Mass Flux Imaging in Sprays

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The paper presents an advanced laser imaging technique for planar mass flux measurements:
Planar Laser-Induced-Fluorescence (PLIF) and stereoscopic Particle Image Velocimetry (PIV) are simultaneously applied for measuring planar, spatially resolved mass flux distributions in sprays at different positions from the nozzle.
The laser induced measuring signals are obtained applying laser light sheet illumination using a double pulse PIV laser system as a light source. The velocity component vertical to the laser light sheet is obtained from the stereoscopically measured PIV signals. The simultaneously detected LIF signal is a measure of the liquid density (mass per unit volume). The combination of both imaging techniques leads to planar mass flux or momentum flux distributions, which provide also information about important spray parameters such as spray pressure, normally measured applying direct contact methods.
Furthermore, evaporation phenomena can be deduced from variations of the total mass flux with increasing distance from the nozzle, because under non-evaporation conditions the total mass flux through a plane perpendicular to the spray axis is constant.
Results from tracer seeded water sprays are presented using this new imaging technique.

1. Introduction

The knowledge of spatially resolved mass flux measurements in sprays is an important issue.
Complementary to drop size and spray geometry, the mass flux value is suitable to characterize spray (nozzle) impact values, which are of special interest for industrial applications like spray cooling, painting, drying, chemical and fuel injection processes.
For example the understanding of spray–gas momentum transfer, which is a crucial parameter for the development of gasoline direct injection systems [1], is mentioned here.
Mass flux measurements in sprays are obtained pointwise with high temporal resolution applying Phase Doppler Anemometry (PDA) [2,3]. Planar mass flux measurements based on local PDA measurements are obtained by scanning which is time consuming. Mechanical patternators collect simultaneously the liquid mass in containers at different spatial positions over an integrated time period. The limited spatial resolution in combination with the lack of capability for on-line operation are the main disadvantages of these conventional patternators.
Arndt et al. [1] have used a high speed strain gage sensor to measure time resolved the total mass rate of different spray injectors.

Laser light sheet imaging techniques based on Mie scattering and LIF are applied for spray visualization and patternation, liquid and vapor mass distribution, global spray droplet sizing (Sauter Mean Diameter) and flow field analysis of the gas and liquid phase, respectively [4].
A comparison of laser light sheet imaging with PDA for droplet size measurements was presented by Leong [5] and Jermy [6].

Laser light sheet imaging based on simultaneous PIV and LIF measurements can record on-line instantaneous mass flux distributions with high spatial resolution. Ultimately, high speed laser light sheet imaging with kHz framing rates has the potential to resolve transient mass flux fluctuations in space and time.

2. Mass flux

The mass flux density *F* of a spray expresses the amount of liquid flowing through a given area per time unit. This value is proportional to the local mass density *r* and the velocity **v** of the fluid.

$$F = r \cdot v \qquad \text{(Eq. 1)}$$

The mass flux density and the velocity are vector quantities. In this case, only the mass flux component F_z perpendicular to the measurement plane is probed. Both quantities, the density and the velocity can be measured simultaneously by the presented laser imaging system. The relative density will be measured by the fluorescence signal arising from a tracer added to the liquid. The velocity is measured with a stereoscopic PIV setup.

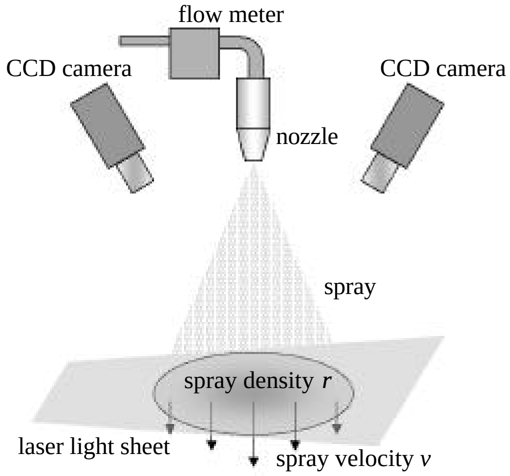

Fig. 1 Measurement principle with a laser imaging system.

A calibration of the system is achieved online from a conventional flow meter assuming the conservation of mass. This means that the liquid does not evaporate and that the full spray field is covered by the laser diagnostic system.

2.1. Laser induced fluorescence

Laser induced fluorescence (LIF) reveals the mass density of the spray. The liquid is doped with a small percentage of a fluorescence active tracer. Under the assumption of a constant tracer concentration, the LIF signal strength is proportional to the density of the liquid. When detecting the signal from a light sheet of thickness d_z which will be collected through the imaging system with a solid angle of *W* from a probe volume *V* under perpendicular viewing angle, the number of collected photons N_{LIF} is given by:

$$N_{LIF} = N_L \cdot \Omega \cdot h \cdot \frac{s \cdot n \cdot V}{d_z \cdot d_y} \qquad \text{(Eq. 2)}$$

where N_L is the number of laser photons in the probe volume, *h* the LIF quantum yield, *s* the differential absorption cross section, *n* the number density of the tracer, and d_y the dimension of the probe volume in the direction perpendicular to the laser beam. The number density of the tracer is directly proportional to the mass density r of the liquid. Hence, the LIF signal S_{LIF} on the CCD chip, which is the fluorescence intensity I_{LIF} per projected pixel area A_{pix}, is directly related to the mass density:

$$r = c_{LIF} \cdot S_{LIF} \ , \qquad \text{(Eq. 3)}$$

where c_{LIF} is a calibration constant for the detection system.

2.2. Particle image velocimetry

The velocity of the spray is determined with a stereoscopic PIV system. Only the out of plane component v_z, which is perpendicular to the light sheet, will be used for the mass flux measurement. In contrast to the density information, the velocity is measured in absolute values. Of course, the velocity determined by PIV is an averaged velocity, which does not resolve the speed of individual droplets. PIV has a bias to the velocity of the bigger particles, especially in the case described in this work, because the signal strength is proportional to the volume of the droplets.

2.3. Mass flux density

The product of the LIF signal and the out of plane velocity reveals the relative local mass flux density. For a calibration, the total mass flux $\dot{m}$ measured by the flowmeter is taken into account. The integration of the mass flux density over the whole spray intersection reveals the total mass flux:

$$\dot{m} = \int_{spray\_area} r \cdot v_z \, dA = \sum_{all\,pixel} \left(r \cdot v_z \cdot A_{pix} \right). \qquad \text{(Eq. 4)}$$

This relation allows the calibration of the mass flux density images. The calibration constant c_{LIF} can be determined by

$$\dot{m} = c_{LIF} \cdot A_{pix} \cdot \sum_{all\ pixel} \left(S_{LIF} \cdot v_z \right) \ . \qquad \text{(Eq. 5)}$$

After calibrating the mass flux density, the same calibration constant can be used to calibrate the LIF images to reveal an absolute spray density map according to Eq. 3.
Multiplying the mass flux distribution with the velocity field leads to a spatially resolved momentum flux density P

$$P = r \cdot v^2 . \qquad \text{(Eq. 6)}$$

The momentum flux is directly correlated with the pressure a spray applies when impinging to a wall or surface.

3. Experimental setup

The experimental setup consists of a continuously operated nozzle from Hago, type 2.00-45-B-SOLID, with water at 6 bar (87 psi) pressure. The water is doped with an appropriate tracer, which will be excited at 266 nm. The measurement plane is located 40 mm below the orifice.
The laser system is based on a double cavity frequency quadrupled Nd:YAG, type Solo 120 from NewWave, which provides two pulses of 266 nm radiation, each with approximately 15 mJ energy. The light from the laser is formed to a sheet of approximately 15 cm width and less than 1 mm of thickness, which defines the measurement plane. The camera system consists of two double frame SVGA CCD cameras, type FlowMaster 3S from LaVision, with Scheimpflug optics and 28 mm lenses with bandpass filters for the fluorescence emission.

The cameras are arranged in a stereoscopic setup tilted about 35° from a perpendicular view. Both cameras receive two images, each from one of the laser pulses.

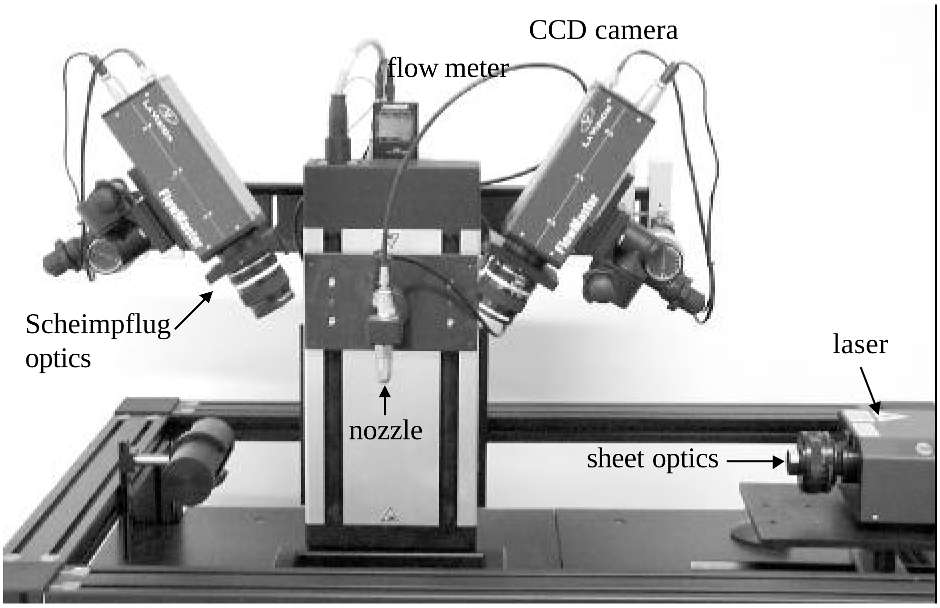

Fig. 2 Experimental setup.

The double images are processed with a stereo PIV algorithm to provide a 3 component velocity vector field. The same images are also used for the LIF intensity field, which represents the density information. A series of 100 images is averaged to provide a mean velocity and relative density field, $v_z(x,y)$ and $S_{LIF}(x,y)$ respectively. For the mass flux calibration, a flow meter measures the total flow rate.

3.1. Evaluation

The particle density for the PIV measurement is determined by the spray properties. In our case the weak droplet density leads to a poor signal quality for the single shot images. In order to improve the results of the PIV measurements, the average correlation method can be applied. With this method, the correlation map derived from each single image is averaged over all 100 images, before the velocity vector field is determined [7]. The resulting 3 dimensional velocity field is shown in Fig. 3.

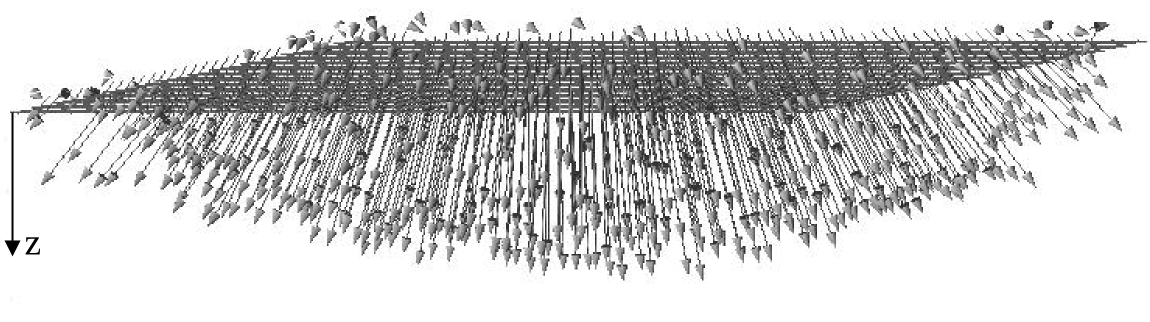

Fig. 3 Resulting velocity field.

The maximum velocity in z direction in the center is about 17.9 m/s.
The LIF images are averaged and the image distortion due to the oblique viewing angle is corrected. The resulting LIF images is shown in Fig. 4.

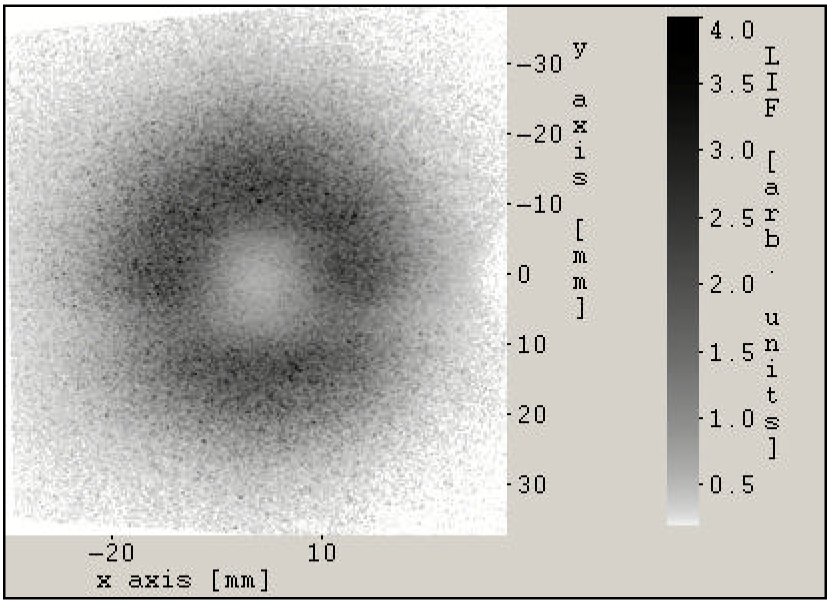

Fig. 4 Averaged fluorescence image.

The fluorescence image and the velocity field are multiplied to achieve a relative mass flux map. The sum over this map is correlated to the total mass flow read out from the flow meter with $\dot{m}$ = 90.8 g/min according to Eq. 5.

3.2. Validation

We validated the optical patternation with a simple mechanical patternator. A tube with 9 mm inner diameter was used to collect the spray fluid at different positions in the measurement plane. At each position, a camera image was taken to allow a correlation of the regions of the mechanical patternation to the optical measurements.

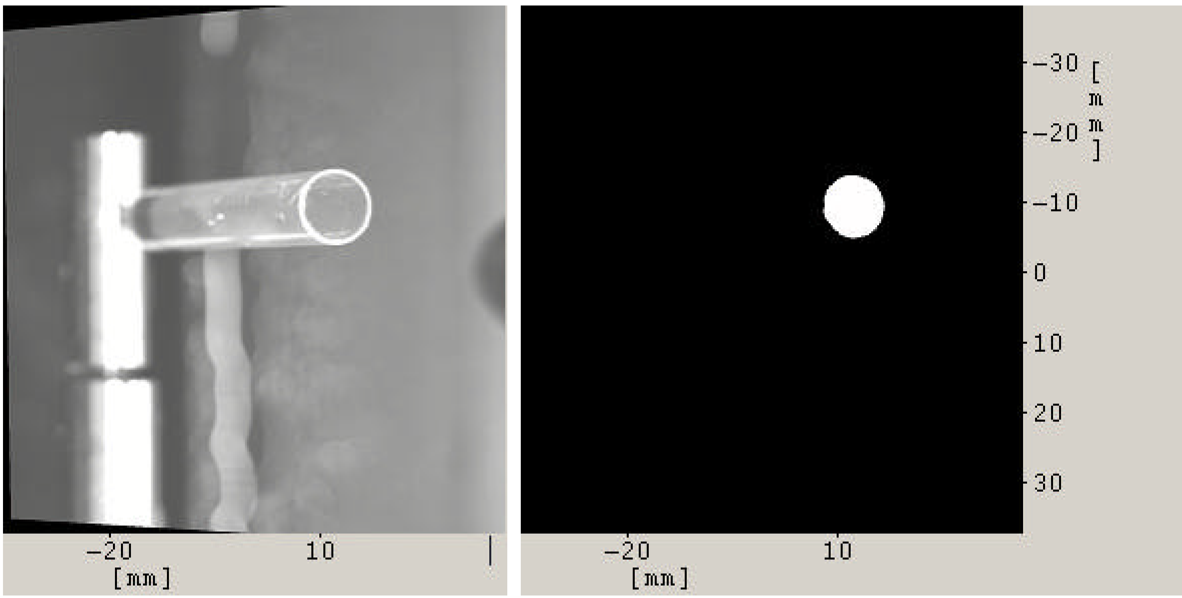

Fig. 5 Location of the mechanical patternator tube (left) and derived image mask for the optical mass flux measurement (right).

The measurement plane was scanned with the tube at different locations. At each location the spray fluid was collected for a certain time and the average mass flux for the tube's orifice area was calculated.

4. Results and Discussion

4.1. Measurement results

The resulting mass flux map is shown in the following figure Fig. 6.

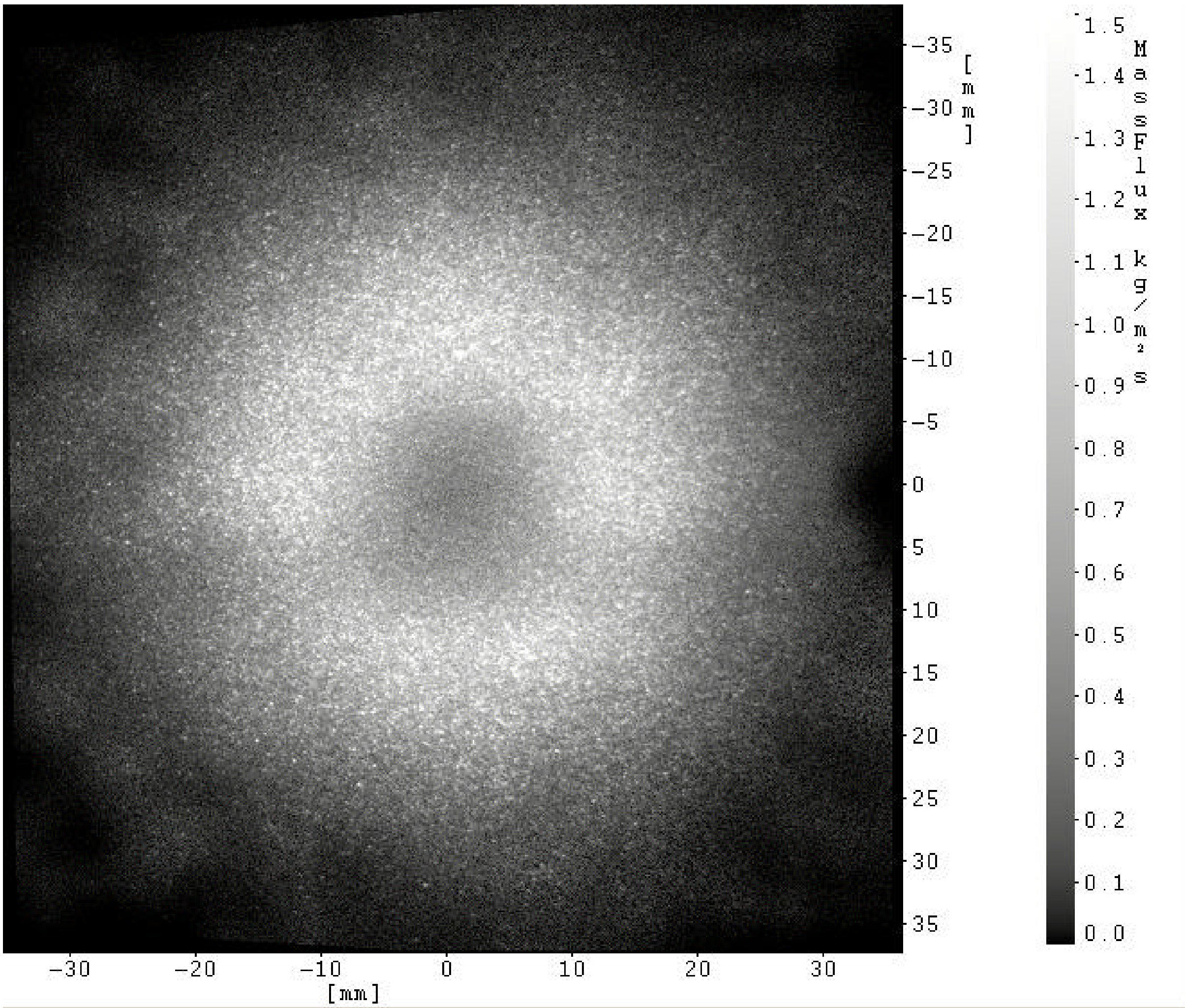

Fig. 6 Mass flux density map derived from optical measurement.

The following diagram Fig. 7 shows a comparison between the optical measurement and the mechanical patternation. The presented values for the optical patternation are obtained from an averaged profile of 8 mm width parallel to the y axis. The results from the mechanical patternation are drawn at their center location.

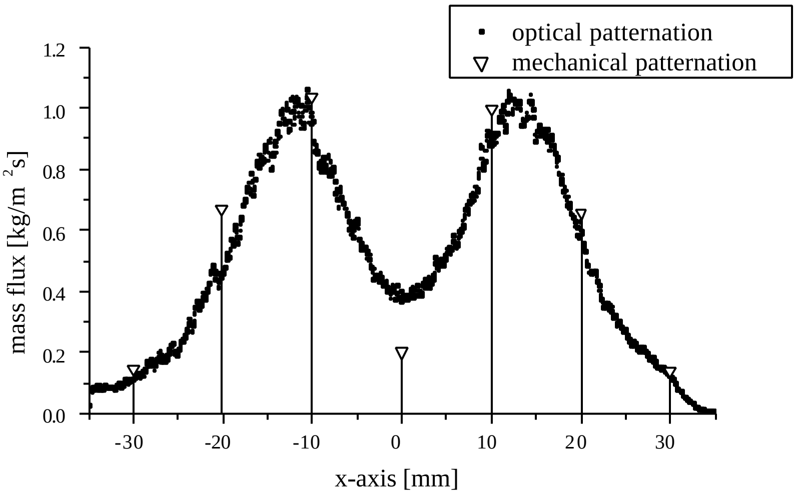

Fig. 7 Mass flux across central line through the spray.

The values correspond to each other except in the center location. In total, 19 different locations in the measurement plane have been compared. The averaged deviation between the optical and mechanical measurement is about 14.2 %, except the center location.

4.2. Discussion

The results show a good agreement between the presented optical method and the simple mechanical patternation used. The advantage of the optical method is its high spatial resolution, the non-intrusive method and the short measurement time. The main uncertainty for the measurement is the bias of the PIV method to the velocity of large droplets, which may be the reason for the high deviation in the center region. An investigation with a method revealing the individual droplet size and velocity can obtain more precise results and in this case the source of the deviation. Possible methods are Mie Scattering Imaging (MSI) [8,9], high-magnification shadowgraphy, or PDA. Nevertheless, the presented imaging technique has complementary benefits compared to the others, like instantaneous planar results with high temporal resolution.

4.3. Outlook

The technique was applied to a non-evaporative fluid. With evaporative fluids, the mass conservation is not fulfilled any longer, which is the basis of eq. 4. Nevertheless, using the presented technique one can measure the evaporation between two spatially separated measurement planes under certain conditions. Evaporation leads to a loss in total mass flux from one plane to the next. For measuring under such conditions it is essential that the fluorescence signal arises from the liquid phase only, which can be achieved by a combination of exciplex tracer techniques.

5. Conclusion

It has been demonstrated that laser light sheet imaging provides useful information for the development as well as quality control of sprays by providing high resolution, on-line measurements of the liquid mass flux without disturbing the two-phase flow.

6. References

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