

Laser-induced gas breakdown as a light source for schlieren and shadowgraph particle image velocimetry

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Abstract. The “schlieren PIV” technique combines schlieren or shadowgraph optics with particle image velocimetry (PIV) equipment to measure the velocities of turbulent eddies in flows with sufficiently strong changes of the refractive index without actual particle seeding. Prior work on this technique used direct laser illumination that produced inadequate schlieren image quality due to coherent artifact noise and other problems. By way of a simple equipment modification, we show the white-light emission of a laser-induced air or argon breakdown to be an improved light source for schlieren and shadowgraph PIV. The Nd:YAG illumination used in standard PIV is converted to a white-light pulse by this means. High-quality schlieren images are obtained and measurements in a helium jet using this new approach compare well with previous data. The method is especially applicable to high-speed flows requiring time delays of 5 μ s or less between the images of a PIV pair. © 2006 Society of Photo-Optical Instrumentation Engineers.
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Subject terms: schlieren; shadowgraph; particle image velocimetry; turbulent flows; laser-induced breakdown; argon gas; light source.

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1 Introduction

Jonassen et al.¹ demonstrated that particle image velocimetry (PIV), a key method of experimental fluid mechanics,² can be combined with traditional schlieren or shadowgraph optics³ to measure the velocities of turbulent eddies in a refractive flow. This technique is successful, under certain limitations, because eddies in the flow can substitute for the particles with which the flow must normally be seeded. In this case, the PIV system (consisting of laser illumination, digital camera, and software) compares the positions of eddies in a pair of images taken with a small known time separation, thence calculating the velocity field.

It was further shown,¹ that white-light strobe illumination of the schlieren/shadowgraph optics is possible when the time interval between the images of a PIV pair exceeds about 5 μ s. However, strobe illumination is more troublesome than laser illumination, which is easily implemented with the PIV system. For the shorter time intervals that are required to measure high-speed flows, the strobe illumina-

tion method fails by being unable to produce two distinct pulses. Each strobe pulse width may be 1 μ s or more, so that the two strobe pulses tend to merge for time intervals below 5 μ s. The twin pulsed lasers traditionally used in commercial PIV systems normally provide the schlieren/shadowgraph illumination directly for high-speed flows, since the pulse width in this case is only a few nanoseconds. This is unfortunate, because direct laser illumination is much inferior to white light in schlieren and shadowgraphy due to coherent artifact noise and diffraction problems at the schlieren knife edge.³ Thus, laser schlieren images are usually of comparatively poor quality with fringing, uneven background illumination, and low sensitivity.

A potential solution to such problems is to “transform” the laser discharge into a white-light flash using laser-induced gas breakdown, then use the resulting white light for schlieren illumination. This was first reported by Zakharin et al.⁴ and was further developed by Beutner et al.⁵ and Murphy et al.,⁶ who focused the beam from a Nd:YAG laser onto a tungsten wire in a pressurized argon chamber. The resulting white light was directed into a standard schlieren system used to image exploding bridge wires.

Laser-induced gas breakdown—the laser-spark—has been studied thoroughly^{7–10} over the last thirty years and has been put to several good uses. The focused laser energy ionizes the gas and heats an oblong plasma ball to the range of 15,000 K, emitting intense broadband light.

We build on the work of Jonassen et al.,¹ Beutner et al.,⁵ and Murphy et al.⁶ by applying noncoherent laser-breakdown light emission to schlieren and shadowgraph PIV for the quantitative measurement of turbulent flows. This has several distinct advantages, especially in that additional flashlamps and timing circuitry and their complications are avoided, and that very short time delays between the images of a schlieren PIV pair are possible with the excellent image quality of white-light illumination.

2 Experimental Setup

The equipment is the same as that described in detail by Jonassen et al.¹ Briefly, a small converging nozzle with an exit diameter of 0.79 mm was supplied with helium gas at a stagnation pressure of 208 kPa to produce a sonic turbulent refractive jet in ambient air. This was imaged by a traditional z -type schlieren optical system employing twin 108-mm-diam $f/8$ parabolic mirrors as field elements. The camera of a commercial PIV system by IDT, Inc., captured the schlieren images. Laser illumination came from a New Wave Research “Gemini PIV” 200-mJ dual-head Nd:YAG laser with a 3 to 5-ns pulse width. As in Ref. 1, a time delay of 5 μ s between PIV frames was found appropriate for the helium jet measurements.

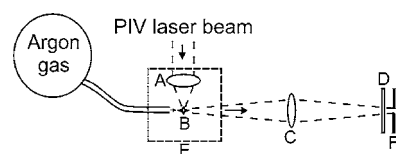


Fig. 1 Laser-spark illumination apparatus: A, double-convex (DCX) single lens; B, laser spark; C, condenser lens; D, optical filters; E, anti-stray-light enclosure; F, schlieren entrance slit.

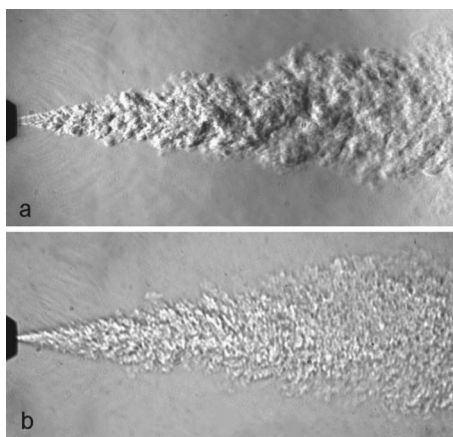


Fig. 2 Example (a) schlieren image of turbulent helium jet illuminated by laser spark in air (knife-edge perpendicular to jet axis) and (b) shadowgram of the same jet illuminated by laser spark in argon.

Here, however, the laser radiation did not directly illuminate the schlieren optics. Instead, the apparatus shown in Fig. 1 was used. A simple lens (12.5 mm diameter and 38 mm focal length) brought the laser beam to a focus in an enclosure that blocks stray light but was open to the atmosphere. The laser-induced breakdown of the air, or of argon gas supplied by a hose at a flow rate of about 0.1 L/s, produced two intense white-light flashes. Part of this light was collected at a right angle to the laser-beam axis by a condenser lens, and was focused on the entrance slit of the schlieren optical system. Neutral-density filters were used to control the intensity of the schlieren illumination. An ordinary schlieren knife-edge cutoff was used.³ It was important to locate the knife-edge parallel to the laser illumination axis, i.e., the long axis of the oblong laser spark. In this case, small changes in the axial position of the spark would not affect the level of schlieren cutoff.

A Newport Corporation 818 series photodetector and oscilloscope were utilized to determine the laser spark duration and minimum interval between images of a PIV pair. The photodetector had a response time of less than 1.5 ns.

3 Results

Initial results with the laser-generated air spark were promising, but the schlieren image contained residual coherent laser radiation along with the laser-spark emission. This was eliminated by an orange low-pass optical filter, since our PIV camera records only monochrome images.

With this modification, schlieren images of excellent quality were obtained, as exemplified in Fig. 2. The only significant difference between the laser-spark in air versus argon was a threefold increase in light output of the latter compared to the former, which was also observed by Beutner et al.⁵ With our optical setup and camera, both sparks yielded more-than-sufficient illumination intensity. However, the brighter argon flash may be important in some applications.

It remains to check the ability of the “schlieren PIV” technique with laser-spark illumination to correctly measure the helium-jet test flow. As in Ref. 1, the axial velocity profile of the helium jet was extracted by the PIV software from the average of 200 schlieren image pairs. An adaptive mesh covered a region of the helium jet 20 to 55 mm downstream of the nozzle exit. The resulting velocity profile (Fig. 3) closely matched the strobe-illuminated schlieren PIV results reported in Ref. 1. Note that these PIV results were path averaged across the axisymmetric helium jet, yielding results lower than the jet centerline velocity.

Both laser-sparks had a measured duration of 10 ns. This was sufficiently brief, compared to the 50 ns minimum time delay of our PIV system, such that no measurement anomalies are expected due to laser-spark duration even when investigating very high-speed flows. Moreover, both images in the PIV pair were of equal intensity and clarity.

4 Conclusion

By way of a simple equipment modification, the white-light emission of a laser-induced gas breakdown becomes a successful light source for schlieren and shadowgraph PIV measurements of turbulent refractive flows. By this means, the Nd:YAG illumination of standard PIV is converted to the white-light pulse necessary for high-quality schlieren

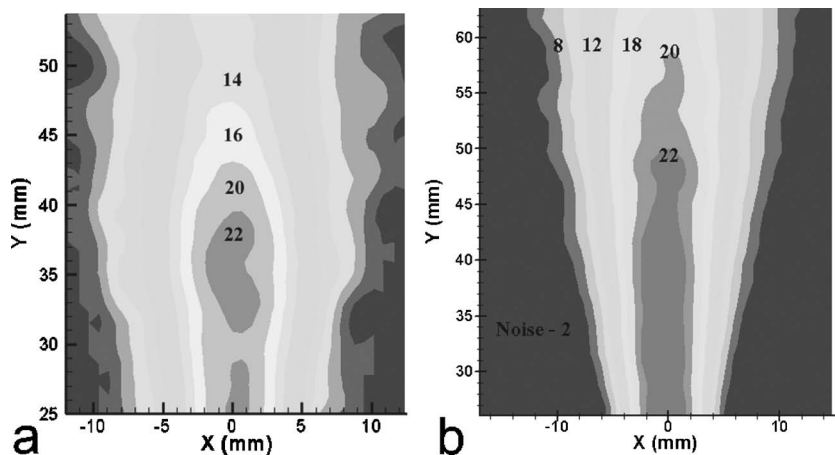


Fig. 3 Axial mean velocity data from the helium jet using (a) laser argon spark-illuminated schlieren PIV and (b) white-light, strobe-illuminated schlieren PIV from Jonassen et al.¹ The nozzle exit is at $Y=0$ mm, and velocity is given in meters per second.

imaging. Laser sparks in both air and argon succeed, the latter being the brighter of the two. PIV measurements in a helium jet using this new approach compare well with previous data, and are made without the necessity to seed the flow with actual particles. The presented method is especially applicable to high-speed flows requiring time delays of 5 μ s or less between the images of a PIV pair.

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