned in a straight line, facing each other, as before. In this case also, the concentration of rhodamine was varied, and an optimum concentration of 50 mg of rhodamine B in 2 litres of distilled water was arrived at to obtain images with a uniform background. The region of interest to be illuminated here is small, and the intensities required are higher due to the higher f-number of the long distance microscope. Hence, unlike in the previous setup, the frosted glass plate of size 15 x 15 cm was placed next to the surface of the diffuser arrangement facing the concave lens, instead of being at a distance from it (i.e. the distance d = 0 in Fig. 3). The region of interest is of size 1.7 mm x 1.3 mm and is at a distance b from the diffuser arrangement. The distance c was 11.5 cm, b was 17.5 cm and a was 20 cm. Diffuser chambers of depths 5 cm and 10 cm were evaluated.

The normalized standard deviation obtained for images with this small field of view was 0.02 with a mean intensity value of 202. The image obtained was more uniform with few speckles compared to the image taken without using the diffuser arrangement. Figure 13 shows the spatial variation of intensity along a horizontal line of the image for a chamber of depth 5 cm for the small field of view. It is observed that the variation of intensity is small (as reflected in the standard deviation).

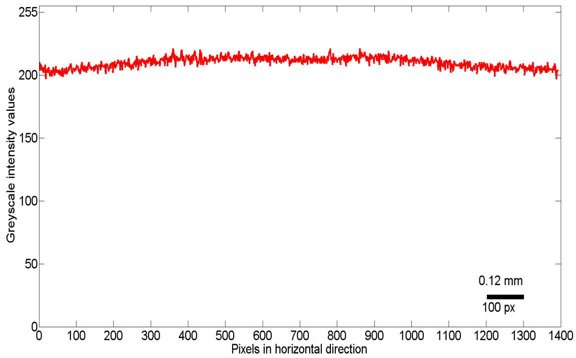

Fig. 13 Spatial variation of intensity along the horizontal direction for a chamber of size 5 cm.

As before, the effectiveness of the dye solution is visible from Figs. 14 and15 which show images of the same calibration target as earlier, imaged now with the long distance microscope. The diameters of the circles are 400 (partly visible at top right), 250, 125, 63 and 20 μm. In Fig. 14 where the laser, diverging lens and frosted glass plate are used to create the background, the presence bright and dark regions and variation in intensity due to speckles is observed. In Fig. 15, where the dye solution was used in addition, the circles are observed against a uniform background and hence can be easily processed by image processing software.

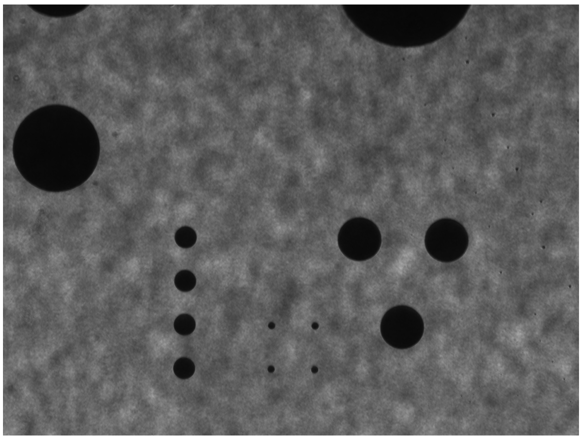

Fig. 14 Photographs of a target with dark filled circles taken with a CCD camera fitted with the long distance microscope. The image is illuminated by the laser. Only the diverging lens and frosted glass plate are used to diffuse the light.

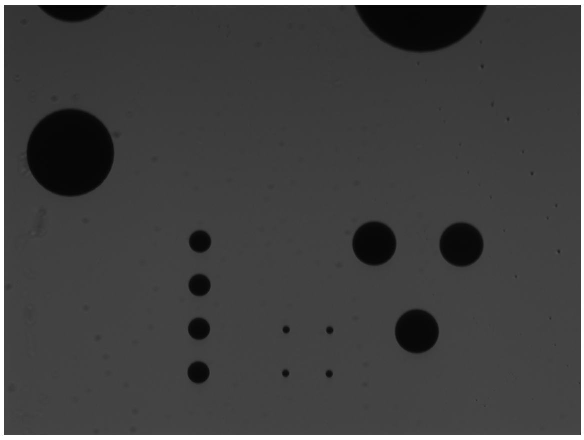

Fig. 15 Photographs of a target with dark filled circles taken with a CCD camera fitted with the long distance microscope. The image is illuminated by the laser. The diverging lens, frosted glass plate, and dye solution are used to diffuse the light.

5 Conclusions

An inexpensive laser diffuser is described, consisting primarily of a solution of rhodamine in distilled water in a glass box, which is easy to construct and can be used for laser diagnostic techniques requiring uniform illumination. For both small and large regions of interest, the variation of intensity values along the center of the image are plotted and it is observed that the variation in intensities is low with few speckles. The performance of the diffuser is comparable to that of commerical diffusers. Thus, the diffuser can be effective for dropsizing and backlit imaging applications.

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