Analysis of the fluorescence signal from a single droplet using a model based on the Lorenz Mie Theory and on ray tracing methods

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Abstract

A fluorescence model based on the Lorenz Mie Theory and on ray tracing methods is applied to a liquid droplet seeded by a dye. An analysis of the bias in the Planar Droplet Sizing and of the signal profiles obtained on a detector with droplets crossing high focused laser beams is proposed.

Introduction

Laser Induced Fluorescence (LIF) is commonly applied in two-phase flow diagnostics, relying on the excitation of fluorescing molecules at a specific wavelength [1–3], and on the conversion of the fluorescence signal into a voltage using an appropriate detector, or into an image using an intensified camera, possibly with bandwidth filters. In the Planar Droplet Sizing (PDS), the combination of the fluorescence with the Mie scattering provides ideally the Sauter Mean Diameter (SMD) field of the spray [3], assuming that the amplitude of the fluorescence scattering depends on the droplet volume and the amplitude of the Mie scattering on the droplet surface area. Nevertheless, a bias is induced in the fluorescence scattering, caused either by the absorption of the laser fluence by the dye, or by the focusing of the laser or fluorescence rays when they traverse the interface entering or leaving the droplet. An other application of the fluorescence lies in the illumination of a moving droplet with highly focused laser beams and in the measurement of the fluorescence signal with one or several detectors at different positions regarding the droplet trajectory. Information about droplet velocity, direction angle or size can be deduced from the signal analysis on each detector

Materials and Methods

The calculations are performed with a fluorescence model [1] based on the Lorenz Mie Theory (LMT) and on ray-tracing methods, assuming that the droplet is spherical. The LMT theory [4] provides either the axisymmetric fluence field inside the droplet considering the Laser as a monochromatic plane wave, or the 3D fluence field obtained with the focused beams. In both cases, the liquid is assumed as a homogeneous mixture with a given absorption coefficient. The ray tracing method (Fig. 1, Fig. 2) relies on the geometric optics to determine the direction inside the droplet of each fluorescence ray emerging from the surface, and hence to deduce its fluorescence value by integrating the fluence along the ray, considering the fluorescence scattering in the liquid phase as isotropic, with a different wavelength than the Laser one and proportional to the local fluence.

The focusing of the laser rays when they traverse the interface can be disabled for the fluence field by using a simpler model based on the Beer Lambert absorption in the laser beam direction. Moreover, the focusing of the fluorescence rays is also investigated, by comparing the complete ray tracing method using the correct real part of the refractive index and a simplified method using a value equal to 1 to disable the deflection of the rays.

Results and Discussion

Regarding the planar droplet sizing, a parametrical study is carried out, considering the empirical correlation (Eq. 1) suggested in previous work [3] between the diameter d and the fluorescence signal of the droplet $S_{fluo,droplet}$. The variation of the b_f exponent versus the imaginary part of the refractive index (Fig. 1) exhibits a fluorescence dependence on the volume ($b_f = 3$) for low absorbing mixtures and a fluorescence dependence on the surface area ($b_f = 2$) for highly absorbing mixtures. In-between, when the focusing of the fluorescence rays is disabled, b_f presents a monotonic decrease from 3 to 2, whereas b_f decreases below values of 2 and then increases again when the focusing of the fluorescence rays is enabled. The values of b_f below 2 are caused by shadow zones which do not contribute to the fluorescence signal, even if they are illuminated by the laser.

Regarding the fluorescence signal obtained with high focused laser beams and a moving droplet, the simulations reveal an excellent measure of the droplet diameter from the width of the signal profile, because no time shift is observed in the fluorescence signal whatever the detection angle (Fig. 2). A further analysis reveals non-

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symmetric profiles obtained with the detector positioned in the yz plane (φ=0°), whereas symmetric shapes with different amplitude are obtained with the detector positioned in the xy plane (Ψ=0°). This suggests an estimation of Ψ in real measurement systems by comparing both side of one profile, whereas φ can be deduced by comparing the amplitude of the profiles from different detectors. Otherwise, the velocity of the droplet can be estimated by using two parallel laser beams and knowing precisely the distance in-between.

$$S_{fluo,droplet} = K_f \times d^{b_f} . \quad (1)$$

Conclusion

A fluorescence model has been successfully applied either to a single droplet. The bias in the PDS method has been precisely quantified, whereas the measurement of the fluorescence signal profile with high focused laser beams is promising, to measure not only the droplet diameter from the profile width, but also the trajectory direction and velocity. Experimental verification of these results is in progress.

Acknowledgement

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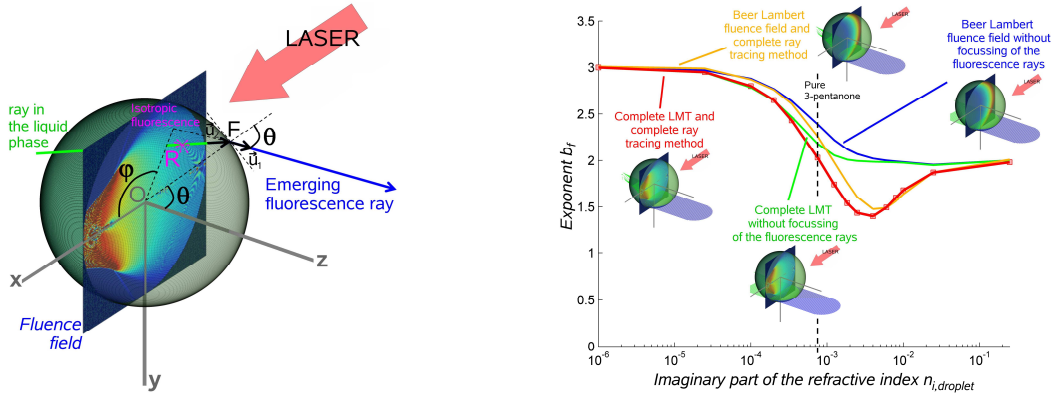

Figure 1. Quantitative analysis of the fluorescence versus the imaginary part of the refractive index

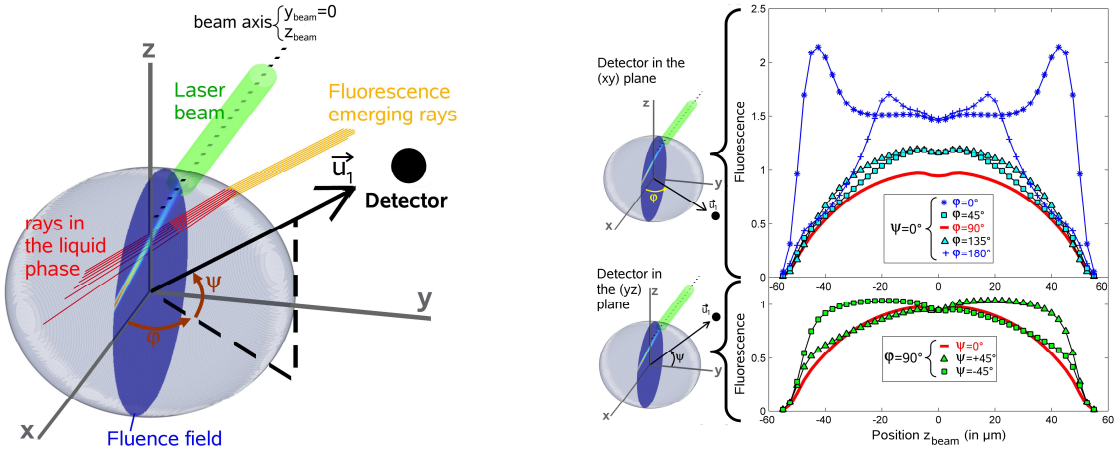

Figure 2. Fluorescence intensity profiles obtained with a droplet crossing one focused laser beam