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Detailed visualization of spray dynamics using Light Sheet Fluorescence Microscopic imaging

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Abstract
We demonstrate the use of Light Sheet Fluorescence Microscopic (LSFM) imaging for viewing the dynamic of atomizing sprays with high contrast and resolution. The technique presents several advantages: first liquid fluorescence gives a more faithful representation of the structure of liquid bodies, droplets and ligaments than Mie scattering does. The reason for this is that the signal is emitted by the fluorescing dye molecules inside the liquid itself and not generated at the air-liquid interfaces. Second, despite the short depth of field (~0.2 mm) obtained when using the long range microscope, the contribution of out-of-focus light is much smaller on a light sheet than on a line-of-sight configuration providing more clearly sectioned images. Finally by positioning the light sheet on the spray periphery, toward the camera objective, the effects due to multiple light scattering phenomena can be reduced to some extent. All those features provide, for many spray situations, images with high fidelity of the liquid fluid, allowing the extraction of the velocity vectors at the liquid boundaries. Here, double frame images were recorded with a sCMOS camera with a time delay of 5 µs between exposures. A typical pressure-swirl atomizer is used here producing a water hollow-cone spray which was imaged between 20 bars and 100 bars in liquid injection pressure. Such data are important for the validation of CFD models simulating liquid breakups in the near-field spray region.

Introduction
Light sheet fluorescence microscopy has become, during the past decade, one of the largest growing techniques in optical microscopy [1-3]. This interest has led to publications in high impact factor journals and the approach has been selected “Method of the year 2014” by Nature Methods [4]. Despite all those recent recognitions in the field of life science microscopy, it should be reminded that laser sheet Fluorescence imaging was already reported for macroscopic imaging more than 30 years ago by Melton and Verdieck for spray visualization [5]. This first attempt for spray study was applied in a hollow cone fuel spray. The spray was irradiated with a sheet of UV laser light, and with appropriate filters, two-dimensional sections of the liquid and vapour fluorescence of the evaporating spray were separately photographed. The separation of the liquid and gas phase was performed by means of exciplex fluorescence. From this publication it can be noticed that the resultant images were blurred due to the detection of multiple light scattering. The authors already mentioned this problem related to the spray optical density, stating: “*As long as the spray is optically thin, the fluorescence from a droplet is proportional to its mass*”. To face issues related to the contribution of multiple light scattering intensities Structured Laser Illumination Planar Imaging (SLIPI) technique was co-developed by Berrocal and Kristensson in 2008 [6,7], showing high contrast macroscopic spray structure of a hollow-cone water spray running at 50 bars pressure of injection. The technique was, then, further applies for both three dimensional reconstruction of the spray region [8-9] and single-shot Mie imaging of the near nozzle region [10-11].

Microscopic imaging is of strong interest for spray analysis, as the atomization process produces liquid structures and ligaments in the order of hundreds of microns, and droplets size ranging from several tenths to a few microns only. However, the transition from macroscopic to microscopic imaging is challenging for spray systems. In opposition with biological or medical samples, where a microscope objective can be placed very close to the sample, the same is not possible for spray systems as the droplets would impinge on the collecting lens. In addition if the spray is studied at high pressure and/or temperature conditions, within an optical chamber, then the minimum distance between the spray and the objective must be respected, usually in the order of a half to one metre. Basic magnification strategies by simply adding a number of extension rings would highlight artefacts from spherical and chromatic aberrations. Therefore the objective must be diffraction-limited and this over the entire field of the camera sensor to obtain the optimum clarity and resolution throughout the imaged field. Such requirements have been recently satisfied by the development of highly performing long-distance microscope

objectives such as the ones developed by “Infinity Photo-Optical Company” (e.g. K-Series Long-Distance Microscopes). Thanks to such objectives, microscopic shadowgraphy imaging has already been well applied for the study of Diesel sprays by Crua et al. [12,14]. Despite using a long-distance microscope which provides very short depth of field (~ several hundreds of microns), thus providing a section of the spray, the main limitation concerns the fact that this does not remove the detection of out-of-focus light. This effect is typical of line-of-sight imaging and also occurs for a backscattering source/camera configuration. By now using a light sheet of width equal to the depth of field of the camera microscopic objective, the illumination itself is optically sectioning the spray, strongly reducing the collection of out of focus light. By also positioning the light sheet at a desired location on the spray periphery, the amount of induced multiple light scattering between the light sheet and the camera can somehow be controlled, allowing extracting valuable information on liquid breakups on the spray periphery even under challenging situations.

In this article we present, to the best of the authors’ knowledge, one of the first applications of LSFM for spray diagnostics. A comparison of the technique with other imaging configuration is first given, to highlight the advantages of LSFM. Then the technique is applied in a hollow cone spray generated by a pressure swirl atomizer running between 20 bars and 100 bars water pressure of injection. To observe the time evolution of the liquid structures near the nozzle tip, series of two images have been recorded with 5 µs time duration between exposures.

2) Material and methods

The spray investigated in this article is a steady state (continuously running) hollow-cone water spray of 60° full spray angle and created using a pressure swirl nozzle of 1mm orifice diameter (Lechler, ordering no. 216.324). It is illuminated from two successive laser pulses of 10 ns pulse duration, generated from two Nd:YAG lasers emitting at 532 nm wavelength. The two laser beams, which are crossed polarized, are spatially recombined using a polarizer beam splitter. The spray is imaged at 90º using a long-range microscope objective, Model K2 DistaMax, mounted on a sCMOS LaVision camera (2560x2160 pixels). The field of view was in the range of 6 mm x 5 mm resulting into 2.3 µm in pixel resolution.

The time delay between the two exposures is fixed to 5 µs and images are recorded using the double frame mode of the camera. A laser sheet of 6 mm in height is formed with an adjustable slit allowing fixing its width as desired (in this case ~300 µm). This way, the thickness of the light sheet can be accurately adjusted to match the depth of field of the long distance microscope objective. Note that using light sheets narrower than the imaged liquid structures can lead to “cutting effects” of those structures. This is particularly true at low injection pressure where large ligaments are generated. The spray is running at room temperature and atmospheric pressure conditions. The injection pressure was fixed from 20 to 100 bars for every 20 bars step. The injected water was seeded with a translucent organic dye, Eosine Y (Xanthene derivative), which is characterized by a quantum yield of 0.36 when mixed with water and 0.68 when mixed with Ethanol according to [15]. The fluorescence emission spectrum peaks at 550 nm when excited at 532 nm. A 532nm notch filter with optical density 6 blocking is fixed on the camera objective to reject the Mie scattered light from the excitation source. Due to the short depth of field of the long range microscope (~200 µm) and the conical structure of the spray a large part of the spray was out of focus. To solve this issue, the injector has been rotated by ~30° angle in order to have its imaged surface conjugates to the image plan of the camera. This is shown on the photographs in Figure 1.

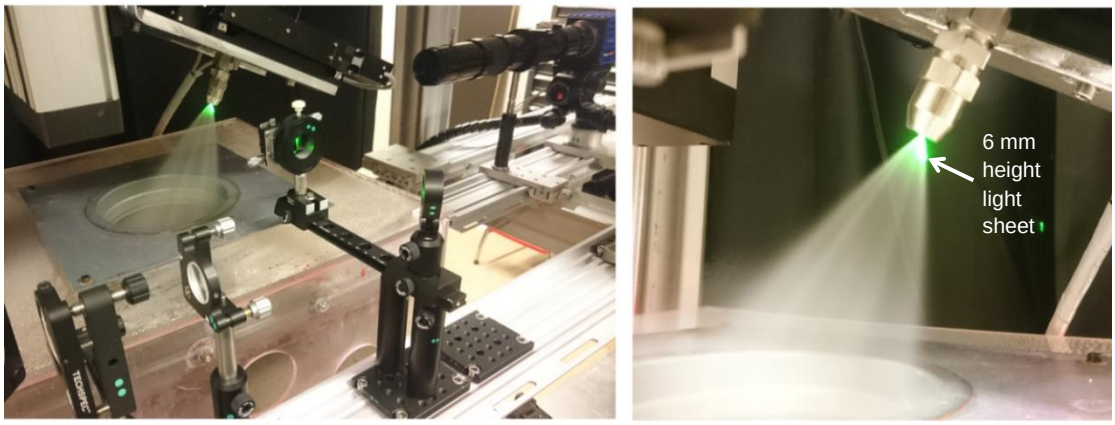

Figure 1. The optical arrangement with the long range microscope objective is shown on the left while the right image shows the illuminated area of the spray. The width of the light sheet is fixed to match the depth of field of the camera using an adjustable slit in front of the spray. The injector is tilted by 30° angle from the horizontal direction in order to keep a sharp image focus over the full field-of-view. Here, the spray is running at 40 bars pressure of injection.

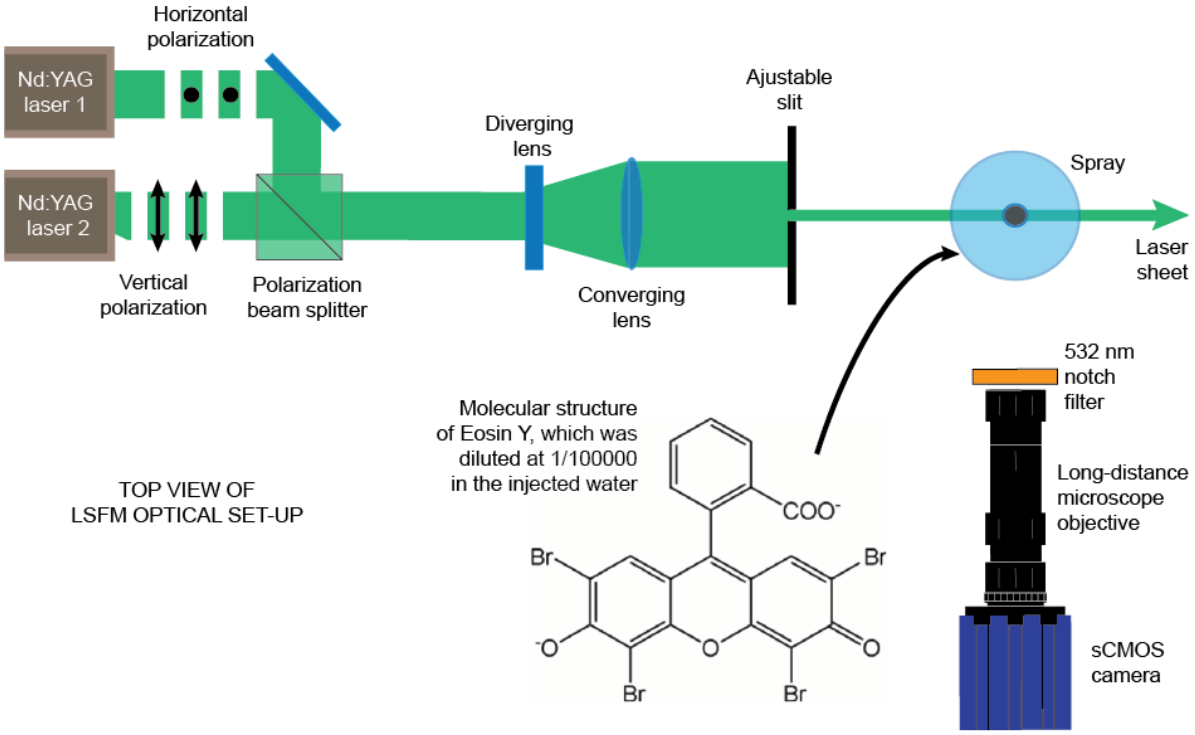

Figure 2.. Schematic of the optical arrangement for LSFM. An adjustable slit has been used instead of a cylindrical lens to create a light sheet of desired thickness (slightly larger ~300 μm than the depth of field of the long-distance microscope objective). A too thin light sheet could cut some large liquid structured at low pressure of injection while a too large light sheet will contribute to undesired out-of-focus signal. A notch filter is used in front of the objective to reject the 532 nm contribution and collect the entire fluorescence signal. Eosin Y is mixed with the injected water to induce fluorescence.

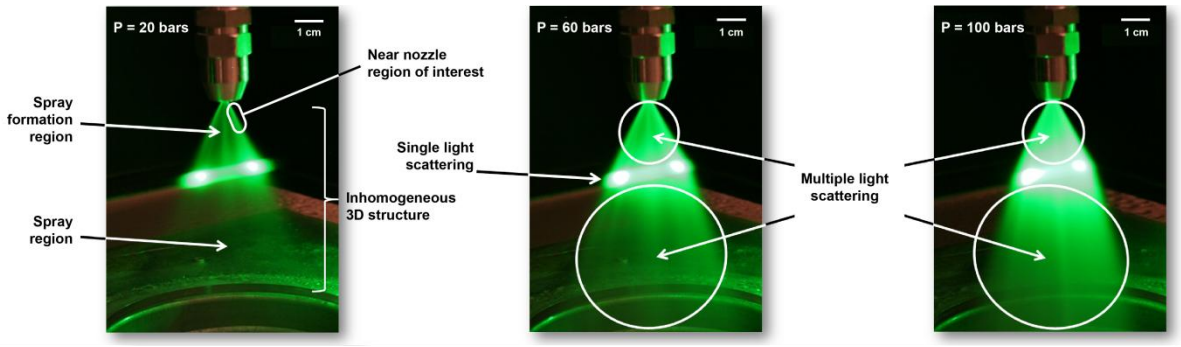

Figure 3.. Occurrence of multiple light scattering when increasing the pressure of injection for the studied hollow cone water spray. In these illustrative photographs, a 532nm CW laser beam is crossing the spray at 3 cm below the nozzle tip and the pressure of injection is increased from 20 to 100 bars. Note that for all presented results only the near field region, at distance 3 to 8 mm below the nozzle orifice is imaged (as indicated on the left-side picture).

To illustrate the effects of multiple scattering and the optical density of the probed spray at different liquid pressure of injection three photographs are as shown in Figure 3. Note that in the experiment describe above; the imaged part of the spray is located right after the nozzle tip. However, due to the tilt of the injector, the first 3 mm were hidden by the injector itself (see Figure 1). Thus, the imaged area corresponds to ~3 to 8 mm below the nozzle orifice.

2) Examples of comparison between LSFM and other optical imaging configurations

1.1) Comparison with light sheet Mie-scattering microscopic imaging

One important aspect of the work presented here is to compare the benefits of LSFM with other optical configurations and detection schemes. In this sub-section we analyse the Mie scattering detection by simply removing the notch filter in front of the camera shown in Figure 4 and by injecting water without adding any fluorescing dye. Note that here we define “Mie scattering” by the light being elastically scattered by any liquid elements present in the spray and not by the spherical droplets only.

While for macroscopic imaging of the spray region, Mie and LIF images usually appear quite similar (apart for the light intensity dependence to droplets surface for Mie and to droplets volume for LIF), this differs strongly in the case of microscopy where the irregular liquid elements are resolved. This observation is illustrated in Figure 4 where the spray is running under the exact same conditions between the Mie and LIF detections: For the Mie scattering detection, parts of the spray are not even visible, especially at low pressure of injection where long irregular liquid elements are present. This can be explained by two reasons:

First the Mie scattering generate a signal only at each liquid-gas interfaces, where there is a change in refractive indices, but not inside the liquid structures themselves (where the refractive index remains constant). Therefore planar Mie images of highly atomizing spray will provide a more faithful representation of the spray than for poorly atomized sprays. This can be seen by increasing the pressure of injection up to 60 bars.

The second reason is that some of the irregular liquid elements directly reflect part of the incident light into the camera producing some light spots of very intense signal, reducing the camera dynamic range or directly saturating the camera sensor. As those intensity contributions originate from direct reflections, the corresponding light keeps most of the incident polarization. Therefore, one way to reduce those effects is to use a linear polarizer orientated in opposite direction than the incident polarization in front of the camera objective. This would increase the camera dynamic range but it will not correct for other artefacts induced by the nature of the Mie scattered light.

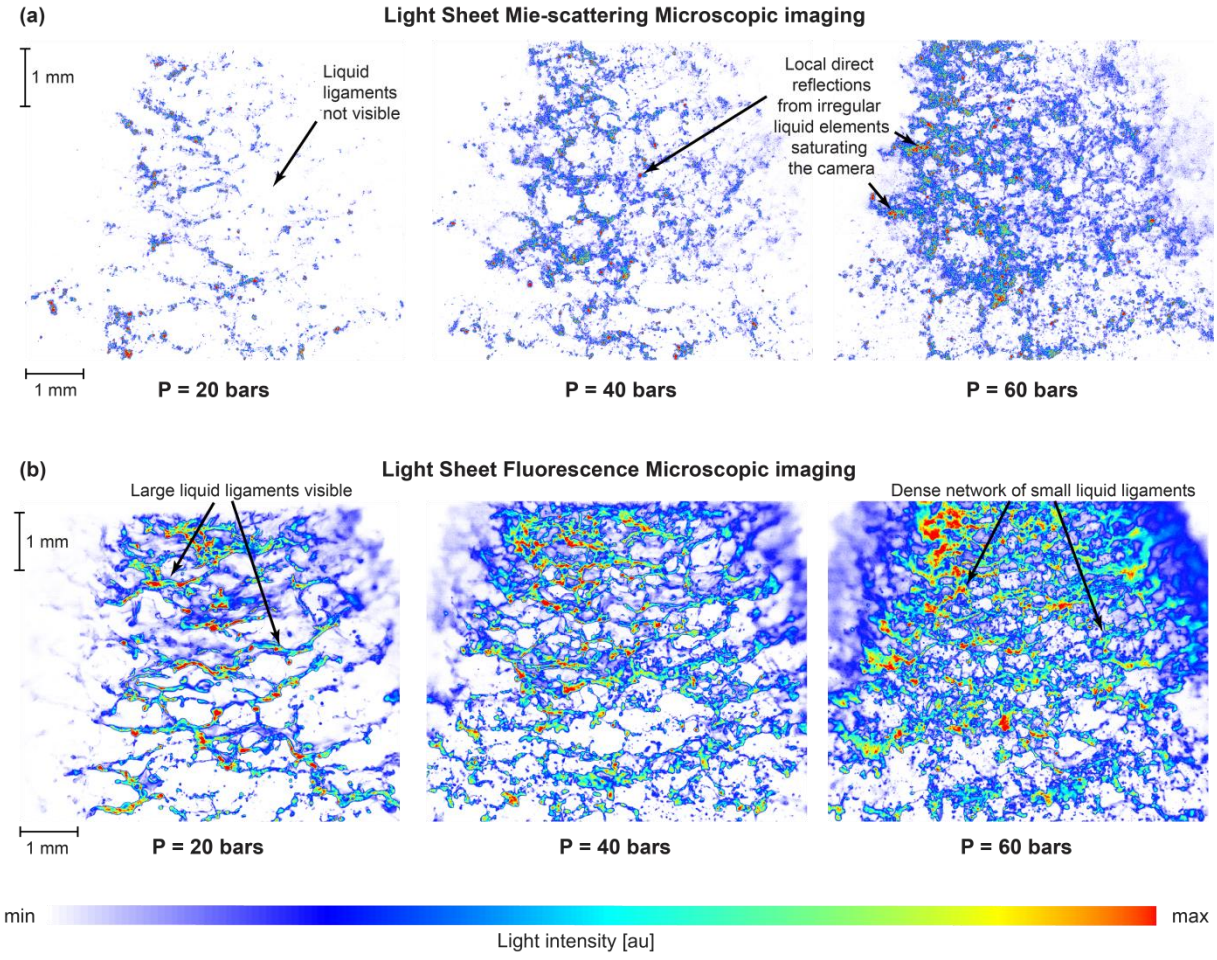

Figure 4. Comparison between light sheet Mie-scattering microscopic imaging and LSFM. While the Mie scattering images are lacking spray information and locally saturate the camera sensor, the LSFM images show a much more faithful representation of the spray structure.

In opposition with the Mie detection, the LSFM images reveal a more faithful representation of the spray structure. This can be explained by the fact that the collected signal does not only come from the liquid-air interfaces, but from the liquid structures themselves which contain the dye molecule. Thus, the light which is being refracted within the liquid structures excites the dye molecules resulting to the glow of the entire illuminated liquid body. While the volumetric dependence of the signal might limit the dynamic range of the camera, this appears not to be as problematic as the effects induced by the strong Mie reflections.

1.2) Comparison with Back Fluorescence Microscopic imaging

In this sub-section a comparison between Back Fluorescence Microscopic (BFM) imaging and LSFM are shown for the hollow cone water spray running at 30 bars pressure of injection. The spray is imaged with the same camera and long-distance microscope objective and running at identical conditions for both detection cases. The transition between the two optical configurations is quickly operated by means of a flip mirror. The optical arrangement of the back-Fluorescence detection is shown in Figure 5(a).

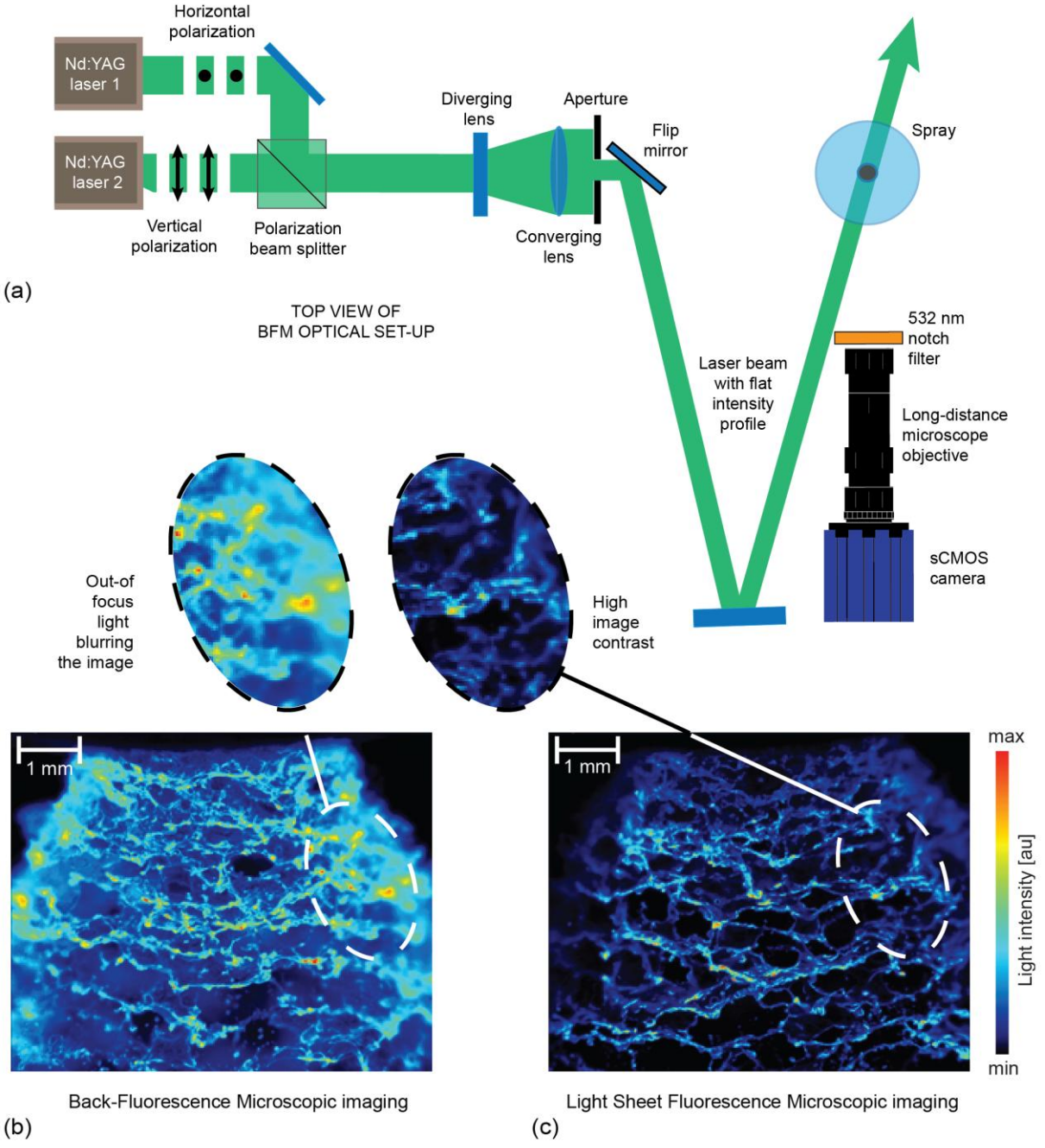

Figure 5. (a) schematic of the optical arrangement for Back Fluorescence Microscopic (BFM) imaging. A flip mirror is used to switch in between the two optical arrangements, BFM and LSFM. (b) and (c) is the resulting image comparison between BFM and LSFM. It is seen that the contribution of out of focus light in BFM is altering the image contrast, which is not the case for LSFM.

It is observed from Figure 5(b) and (c) that the image contrst is significantly enhanced with LSFM thanks to the reduction of out of focus light generated when using BFM.

1.3) Comparison with white light shadowgraphy

The purpose of this sub-section is only to illustrate the possible advantages of LSFM over shadowgraphy microscopic imaging. In contrast with the rest of the article where the same hollow-cone water spray is studied, here, two GDI sprays are investigated at 80 bars pressure of injection, for comparison purpose only. It should be noted that this comparison is not fully fair, as it is not the same exact spray system which is investigated and the used imaging systems (illumination wavelength, cameras and long-distance objectives) are not identical. Therefore, this comparison only intends to highlight the benefits in using LSFM.

Figure 6 shows the image comparison between the two approaches. Image (a) corresponds to a GDI injector studied with white light shadowgraphy, using short pulsed LED illumination by H. Zaheer [16]. The author mention in his M.Sc. thesis that the injector is oriented in a way such that its interface is not obstructed by other jets and can be viewed clearly.

In opposition, the second GDI injector, which belongs to LTT-Erlangen (Lehrstuhl für Technische Thermodynamik), had no specific orientation as it can be seen in (b). In this case by using LSFM, the effects of the other out-of-focus plumes do not affect much the image contrast and quality of the images spray jet. It is also observed that the nozzle orifice is visible and that the dimension of the jet itself does not match with the orifice diameter. This is a desired design for inducing cavitation effects prior to injection in order to enhance primary atomization. Those jet instabilities are visible from shot to shot using LSFM.

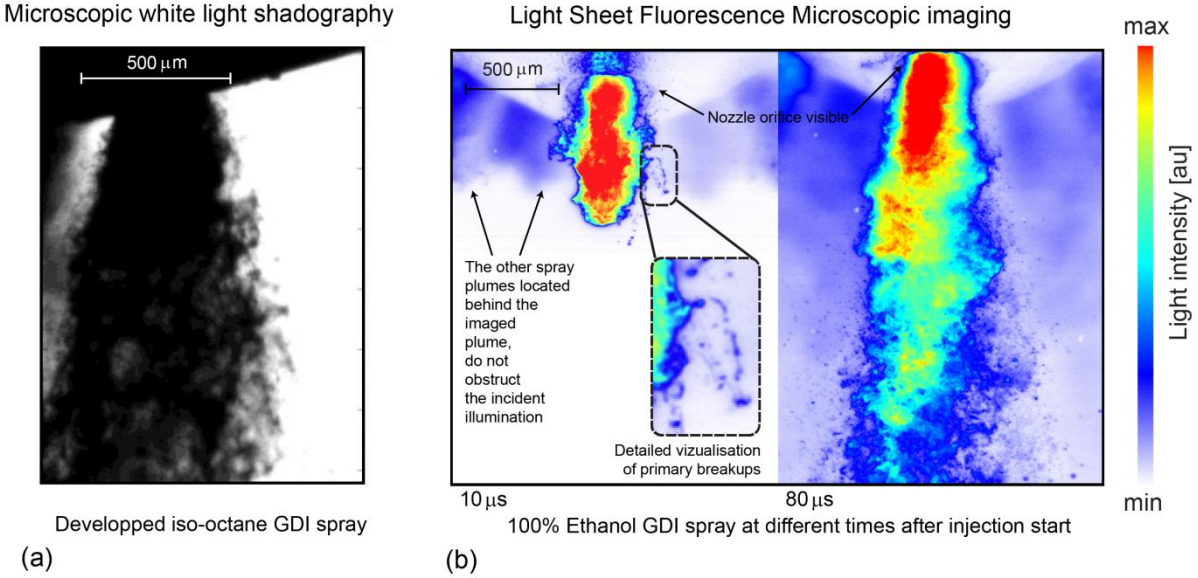

Figure 6. Comparison of microscopic images for two GDI sprays injected at 80 bars pressure of injection: In (a) a light sheet is used to illuminate the spray plume from the left hand side and the fluorescence signal is recorded. High resolutions detailed of the liquid gas interfaces are clearly visible together with the nozzle orifice [recent results produced at LTT-Erlangen, Germany]. In (b) an example (from H. Zaheer [16]) of back-illumination using high-power pulsed LEDs, is shown creating a shadowgraphic image of a similar spray.

3) Results and Discussion

The LSFM images of the hollow cone water spray, running from 20 bars to 100 bars pressure of injection, are shown in Figure 7. For each indicated injection pressure two magnified images are provided for a better visualization of the liquid structures. The time interval between in-between the two magnified images is 5 µs, allowing the observation of liquid displacement and deformation.

- At 20 bars pressure of injection, large horizontal liquid filaments are observable below the nozzle tip. Even though the pressure of injection remains relatively low, there is no presence of a continuous liquid sheet, but rather of a network of interconnected ligaments. Those horizontal ligament/filaments can be over a millimetre long and ~hundred microns in width. The strong fluorescence originating from those structures indicates that they are fairly thick (in the third dimension). After 5 µs, it is observed that those structures do not deform much and have a velocity in the range of 50 m/s.
- At 40 bars and 60 bars pressure of injection a broadening of the ligaments in the vertical direction is apparent in comparison with the 20 bars case. However the reduction in fluorescence intensity maxima indicates that

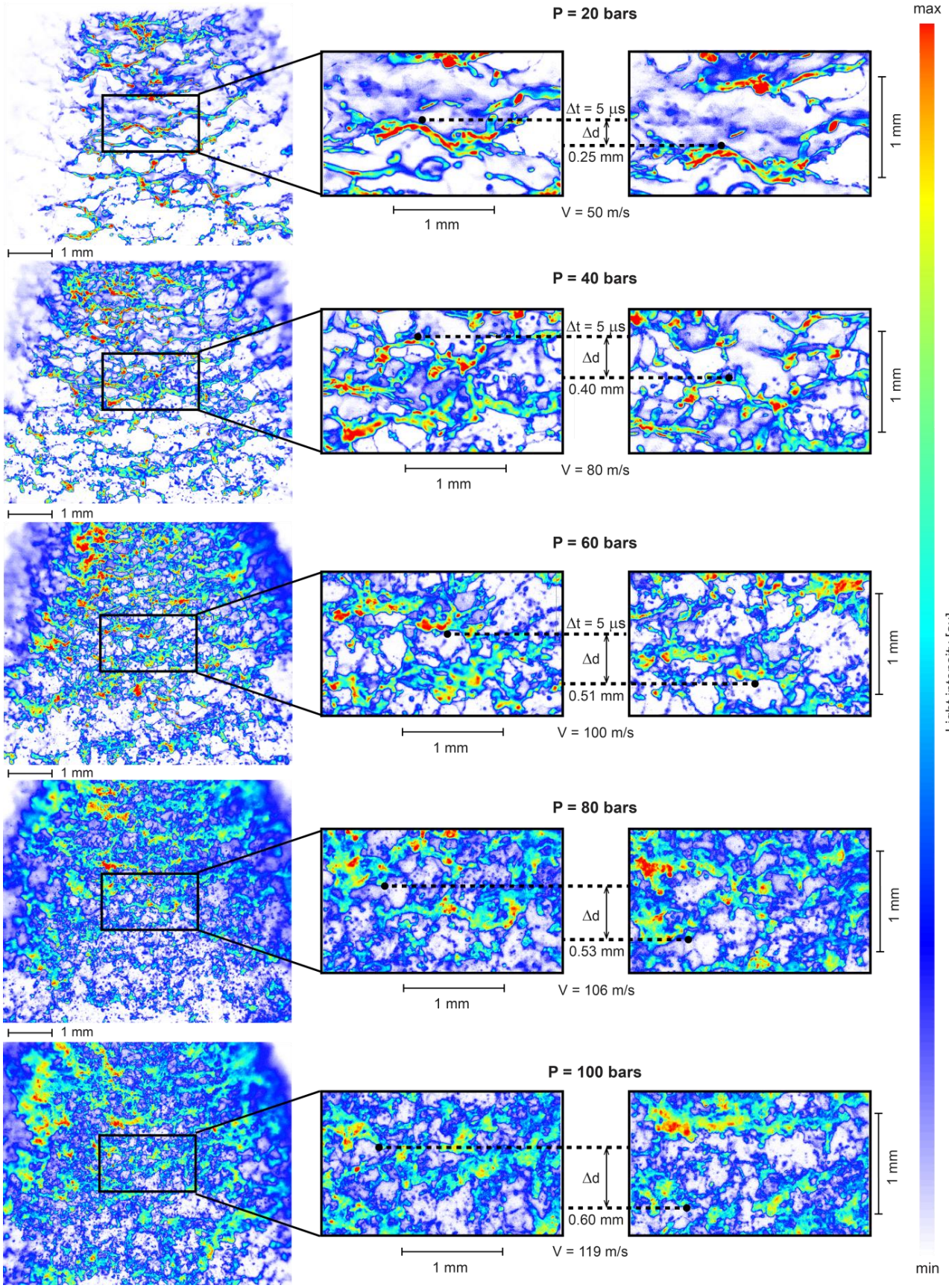

Figure 7. LSFM images of the liquid structures in the near field region (between 3 and 8 mm below the nozzle tip) of a hollow-cone water spray. The water pressure of injection ranges between 20 and 100 bars. Zoomed views are shown on the right side where the displacement of liquid structures can be observed when applying a time delay of 5 µs between exposures. While at low water injection pressure the shape of liquid bodies remain identical between on the two exposures, this is not true anymore at high pressure of injections where the liquid structures are subjected to rapid deformations.

those illuminated structures are of smaller volumes. Therefore it is deduced that liquid body are thinner in the third dimension and will be further responsible to the formation of smaller droplets. The displacement of the liquids bodies within the indicated field of views ranges around 80 m/s and 100 m/s respectively. Even though some deformations are now visible on those structures, after 5 μs, liquid patterns can be easily recognised and tracked.

- At 80 bars and 100 bars pressure of injection, the observed “liquid network” do not appear horizontal anymore with the presence of less and smaller voids in the images. Once again, the detected fluorescing signal has reduced in comparison with the previous cases demonstrating the presence of even thinner liquid structures. The velocities of those liquid structures are ~106 m/s at 80 bars and ~119 m/s at 100 bars water injection pressure. In those cases, the deformations of the liquid bodies within the 5 μs time separation are really important and it becomes difficult to track any “identical” liquid structure.

Conclusions

Light Sheet Fluorescence Microscopic imaging has been applied for the study of an atomizing water spray generated by a pressure swirl atomizer. This attempt, which has not been fully investigated in the past, is successfully achieved here thanks to:

- The recent development of highly performing long-distance microscope objectives where the limit of image resolution was here due the pixel resolution, and not by the imaging system.
- The use of highly sensitive sCMOS cameras having around 55% quantum efficiency allows not using any intensifier optimizing the full pixel array (2560x2160) of the sensor.
- The use of a fluorescing dye with good quantum yield in order to generate fluorescence signal as strong as possible even for a standard 532 nm excitation wavelength.

It is observed that the LSFM provide a higher image contrast than any of the line of sight configurations (forward and back detection). In addition it offers the possibility to clearly observe the nozzle orifice itself, which is hardly achievable with shadowgraph images. Finally, for the study of the near nozzle region, where evaporation is not yet occurring, the fluorescence signal remains a faithful signature of the liquid bodies themselves. This appears not to be the case for the Mie scattering detection, where microscopic representation of the spray is questionable on a light sheet configuration. Series of LSFM spray images can be of great importance for better understanding the atomization process occurring in the spray formation region and can be very attractive due to the simplicity of its optical arrangement and fairly low cost.

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