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Technical Notes

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Characterization of Schlieren Light Source Using Laser-Induced Optical Breakdown in Argon

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Introduction

SCHLIEREN imaging systems are widely used for both qualitative and quantitative flow visualization in compressible flows and active index of refraction flowfields such as two-index mixing problems or combustion flowfields. A common implementation of schlieren imaging uses a pulsed light source to provide instantaneous measurements in unsteady flowfields. A variety of pulsed light sources has been used in the past with schlieren imaging systems, including arc lamps, incandescent bulbs, flash tubes, spark gaps, and light-emitting diodes.[1] Lasers have been used to provide a narrow linewidth illumination source, which is useful for filtering broad spectral emissions from plasmas or flames, but at the cost of image degradation due to laser speckle. A recent technical note described the use of a laser-induced spark as a point source, which could be inserted in the flowfield avoiding the need to integrate through the density fluctuations associated with the boundary layers on the wind-tunnel walls.[2] Recent papers have also described the use of a laser-induced spark as a light source for schlieren imaging in a plasma flow[3] and an exploding wire bridge,[4] both applications that benefit from a very high-intensity schlieren light source.

Our objective in this Technical Note is to characterize a laser-induced spark schlieren imaging technique that provides a very high-intensity light source, with short time duration and with repeatable temporal and spatial characteristics. Spatial and temporal variations in intensity are reported for this light source, as well as a comparable light source using a laser discharge in air. This light source has proven especially useful in performing schlieren flow visualization of flowfields having strong emissions in the flow region of interest. The resulting images have much higher contrast, and saturation in the image can be avoided. As an example of the versatility of this light source, a series of images that show the shock and vortex ring formation resulting from a laser induced shock in quiescent air is included in this Technical Note. Even in the vicinity of the spark discharge, the light source described here allows a schlieren image to be obtained without local saturation.

Motivation

The motivation for the development of this light source arose when the authors studied the development and interaction of a spark created by laser-induced optical breakdown in air with shock waves formed in supersonic flows.[5,6] In these studies, the laser-induced breakdown was formed in the freestream of a supersonic wind tunnel to examine the interaction of the resulting shock wave and thermal spot with shock-shock interactions (studying the formation of Mach and regular reflections at the Von Neuman angle)[5] and intersection of oblique shock waves with the bow shock formed in front of a blunt body leading to an Edney IV type interaction.[6] A schlieren imaging system was used to study this flow, but a complicating aspect of the experiment was that the laser-induced breakdown created such a high-intensity broadband light source in the flow that it locally saturated the schlieren imaging camera, making measurements near the formation of the spot difficult. In addition, to study the temporal evolution of flowfield and interaction of laser induced optical breakdown with shock waves, an accurate programmable time delay was necessary to track the evolution of the flowfield accurately and obtain phase-averaged measurements.

Therefore, a schlieren light source was developed using a second pulsed Nd:YAG laser. The second laser was focused to form a laser-induced breakdown spark in a small chamber that was continuously purged with argon gas. Because argon gas has a lower ionization threshold than nitrogen, it takes less energy to induce the breakdown process in argon compared to air, and the discharge that is formed was found to be significantly more intense and slightly more stable. The threshold laser power to ionize argon at one atmosphere pressure has been reported in literature to be 400 kW, compared to 1200 kW for nitrogen at the same conditions.[7]

The advantages of this technique include a very high-intensity light source with resulting improvements in contrast in the schlieren image, a controllable time delay based on external triggering of the laser light source, and a short time duration for the light source for measurements in unsteady flows, such as moving shock systems. In addition, the laser-induced spark discharge was electrically isolated from the other laboratory equipment, reducing the electronic noise in those components, whereas typical strobe light sources can create a significant amount of electromagnetic noise while discharging, and this noise is picked up by other instrumentation such as pressure and temperature transducers and their associated lead wires.

Experimental Apparatus

Figure 1 shows a schematic of the experimental setup. A frequency doubled Nd:YAG laser (532 nm, 250 mJ per pulse) was focused with a 76-mm-focal-length lens to form a laser-induced spark used as the schlieren light source. This spark was formed in a cavity having two intersecting cylindrical paths for the optical

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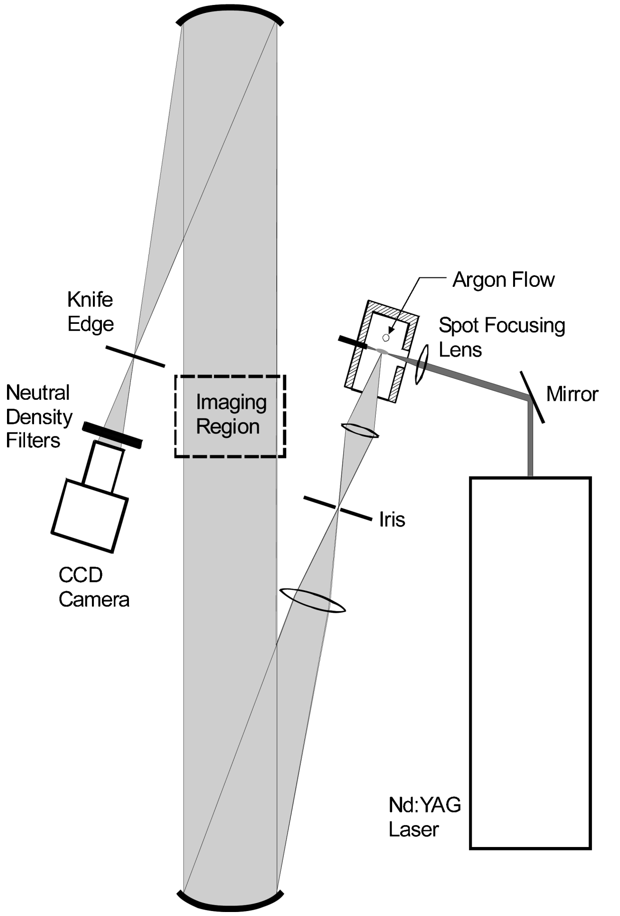

Fig. 1 Schematic of optical layout.

path of the laser beam and the spot-imaging lens. No windows were used on the chamber to avoid internal reflections and damage to optical elements in close proximity to the spark discharge. Argon was continuously bled into the chamber at a rate of approximately four liters per minute. A 1-mm-diam thoriated-tungsten rod was inserted into the chamber to serve as a beam block for the focused laser beam. A 50 mm $f = 1.2$ camera lens was used to image the spark onto an iris, which allowed additional laser reflections to be blocked in the schlieren optical path. A 500-mm-focal-length lens was placed in the optical path to create a virtual image of the spot at the focal point of the primary mirror of the z-path schlieren system, resulting in a collimated beam for the schlieren system. The secondary mirror in the schlieren system focused the beam onto a horizontal knife edge, and the resulting images were recorded with a Pixelvision 16-bit charge-coupled-device (CCD) camera with a 200-mm zoom lens and an indicated $f = 3.5$. Camera exposures for all images shown here were 25 ms. A background subtraction and a flat-field correction were applied to all recorded camera images.

Direct images of the laser-induced optical breakdown discharge used as the schlieren light source were taken with the CCD camera and were analyzed to examine the effects of the argon bleed on the spot intensity. In the current implementation, the laser-induced breakdown spot using argon bleed resulted in a 450% more intense light source (caused by both increased spot size and intensity) than a laser induced breakdown spot in air. The temporal duration of the discharge formed in argon was measured to be 148 ± 2 ns (full-width half-maximum), compared to 84 ± 2 ns for the discharge formed in air. The pulse-to-pulse jitter of the discharge is determined by the electronics of the Nd:YAG laser and is on the order of 3.5 ns for the current system with a temporal laser pulse width of 10 ns in duration. The strobe light used for comparison in these experiments had a duration of 1.47 ± 0.02 μs (although it is noted that improved strobe light sources on the order of 10 to 100 ns are available from various manufacturers).

Temporal intensity variations were analyzed by examining the standard deviation of image intensity in the schlieren system. Images

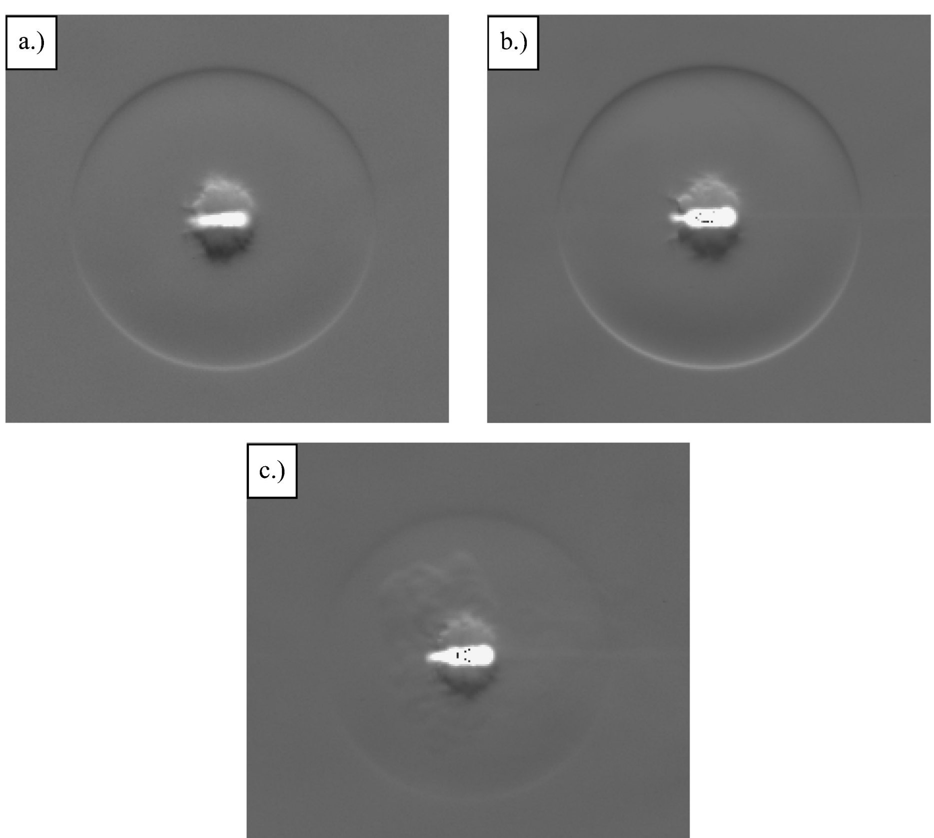

Fig. 2 Schlieren measurements of a shock wave and thermal spot 20 μs after the formation of a laser-induced spark discharge in air, imaged using a) a separate time-delayed laser-induced spark in argon as a light source, b) a laser-induced spark in air as a light source, and c) a xenon strobe light source.

were obtained from the schlieren system, in quiescent air, to evaluate the pulse-to-pulse intensity fluctuations when utilizing a laser-induced optical discharge as a light source. The schlieren images taken using a laser-induced optical discharge formed in air as a light source had a standard deviation of 7.8%. For the laser-induced optical discharge formed in argon, the pulse-to-pulse variation was slightly lower with a standard deviation of 5.2%

To demonstrate the quality of laser-induced optical breakdown schlieren source, especially in flows containing an optical discharge, measurements were performed with this system of the shock and vortex rings resulting from a spark discharge in air using three different light sources (a spark discharge in air, a spark discharge in argon, and a Strobotac 1538-A light source). The source position and knife-edge were kept constant for these tests.

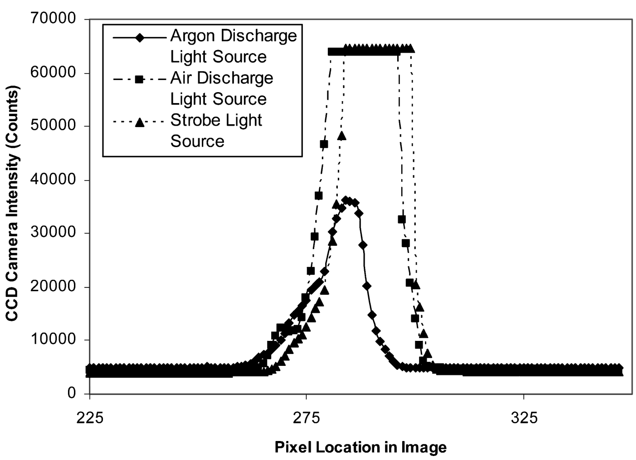

Fig. 3 Intensity traces through the laser spot images in Fig. 2, showing saturation in the camera in Fig. 2b and 2c images but indicating no saturation in Fig. 2a image.

Figures 2 and 3 show examples of these measurements. A second frequency-doubled Nd:YAG laser (92 mJ/pulse) was focused with a 7.62-mm lens to form a laser-induced breakdown spot in the measurement region of the schlieren system. The resulting shock wave and thermal spot can be seen, as recorded by the schlieren system 20 μs after the formation of the discharge event using the laser-induced spot in argon as a light source Fig. 2a, the laser-induced spot in air as a light source Fig. 2b, and the strobe light as a light source Fig. 2c. These images in Figs. 2 and 4 represent a measurement area of 30-mm width. For all of these images, neutral density filters were added to the camera imaging system, and the camera images have been rescaled to approximately balance the overall intensity of the images. This rescaling allows a more direct comparison of the contrast resulting in these images. In both Figs. 2b and 2c, a significant area around the spark discharge is saturated in the camera images. Figure 3 shows line plots of the intensity through the spark discharge images in Fig. 2. Again, these intensity plots clearly show that the spark discharge saturates these images when either a Strobtac or a spark discharge in air is used as a light source. By comparison, the laser-induced spark source in argon provides sufficient light source intensity so that good contrast can be maintained in the region of the spark source in the flowfield. Although the immediate vicinity of the spark in the flowfield still appears as a bright region in Fig. 2a, it is not saturated in the CCD camera, as can be seen in Fig. 3. The short duration of a laser-induced spark light source also allows a better resolution of the shock structure than the strobe source shown for comparison in Fig. 2c.

Figure 4 shows similar flow measurements 100 μs after the discharge event. In these images, the shock is no longer in the field

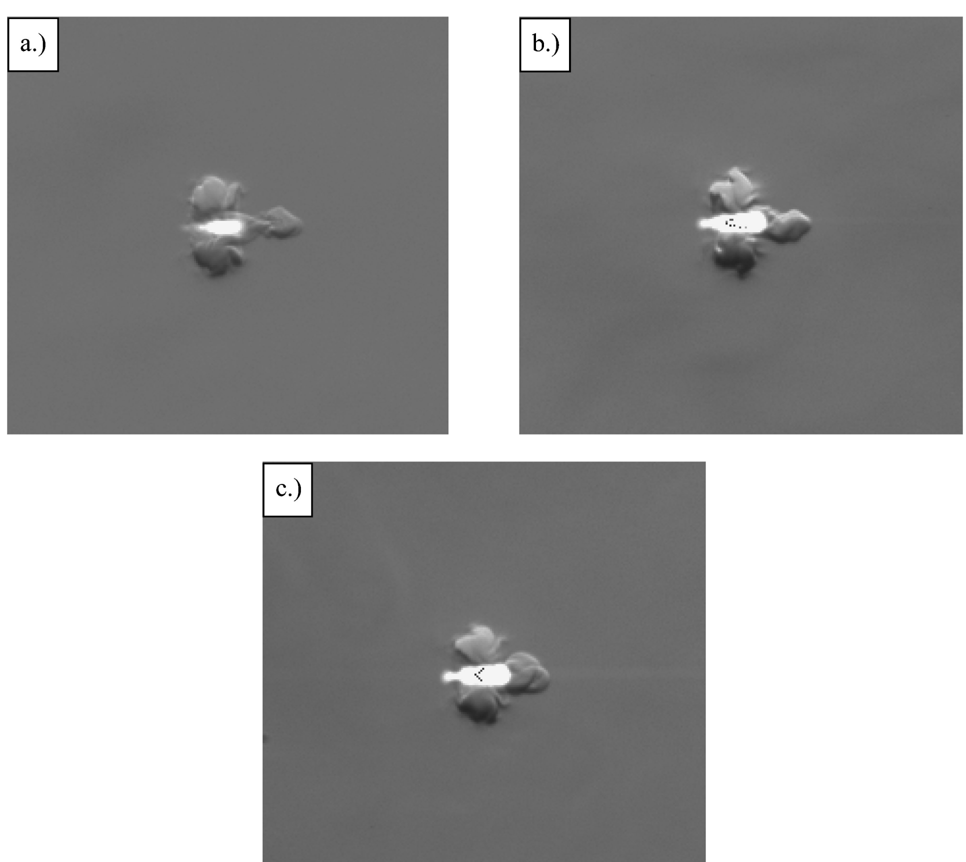

Fig. 4 Schlieren measurements of the thermal spot remaining 100 μs after the formation of a laser-induced spark discharge in air, imaged with a) the laser-induced spark in argon, b) in air, and c) a strobe light source. Improved contrast in the immediate vicinity of the spark discharge is achieved with a higher-intensity schlieren light source in panel a. (Note that it is not saturated in the actual image.)

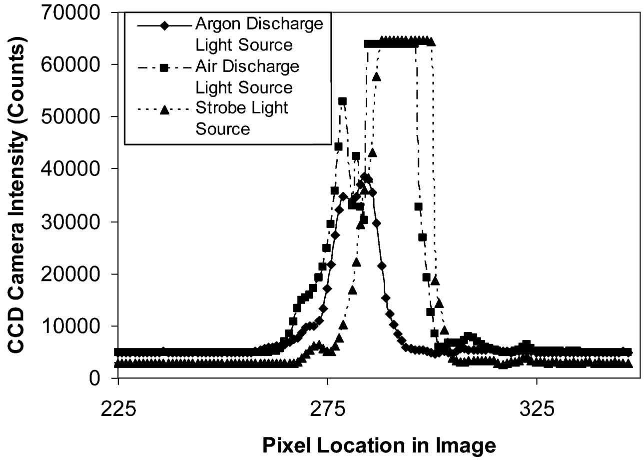

Fig. 5 Intensity traces through the laser spot images in Fig. 4, showing saturation in the camera in Fig. 4b and 4c images but indicating no saturation in Fig. 4a image.

of view, and the vortex rings in the vicinity of the spark discharge have formed and begun to expand, and the thermal spot remains. Although taken 100 μs after the spark discharge, and well after many of the interesting flow structures from this event have formed, the local saturation as a result of the broadband emission of the discharge event remains in Figs. 4b and 4c but is again eliminated in Fig. 4a. Figure 5 shows intensity traces through the Fig. 4a, 4b, and 4c images, again showing the saturation present in Figs. 4b and 4c.

Conclusions

An argon-purged open chamber has been used to create a high-intensity laser-induced spark light source for use in a schlieren system. This light source is approximately 450% higher intensity than a similar discharge in air, providing improved contrast in schlieren images for flowfields that generate strong emissions. In addition, the spark formed in argon shows slightly less intensity variation from shot to shot. This light source can be easily synchronized with triggering events in the flowfield, and the short duration of the laser-induced optical breakdown discharge makes it well suited for imaging moving shocks and turbulent flows. In addition the source has a high enough intensity to make it suitable for schlieren measurements in processes such as flames and plasmas that have their own natural emission.

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