ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/12314005.1165976

LASER BASED DIAGNOSTIC SYSTEM FOR SPRAY MEASUREMENTS

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Abstract

The paper discusses the capabilities of the laser diagnostic system for dispersed multiphase flows measurements, which was recently commissioned at the Institute of Heat Engineering (ITC) at Warsaw University of Technology. The system presented in the paper is multifunctional and is capable to use different measurements techniques such as shadowgraphy, Mie scattering (scattering on the gas-liquid interface) and LIF (laser induced fluorescence). It provides possibility of switching from one technique to another depending on the characteristics of the observed combustion/injection mixing process. The operational features are discussed in-detail. The study presents the required and possible system setups. Special attention was focused on the system components, which are needed for relevant measurement techniques. Moreover, the limitations of the measurement techniques are discussed and the example measurements are presented. The study shows that using different techniques extends the measurement capabilities of the system with minimum investment costs. This results from the fact that certain system components for different techniques are the same. Moreover, one can conclude that the system design allows certain measurement methods to be applied simultaneously, which results in synergy by making possible drawing more advanced conclusions on observed phenomena.

Keywords: *spray, shadowgraphy, Mie scattering, LIF, laser induced fluorescence*

1. Introduction

Spray combustion takes place in many power and energy systems such as furnaces, industrial burners, gas turbines and reciprocating engines. The process of combustible mixture preparation strongly influences the combustion process. The crucial combustion parameters like emissions and energy conversion efficiency are directly dependent on quality of prepared mixture. Therefore, the proper spray formation is of crucial importance. For many years, the issue of spray combustion concerned only diesel engines but for the last two decades, it also concerns spark ignition engines. Therefore, the process of liquid fuel distribution through direct injection becomes of high interest [9, 10].

Sprays however, are also present in other devices like after treatment systems (urea-water solution injection) fire extinguishers, medical atomizers, agriculture atomizers, and many others. In all these applications, the process of spray formation needs to be adjusted to specific conditions.

Description of liquid fuel injection in subcritical conditions has been improved since Rayleigh's experiments in the end of 19th century [1] when he observed that round liquid jet is unstable when its length exceeds its circumference. For many years, his theory was developed by number of researchers resulting in proper understanding and description of liquid jet behaviour.

A liquid jet, after it is released from the nozzle, undergoes disintegration, which differs depending on the liquid and ambient gas properties, injection parameters and ambient conditions. Jet breakup has been divided into regimes basing on the differences in the jet appearance. In many studies [2, 3] researchers distinguish four different regimes of liquid jet breakup:

1. Rayleigh regime,
2. First wind-induced regime,
3. Second wind-induced regime,
4. Atomization regime.

In high-pressure direct injection where the Weber number is very high, the jet undergoes the atomization breakup. Therefore, this type of break up is of highest importance in combustion systems. This type of breakup due to high number of very small droplets poses a biggest challenge for successful measurements.

Optical diagnostics of spray formation is not a new branch of science. However, there are more and more advanced techniques available, which can be used for this purpose. In the last decades, the spray formation was mainly observed by Schlieren and shadowgraphy techniques. These are the techniques which are still of high importance and widely used, but in terms of spray measurement they can provide information only on gaseous phase (or fine mist) penetration and spreading angle. There are however many more parameters beside gaseous phase penetration and spray angle describing sprays, which are important. The main parameters used for spray characterization are shown in Fig. 1.

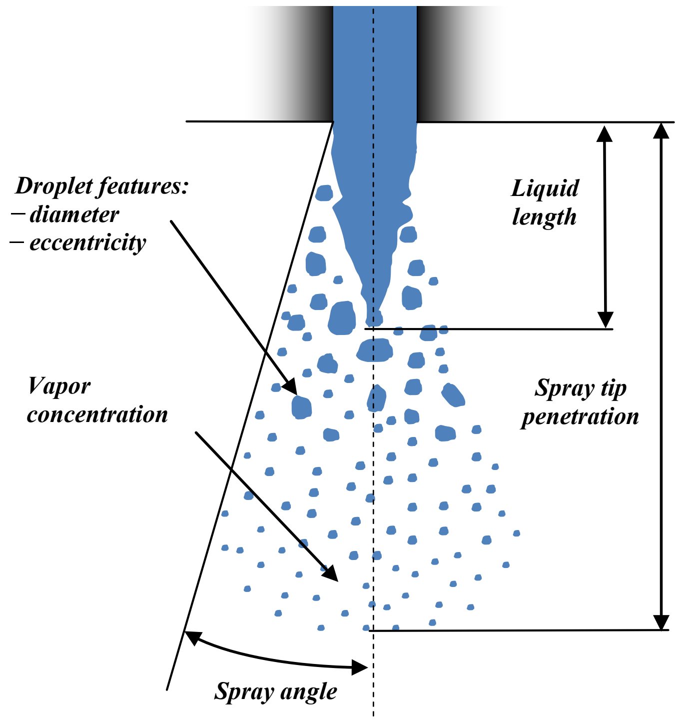

Fig. 1. The main parameters used for spray characterization

2. System overview

The laser system presented in the paper is multifunctional and can be used for both, combustion and spray research. In this study, only spray measurements are considered. The presented system is capable to use different measurements techniques:

– Shadowgraphy,
– Mie scattering (scattering on the gas-liquid interface), and
– LIF (laser induced fluorescence).

Each of these techniques requires different set of components; however, the main components are common for all of them. The system setup for LIF measurement is shown in Fig. 2. The measurement techniques are described in detail in next chapter.

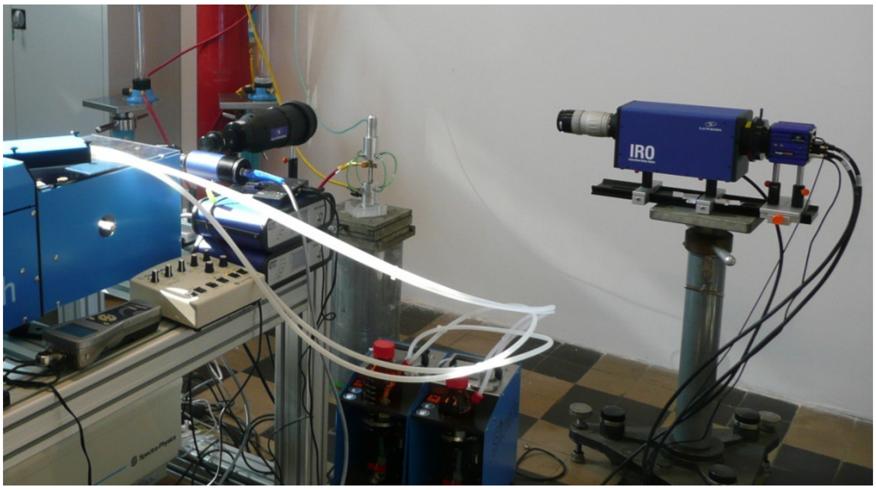

Fig. 2. The system setup for LIF measurements

The core of the system is two lasers. The first one is solid state Nd:YAG laser Quanta-Ray Pro-230. The maximum energy generated by this laser is of 1250 mJ, 650 mJ, 375 mJ and 130 mJ for 1064 nm, 532 nm, 355 nm and 266 nm respectively [3]. The second one is the dye laser Sirah Cobra-Strech that is a tunable laser capable to modify the wavelength of the beam generated by the Nd:YAG laser within the wide range. The lasers are located at one stand. The lasers are presented in Fig. 3. One needs to be aware that not all of techniques require both lasers.

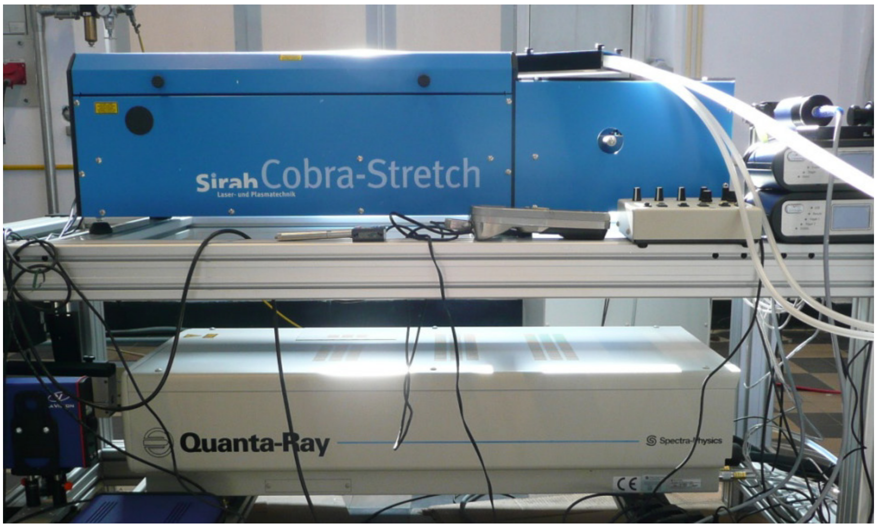

Fig. 3. Sets of two lasers; Nd:YAG on bottom (pump laser), and dye on top

The Nd:YAG laser was configured so 4 different wavelengths are possible to be generated. Moreover, 3 different wavelengths can be generated at the same time. However, only in two configurations, 1064 nm, 532 nm and 355 nm or 1064 nm, 532 nm and 266 nm. The schematic optics providing such functionality is shown in Fig. 4.

In the arrangement where two lasers are used the solid-state laser is used as a pump laser for the dye laser. In this configuration, the beam from solid-state laser is directed to the dye laser, which converts the wavelength to the desired one. The schematic optics of the dye laser is shown in Fig. 5.

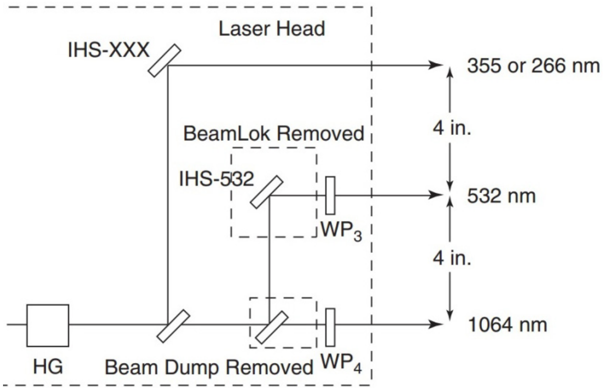

Fig. 4. The schematic optics providing functionality of generating 3 different wavelengths at the same time (1064 nm, 532 nm and 355 nm or 1064 nm, 532 nm and 266 nm); HG stands for harmonic generator and IHS for internal harmonic separator [4]

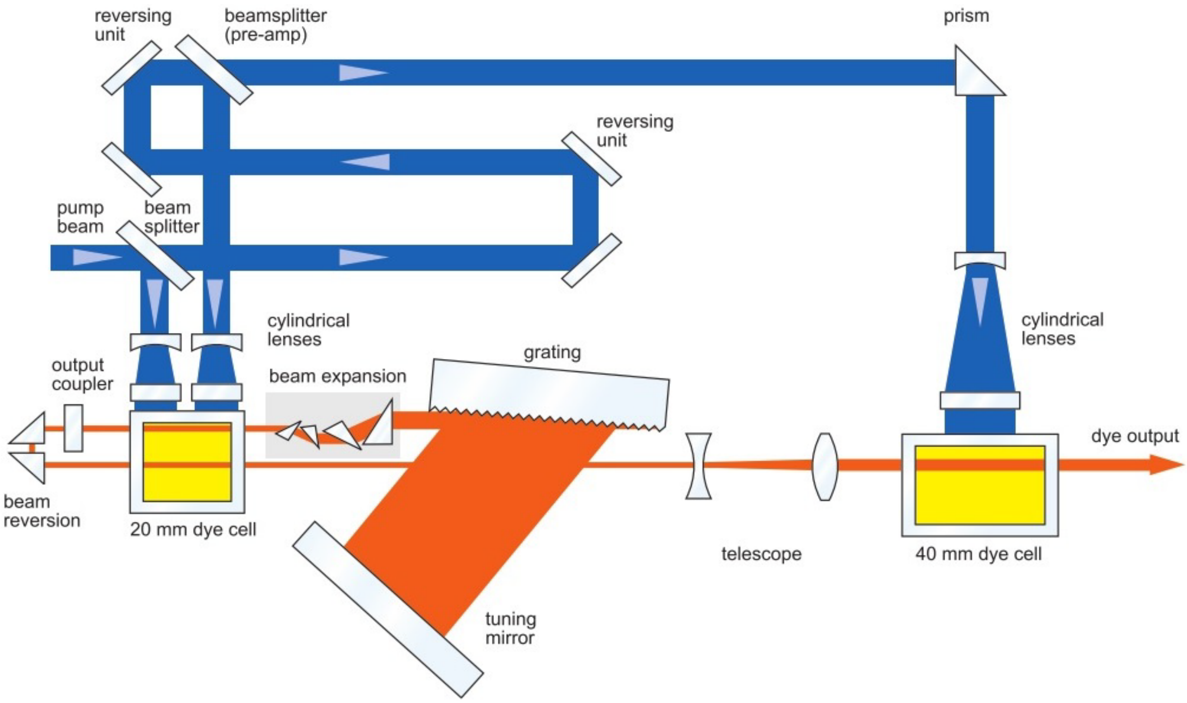

Fig. 5. The schematic optics of the dye laser; pump beam is the beam directed from Nd:YAG laser [5]

The dye laser was additionally equipped with so-called Frequency Conversion Unit (FCU), which is actually a second harmonic generator (SHG). The dye laser and SHG are integrated in one device. The schematic optics of the SHG is shown in Fig. 6.

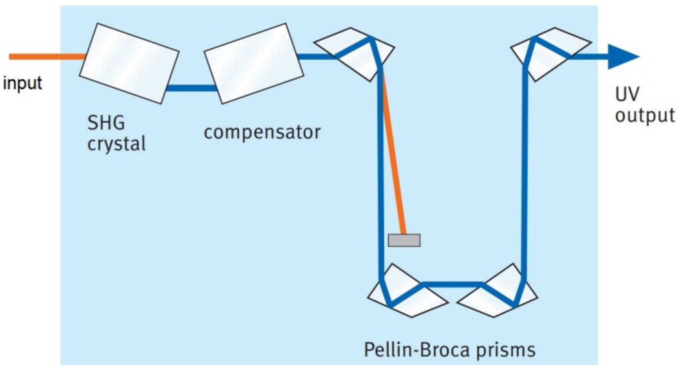

Fig. 6. The schematic optics of the SHG integrated with dye laser [6]

3. Shadowgraphy technique

Shadowgraphy technique is based on light generated by Nd:YAG laser therefore, in this arrangement the dye laser is not used. The schematic setup of the system for shadowgraphy measurements is shown in Fig. 7.

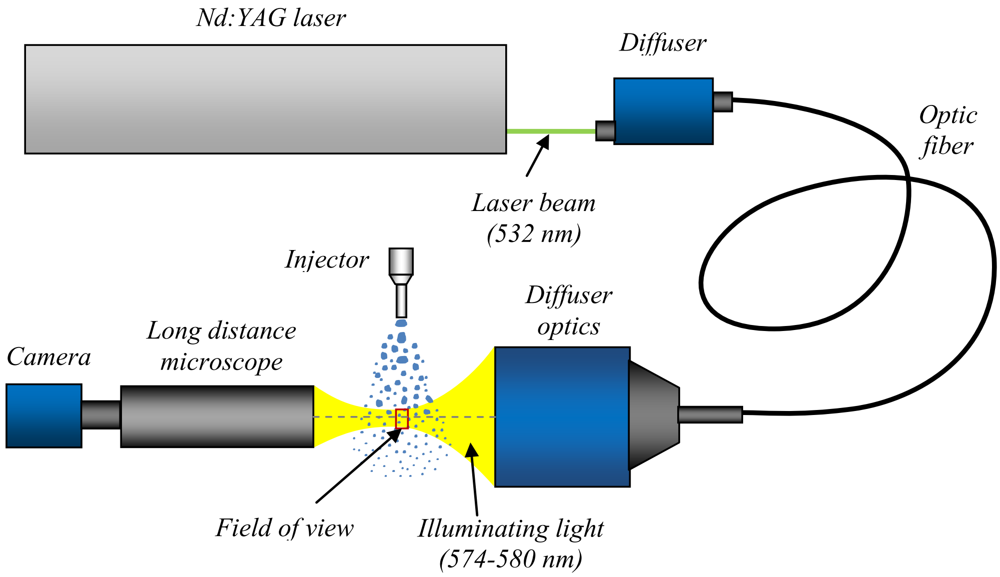

Fig. 7. Schematic setup of the system for shadowgraphy measurements

As it is shown in Fig. 7, there are additional elements, which are needed in this setup:

1. beam diffuser,
2. optical fibre,
3. diffuser lens,
4. long distance microscope,
5. sCMOS camera.

The elements 1-3 are at the side of light generation, while the elements 4 and 5 are the elements on the observation side. All these elements were shown in Fig. 8. It is worth noting that the diffuser besides diffusing the light generated by laser also changes its wavelength.

Fig. 8. Diffuser optics (on top) – diffuser, optic fibre and diffuser lens respectively from left, long distance microscope (bottom left) and sCMOS camera (bottom right)

The shadowgraphy technique allows observing individual droplets as well as liquid ligaments. The system allows determining both droplet diameter and eccentricity. Moreover, the system is equipped with powerful software for statistical analysis of large sets of images. The example image obtained with shadowgraphy technique is shown in Fig. 9.

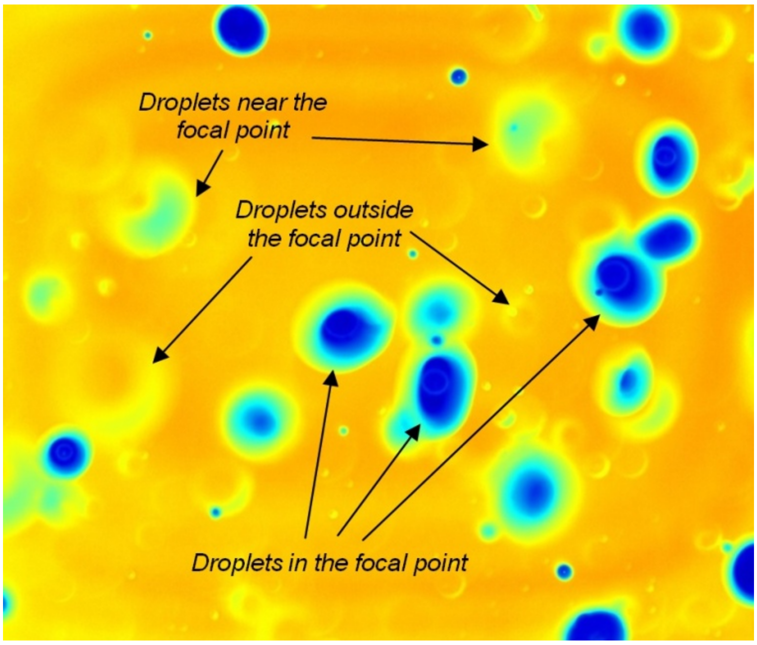

Fig. 9. Example image of the droplets obtained by shadowgraph technique

4. Mie scattering technique

Mie scattering technique is a method based on recording the scattered light on a gas-liquid interface. It is used for liquid length determination. This method can be implemented without the use of pulse lasers and without sheet optics using so-called integral illumination. Such approach was used in [7]. Using sheet optics however, allows illuminating the droplets and ligaments in the plane of interest. The pulse Nd:YAG laser in turn is a reliable strong source of light. The schematic setup of the system for Mie scattering measurements is shown in Fig. 10.

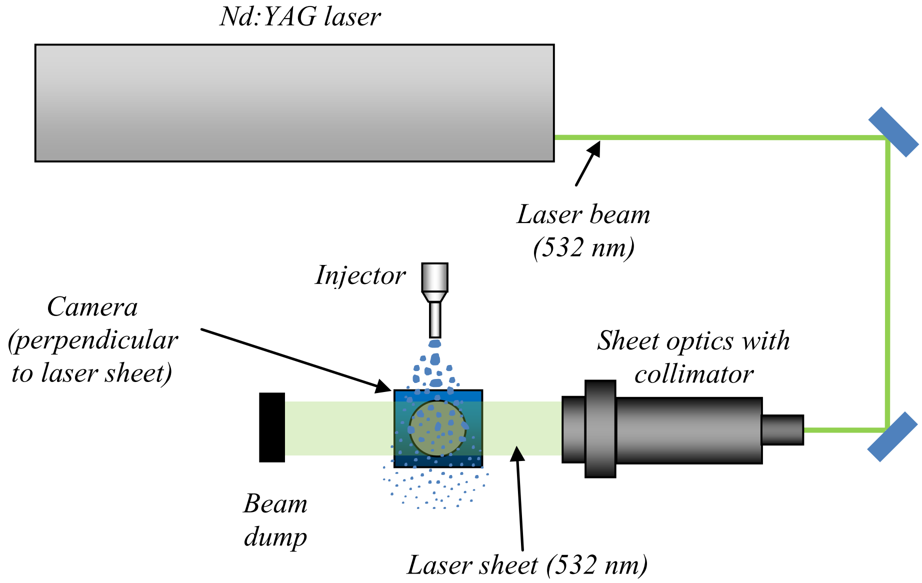

Fig. 10. Schematic setup of the system for Mie scattering measurements

5. LIF technique

LIF technique also termed as PLIF (Planar Laser Induced Fluorescence) may be based either on Nd:YAG laser or on dye laser. Both arrangements are possible. The energy generated by Nd:YAG laser is higher. However, only certain wavelengths are possible to be used. The schematic setup of the system based on Nd:YAG laser is shown in Fig. 11.

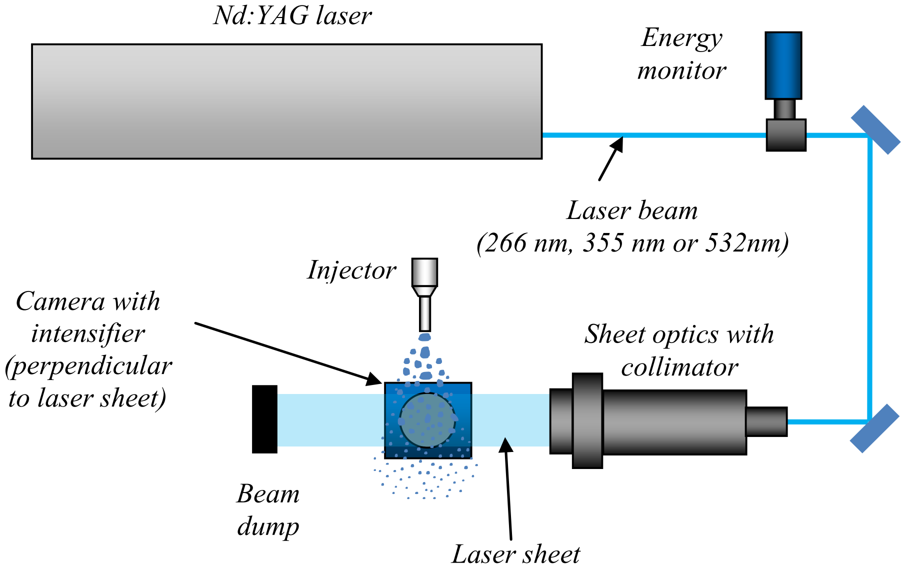

Fig. 11. Schematic setup of the system for LIF measurements

The energy of the YAG Laser may slightly differ between the pulses. Therefore, the illuminated molecules may be excited with different energy and thus the emitted radiation will also differ between the frames. This in turn may lead to missconclusion that observed parameter changed. In order to compensate these differences the system was equipped with so-called online energy monitor. This device consists of a broadband photosensor, which allows measuring the relative laser pulse energies. The measured relative energy values are taken into account during the post processing of the results.

The LIF method may serve for liquid length determination and for fuel vapour visualisation. With the addition of special tracer with similar evaporation, characteristics as fuel of interest this method may allow to simultaneously determining liquid and vapour. This approach was proposed by Melton [8] and it is termed as LIEF (Laser Induced Exciplex Fluorescence) or PLIEF (Planar Laser Induced Exciplex Fluorescence).

The LIF method may be combined with Mie scattering method for global droplet sizing determination. It results from the fact that LIF signal is dependent on droplet volume while Mie signal is dependent on surface of the droplet. By dividing these two signals, the droplet diameter can be determined. This method is valid for droplets (after certain distance from nozzle outlet) and it is called LIF/Mie technique.

This methodology requires however additional camera or special optics allowing to record two images on one camera. The system will be upgraded for such functionality in the near future.

Conclusions

The system presented in the paper is multifunctional and is capable to use different measurements techniques: shadowgraphy, Mie scattering (scattering on the gas-liquid interface) and LIF (laser induced fluorescence). As it was shown, different techniques can be based on the same lasers, which are the most expensive components. This allows extending the measurement capabilities with minimum investment costs. Moreover one can conclude that the system design (there simultaneous laser beams generated by Nd:YAG laser) allows certain measurement methods to be applied simultaneously.

The further planned investment will extend the functionality of the system even more and will allow determining global droplet sizing by means of LIF/Mie method.

Acknowledgements

The paper was supported by the National Science Centre in Poland, granted on the basis of decision No. DEC – 2011/01/D/ST8/07142.

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