Vanselow. Christoph ; Stöbener, Dirk ; Kiefer, Johannes ; Fischer, Andreas

Revealing the impact of laser-induced breakdown on a gas flow

Journal Article as: peer-reviewed accepted version (Postprint)

DOI of this document*(secondary publication): https://doi.org/10.26092/elib/3199

Publication date of this document: 10/08/2024

* for better findability or for reliable citation

Recommended Citation (primary publication/Version of Record) incl. DOI:

Christoph Vanselow and Dirk Stöbener and Johannes Kiefer and Andreas Fischer. Revealing the impact of laser-induced breakdown on a gas flow. 2019. In: Measurement Science and Technology, 31 (2), 027001, https://dx.doi.org/10.1088/1361-6501/ab471e

Technical Note

Revealing the impact of laser-induced breakdown on a gas flow

Christoph Vanselow[1], Dirk Stöbener[1,3], Johannes Kiefer[2,3] and Andreas Fischer[1,3]

[1] Bremen Institute for Metrology, Automation and Quality Science (BIMAQ), University of Bremen, Linzer Straße 13, 28359 Bremen, Germany
[2] Technische Thermodynamik, University of Bremen, Badgasteiner Straße 1, 28359 Bremen, Germany
[3] MAPEX Center for Materials and Processes, University of Bremen, Bibliothekstraße 1, 28334 Bremen, Germany

E-mail: c.vanselow@bimaq.de

Abstract

Laser-induced breakdown spectroscopy (LIBS) is an optical, and thus non-contact, but not non-invasive, measurement technique. Investigating the impact of laser-induced breakdown on a gas flow, combined LIBS and particle image velocimetry (PIV) measurements are performed. In the considered laminar air flow, the induced velocity field disturbance has an extent of about 0.7 cm with magnitudes up to 0.9 ms^{-1}. As a further result, the combination of LIBS with other measurement techniques or high-speed LIBS measurements are found to require a minimal time delay of about 500 µs in order to ensure influence of the preceding LIBS pulse on the considered gas flow of about 10 % relative velocity deviation. For a reduction to 0 % relative velocity deviation a time delay of about 20 ms is estimated for the investigated flow. Smaller time delays may occur in turbulent flows or flows with higher velocities.

Keywords: particle image velocimetry, laser-induced breakdown spectroscopy, flow diagnostics

(Some figures may appear in colour only in the online journal)

Introduction

The invention of the laser and the subsequent development of laser-based diagnostics has advanced combustion research [1, 2]. In contrast to mechanical probing, optical methods are commonly characterized as non-contact or non-intrusive. One of these optical methods is the laser-induced breakdown spectroscopy (LIBS), which is an emerging tool for flow diagnostics [3]. It is mainly used to determine the local element composition and for instance to derive the fuel/air ratio [4, 5]. In recent years, its potential for thermometry has been explored as well [6]. Although LIBS is an optical non-contacting technique, it is not non-intrusive. The laser-induced breakdown generates an acoustic wave, which travels through the investigated flow field influencing the velocity distribution [7]. Furthermore, the separation between atoms/ions and electrons during the plasma formation leads to short-term expansion before the recombination process [8]. Besides the molecular composition after the recombination, a reduction of the local density due to heat expansion still remains. Currently, it is unclear to what extend the plasma has a mechanical impact on the flow to be investigated.

In the present note, particle image velocimetry (PIV) is applied [9, 10] to examine the impact of LIBS measurements on the flow field. Additionally, with the aim of minimizing the measurement errors, a rule of thumb is developed for the combination of LIBS with other diagnostic methods, as well as for high repetition rate LIBS. For this purpose, after a brief description of the measurement setup, the results of two different experiments regarding the timing between PIV and LIBS measurements are presented. In the first experiment, the light pulse of the LIBS laser and the first light pulse of the PIV laser are emitted simultaneously in order to quantify the absolute impact of the induced plasma on the flow field. In the second experiment, the first PIV laser pulse starts after a previous LIBS laser pulse by applying different delays, which allows to study the impact duration of the induced plasma on the flow field.

Measurement setup

A jet air flow from a nozzle with a diameter of 4.2 cm is used as a test flow in order to quantify the impact of the laser-induced plasma on the flow field. The mean velocity of the air flow in the center of the nozzle outlet amounts to 0.12 $\mathrm{ms^{-1}}$ and is controlled by a mass flow controller. The nozzle symmetry axis is the y-axis and is located at $y = -7$ cm with the center at $x = 0$, see figure 1. The LIBS laser pulse (1064 nm, 50 mJ) with a pulse length of 8 ns is generated by a laser of type M-Nano from the company Montfort Laser GmbH. The LIBS laser beam is focused at $(x, y) = (0, 0)$ with a 79 mm aspheric converging lens. The $\frac{1}{e}$-diameter of the LIBS laser focus is estimated to be 15 µm assuming a Gaussian beam. The plasma light emission is analyzed by a fiber-coupled spectrometer. The PIV light sheet illumination in the x-y-plane (thickness <0.5 mm) is provided by an Evergreen model frequency-doubled Nd:YAG pulsed laser (532 nm, 200 mJ) manufactured by Quantel with a pulse length of <10 ns. The PIV measurements were performed with a separation time between the PIV laser pulses of 500 µs and a repetition rate of 10 Hz. Tracer particles made of titanium dioxide with an average size of 0.4 µm are seeded to the gas flow. The particles are observed with a 5.5 Mpx sCMOS camera (Andor Zyla) utilized with a 50 mm focal length objective (Zeiss Planar T* 1,4/50). Furthermore, a band pass filter with a central wavelength of 532 nm is used in order to filter disturbing light emissions of the recombining plasma in the PIV images. The resulting spatial resolution in the PIV measurement plane is 56 µm $\mathrm{px^{-1}}$ and for the PIV evaluation, the interrogation window size of $16 \times 16\ \mathrm{px^2} = 0.9 \times 0.9\ \mathrm{mm^2}$ is used without overlap.

Results

This section describes the results of the combined LIBS and PIV measurements, starting with the simultaneous emission of the LIBS laser pulse and the first PIV laser pulse. Besides a potential impact on the jet flow by the induced plasma, the LIBS measurement also disturbs the PIV measurement by the light emission of the recombination process, resulting in a saturated spot in the PIV raw images, see figure 2(a). Since the breakdown is a statistical process, the blind spot differs in its dimension and also in the location. Further, multiple breakdown spots are possible, which complicates the elimination of the light emission of the recombining plasma in the

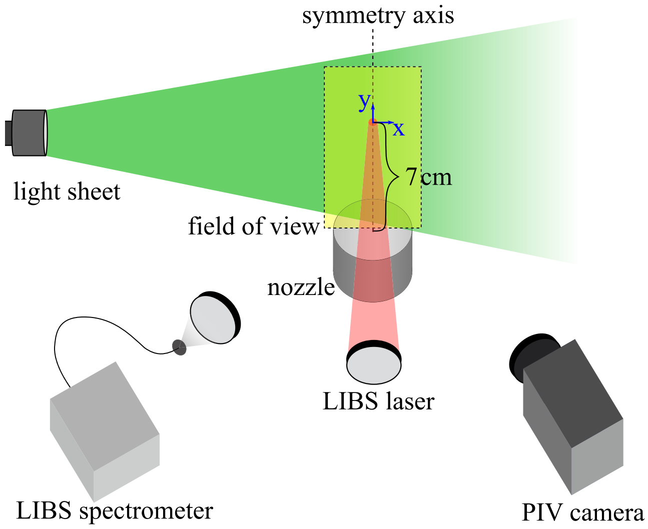

Figure 1. Measurement setup for combined measurement of LIBS and PIV in an air jet flow.

PIV images by image processing. Here it is chosen to filter erroneous vector evaluation results using a validation step with a minimum signal-to-noise ratio of 2.0 and a minimum peak height ratio between the two highest correlation maxima of 1.3. Additionally, a moving average filter invalidates vectors, which deviate more than 20% of the average adjacent velocity. The mean velocity field $\vec{v} = (v_x, v_y)^T$ of the air flow is depicted in figure 2(b). Here, the acceleration of the flow towards the positive y-direction is induced by the suction of the seeded flow from the top, resulting in a maximal velocity of about 0.45 $\mathrm{ms^{-1}}$. The laser-induced breakdowns from LIBS show a significant impact on the laminar flow field. At the LIBS measurement spot (x,$y = 0$), a radial extending zone is apparent with a maximal mean velocity of 1.2 $\mathrm{ms^{-1}}$, which is four times higher than the mean reference velocity of 0.3 $\mathrm{ms^{-1}}$ measured without LIBS pulses at the same location. So, the induced velocity is about 0.9 $\mathrm{ms^{-1}}$. Note, that the measured induced velocity depends on the separation time of the PIV laser pulses, since the expansion of the gas is a short-time process compared to the PIV separation time. Therefore, the separation time of the PIV pulses has an averaging effect which attenuates the measured induced velocity.

Besides the maximal induced velocity, the extent of the affected flow is determined with the two dimensional divergence theorem

$$\iint_A \vec{\nabla} \cdot \vec{v}\, \mathrm{d}A = \oint_S \vec{n} \cdot \vec{v}\, \mathrm{d}S, \tag{1}$$

where A is the area surrounded by the boundary S and $\vec{n}$ is the normal vector on the path element dS. The expansion of the fluid induced by the breakdown can be interpreted by the divergence $\vec{\nabla} \cdot \vec{v}$ of the velocity field $\vec{v}$. Calculating the divergence for varying circle boundaries $S(R)$ as a function of the radius R, the extent of the induced flow is estimated by the radius R_e, where the divergence is no longer measurable. So, equation (1) is divided by the area A and the right hand site is calculated for a varying radius R, see figure 3. The course of the measured divergence of the flow shows a slightly negative

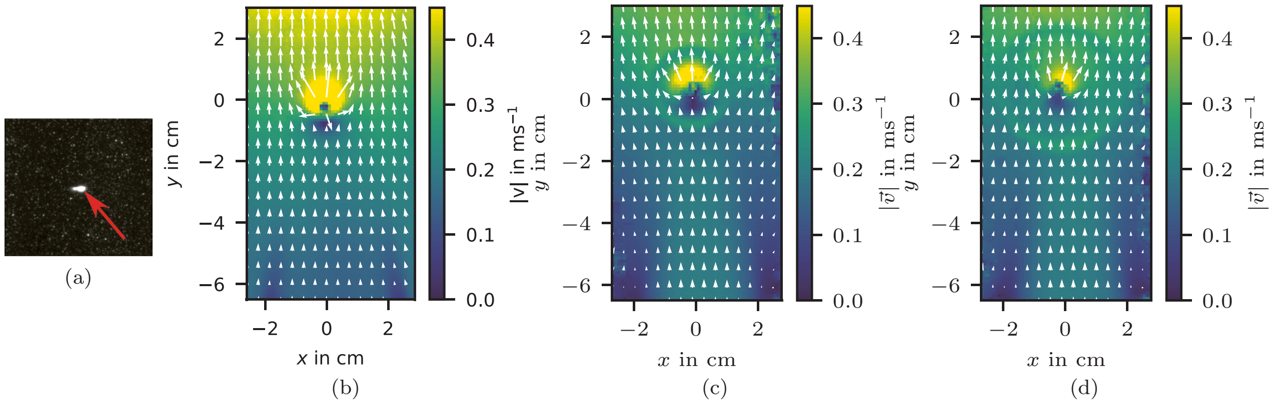

Figure 2. Results of the PIV measurements combined with LIBS. (a) Saturated spot marked by the arrow on a PIV raw image due to the light emission of the recombining plasma. (b) Mean velocity field of the air flow disturbed by an induced breakdown. (c) and (d) Mean velocity field of the air flow disturbed by a previously induced breakdown with a PIV pulse delay of (c) 50 µs and (d) 60 µs, respectively.

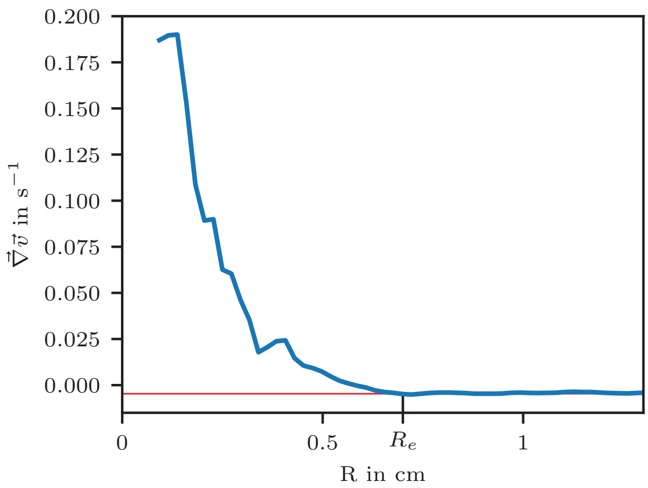

Figure 3. Divergence $\vec{\nabla} \cdot \vec{v}$ of the measured velocity field for circles with radius R.

baseline, which results from the acceleration of the suction and is reached at about $R_e \approx 0.7$ cm. Assuming a symmetric impact of the laser-induced breakdowns on the velocity field, the radius R_e determined for the two dimensional measurement plane is extrapolated to a spherical volume with a radius of 0.7 cm.

In a second measurement, the delay Δt between the LIBS and the first PIV laser light pulse is varied in order to determine a decay time characterizing the temporal extent of the induced flow by the LIBS breakdown. In figures 2(c) and (d), the mean velocity fields for time delays of $\Delta t = 50$ µs and $\Delta t = 60$ µs are depicted, respectively. As a result, a significant influence on the flow field remains even after 60 µs. Furthermore, the radial propagation of the induced shock wave in the mean flow field is visible. Since the shock wave propagates with the speed of sound, the influence on the flow field can be estimated for each setup individually by calculating the propagation distance of the shock wave for the duration until the subsequent measurement begins. The decay time τ of the induced flow is determined by the calculation of the mean relative velocity deviation between a reference measurement without the LIBS pulse and a measurement with the time separated LIBS pulses. The mean relative velocity deviation is determined within a radius of 0.7 cm around the breakdown spot and is plotted against the time delay Δt in figure 4. The temporal decrease of the induced flow shows two different characteristics. In the short term, an exponential decrease with an offset of about 10 % can be observed. The offset of about 10 % is reached after 500 µs. Then, a linear decrease becomes dominant and is indicated by the dashed line fitted to the last five measurement points from 500 µs to 10 ms. The two different characteristics can be explained by the comparatively fast recombination process of the induced plasma and a slow removal of the recombined heated gas by the jet flow velocity of about 0.3 ms^{-1}. The extrapolation of the fitted line predicts a decay to 0 % velocity deviation after 21 ms. This prediction is supported by an estimation of the amount of time the flow removes the heated gas. The mean flow velocity at the LIBS measurement spot, measured without induced breakdowns, amounts to 0.3 ms^{-1}. So the gas needs 23 ms to overcome the radial distance 0.7 cm, which is used to calculate the mean velocity deviation. As a result, the repetition rate of LIBS measurements should adhere a minimal decay time of about 500 µs in order to reduce the relative deviation of the mean flow velocity to 10 %. Otherwise the velocity field and thus the measurement object itself is still influenced by the previous breakdown. This corresponds to a maximal repetition rate of about 2 kHz for the considered experiment. However, considering a repetition rate of about 2 kHz a measurement deviation of the local density due to heat expansion can be assumed. For negligible influence on the examined flow field, a waiting time of about 21 ms is estimated.

Conclusion

LIBS is an emerging tool for flow diagnostics for e.g. the determination of the fluid species or density/temperature measurements. Although, LIBS is an optical measurement technique, it has an impact on the measurement object, which is quantified within this note considering a laminar air flow as an example. Simultaneous LIBS and PIV measurements show an increase of the mean velocity of 0.9 ms^{-1} in the spot of

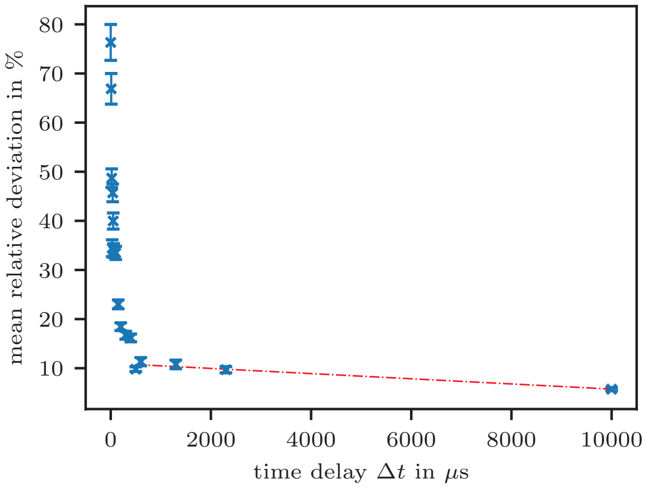

Figure 4. Mean relative deviation of the mean flow field over the time delay Δt between the LIBS and first PIV pulse.

the induced breakdown. The extent of the affected flow is estimated by the measurable divergence of the velocity field induced by the expansion of the breakdown process. The flow field is influenced within a radius of 0.7 cm around the LIBS focus point. Furthermore, a decay time of the induced flow of about 500 µs is identified for a reduction of the influence on the flow field below 10 % relative velocity deviation. For negligible influence on the flow field, a waiting time of about 21 ms is estimated for the examined laminar air flow, which corresponds to a repetition rate of 48 Hz. Note that higher repetition rates are achievable with highly turbulent flows or flows with higher mean flow velocities due to a faster decay and translation process, respectively.

In high-speed LIBS applications, the maximum repetition rate of about 2 kHz should be maintained to obtain a negligible influence of the previous breakdown on the flow. For combined LIBS and PIV measurements, it is recommended to start the measurement cycle with the two separated PIV laser pulses and then emit the LIBS laser pulse to avoid the influence of the LIBS induced flow on the PIV measurement. In addition to the impact of the breakdown on the gas flow and thus the impact of the LIBS measurements on the PIV measurements, the PIV measurements also have an impact on the LIBS measurements. The seeded particles will add additional emission spectra of the used particle material to the LIBS signal. A quantification of this effect remains an open task.

Acknowledgment

The authors would like to thank Montfort Laser GmbH, Austria and its CEO Dr. Daniel Kopf for the loan of the LIBS laser. Furthermore, J. K. gratefully acknowledges support from Deutsche Forschungsgemeinschaft (DFG) through grants KI1396/3-1, KI1396/3-2, and KI1396/6-1.

ORCID iDs

Christoph Vanselow https://orcid.org/0000-0002-1233-4476
Dirk Stöbener https://orcid.org/0000-0002-1624-2106
Johannes Kiefer https://orcid.org/0000-0002-0837-3456
Andreas Fischer https://orcid.org/0000-0001-7349-7722

References

[1] Eckbreth A C 1996 *Laser Diagnostics for Temperature and Species in Unsteady Combustion* (Netherlands: Springer) (https://doi.org/10.1007/978-94-009-1620-3_18)

[2] Ehn A, Zhu J, Li X and Kiefer J 2017 Advanced laser-based techniques for gas-phase diagnostics in combustion and aerospace engineering *Appl. Spectrosc.* **71** 341–66

[3] Musazzi S and Perini U (ed) 2014 *Laser-Induced Breakdown Spectroscopy* (Berlin: Springer) (https://doi.org/10.1007/978-3-642-45085-3)

[4] Eseller K E, Yueh F Y and Singh J P 2008 Laser-induced breakdown spectroscopy measurement in methane and biodiesel flames using an ungated detector *Appl. Opt.* **47** G144

[5] Joshi S, Olsen D B, Dumitrescu C, Puzinauskas P V and Yalin A P 2009 Laser-induced breakdown spectroscopy for in-cylinder equivalence ratio measurements in laser-ignited natural gas engines *Appl. Spectrosc.* **63** 549–54

[6] Williamson A P, Thiele U and Kiefer J 2019 Comparison of existing laser-induced breakdown thermometry techniques along with a time-resolved breakdown approach *Appl. Opt.* **58** 3950

[7] Lorenz S, Bärwinkel M, Stäglich R, Mühlbauer W and Brüggemann D 2015 Pulse train ignition with passively Q-switched laser spark plugs *Int. J. Engine Res.* **17** 139–50

[8] Kawahara N, Beduneau J L, Nakayama T, Tomita E and Ikeda Y 2006 Spatially, temporally, and spectrally resolved measurement of laser-induced plasma in air *Appl. Phys.* B **86** 605–14

[9] Adrian R J 2005 Twenty years of particle image velocimetry *Exp. Fluids* **39** 159–69

[10] Fischer A 2017 Imaging flow velocimetry with laser Mie scattering *Appl. Sci.* **7** 1298