Proceedings of the Seventh Fuel and Combustion Conference of Iran
Feb. 13 - 14, 2018, Sharif University of Technology, Tehran, Iran
FCCI-2018-1082

High Speed Schlieren by Using High Power Light Emitting Diodes

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Abstract
This paper describes the details of a novel high-speed schlieren imaging setup. In addition to the very precise layout in the schlieren setup, it is necessary to freeze the phenomenon in order to have a high resolution in the temperature contours. For high-speed imaging, a high-power diode has been used in over-current conditions. LED is a novel light source that have many advantages over lasers. By reducing the duty cycle, it is possible to increase the power of every pulses. Eventually, high quality images can be captured by synchronization of camera and the light source. Some factors including the effect of high speed imaging, setting the precise location of knife, and capturing low temperature gradient were investigated to have a high resolution and high quality schlieren setup. The results show that schlieren setup has an acceptable accuracy in detecting low temperature gradients and can be used to study the flame features.
Key word: Schlieren, high speed imaging, Light Emitting Diode

Introduction
Schlieren is an imaging method to study the flow of fluids with density variation. Schlieren was introduced by Toepler in 1864 to examine non-homogenous supersonic motions [1].
One of the factors of change in the density is temperature variation. Therefore, the Schlieren method is widely used in combustion studies. Today, almost all of the modern combustion laboratories are equipped with a schlieren imaging system. The schlieren images can be used to identify the flame front, the flame structure, as well as the distribution of temperature contours in the flame field. In addition to expensive mirrors and high precision adjustment systems, this imaging method also requires a high-power pulsed light source. Recently, new sources of light have been used instead of lasers at the schlieren setups. One of the most commonly used are Light Emitting Diodes (LED) [2]-[6]. Buttsworth and Ahfock developed a LED drive circuit with maximum current about 12 A and pulse width in the range of 1.5-38 microsecond. They used this illumination system to visualize hot air jet by schlieren imaging. In addition, they presented a financial comparison between LED and some other commercial stroboscopes. Their report illustrated that LED is a cost effective solution for flow visualization as a high speed pulsing light source [2]. After extensive studies on the feasibility of using the LED in the particle velocimetry, Willert et al. reviewed the performance of LEDs in the schlieren imaging. Comparing of the use of LEDs in the schlieren systems with laser as well as gas discharge lamps, they extracted the following results:
1- Using LED in continuous and pulsed conditions simultaneously makes it possible to be aligned the schlieren system much more easily than the others.
2- Due to low bandwidth, the chromatic aberrations reduce in LEDs. On the other hand, there is no evidence of speckle points on the sensor screen unlike laser coherent light.
3- Repeatability of the LEDs performance in pulse frequency uniformity, pulse exposure time, and brightness per pulse is more than the other light sources [3]-[5].
Wilson et al. examined a weak, under-expanded helium jet with high-quality schlieren images. They modified the original Willert circuit. A quantitative comparison between LED and HID lamp was demonstrated in that work. Findings showed that LEDs are ideal for low cost, high-speed schlieren imaging [6].
In the present paper, we examine the various aspects of developing a schlieren setup. In the first section, the operation of LED and its triggering are fully investigated. Then, the principles of a schlieren setup are presented and a common arrangement for combustion study is introduced. Ultimately, the accuracy and resolution of the schlieren setup have been analyzed from different points of view and the temperature contours of a flame are shown as the output of this system.

Light Emitting Diode

A light emitted diode (LED) is a semiconductor that irradiates visible light by passing electrons. The color of the light emitted from the LED varies depending on the gap energy of the semiconductor chip used in it. The irradiated LED light is non-collimated and non-coherent, with short optical bandwidth.

The light radiation of the semiconductor crystal is made by the presence of the P-N conjunction, due to the addition of impurities at the boundary of this connection. In general, the emission of light from a semiconductor by its placement in an electric field is called electroluminescence, which is the nature of the phenomenon completely different from light radiation from a solid surface based on Planck's theory. Figure 1 illustrates the operation of a LED. As seen, the electrons located on Wales energy band, namely N region, leave their places due to the electrical field, and consequently they creates holes in that area. These electrons are emitted to the pre-empty holes of the conduction band, namely P region. Since the electron energy band differs in two regions, P and N, the released energy dissipates in the form of heat or light through the passage of the P-N bond. In silicon and gallium crystals, the energy is released by heat. While Gallium arsenide phosphide and gallium phosphide crystals release the energy as light.

The electroluminance phenomenon, though discovered in 1907, Losev gave a realistic example of a LED for the first time in 1927. Since 1961, the thought of creating a commercial product similar to what we know today as LED is introduced by Biard and Pittman [8]. Among light sources made by humans, LEDs are far superior in efficiency and life time. Today, with the technological advances made in the development of this electronic instrument, the commissioning of optical diodes in high current and subsequently high exposures is possible. Also, the nature of LED is highly controllable, and one can use LEDs in the order of the nanoseconds pulse width and megahertz frequency in very high precision pulse conditions. Whereas, in lasers, firstly, the pulse width is not controlled continuously, and secondly, due to the time needed to amplify the light in each radiation, the radiation frequency is low and in the order of 100 Hz at the best conditions.

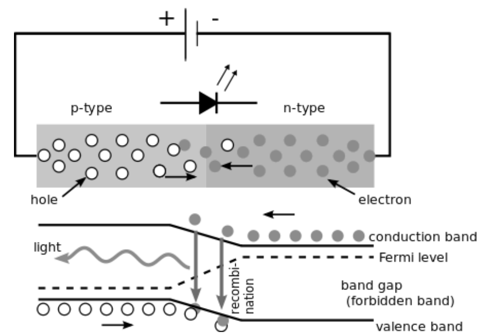


Fig 1. Light Emitting Diode performance [7]

Therefore, not only the common lighting systems have been replaced by the LEDs today, but the LEDs are an alternative to the laser light due to their power and controllability.

Comparing the LEDs and lasers, since the light emitted in a diode has a limited pulse width versus the single-frequency light of a laser, the speckles made by the interference phenomenon in the laser are not seen in the LEDs. Therefore, the resulting images have a higher resolution [9]-[10].

Among the diodes availability in the markets, Lumens Corporation has the most powerful and reliable diodes, with the family of CBT and PT diodes having characteristics suitable for use in pulsing conditions [11].

As mentioned, LED is used as a pulsed light source in our imaging setup. LEDs can be used in continuous or pulsed conditions. If LEDs are used in pulse conditions, there is also the ability to synchronize with single or multiple cameras. Compared to the laser light, LEDs have the following advantages:

1- Health Security: The light generated by the LED does not have the capability to focus on a thin beam such as a laser. Therefore, the risk of high-energy exposure beams will not be present.

2- Volumetric illumination: The volumetric illumination is used for backlight illumination like shadowgraphy and schlieren imaging. The radiometric flux generated by the LEDs has the optical density necessary to illuminate the measured volume. In addition, the extended emitting surface is fitted for the schlieren setup with the best quality.

3- Flexibility: The LEDs are easier to control than lasers. On the other hand, low weight and low sensitivity of LEDs are the advantages of LEDs in comparison of the lasers. In addition, LED light sources do not require shields against reflection.

4- Economical: In terms of cost, the use of LEDs is quite cost effective compared to the lasers.

Triggering Light Emitting Diodes

In order to set up LEDs with 1) high repetition frequency, 2) short pulse width, and 3) high power,

we need to carefully design a relatively complex power electronic circuit. Combination of the previous three features, requires accurate design and construction of electronic boards. Therefore, to generate a pulse state, a volt potential source and a switching circuit would be used, as shown in Fig. 2. As seen in the figure, a simple circuit diagram consists of a voltage source (Vs), a power switch (T1), an optical diode (D1), and a circuit generating digital pulse.
Another noteworthy point is synchronizing the light pulses and camera shutter exposures.

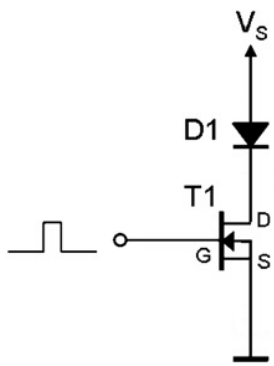


Fig 2. Schematic of Pulse Light Source Circuit

Figure 3 illustrates the pulse timing that requires to be implemented by a digital circuit. As seen in the figure, the light pulse is emitted for about a few hundred nanoseconds after the camera shutter for freezing the high speed phenomenon [9]-[10].

Schlieren Imaging Method

In the recent decays, the optical measurement techniques is widely applied for characterizing heat and mass transfer processes in fluids science. The optical measurement equipment usually works based on inherent characteristics of light for instance scattering or refraction. The interaction of light with matter is called scattering classified according to the ratio of light wavelength to the object characteristics length.
The principals of some measurement methods such as Rayleigh and Raman scattering, particle image velocimetry (PIV), laser Doppler velocimetry (LDV), phase Doppler anemometry (PDA), and laser induced fluorescence (LIF) is the light scattering by small scale particles [1]. Refraction is the change in direction of wave propagation due to a change in its transmission medium [12]. Interferometry, schlieren, and shadowgraph methods are defined as the refractive optical configurations.

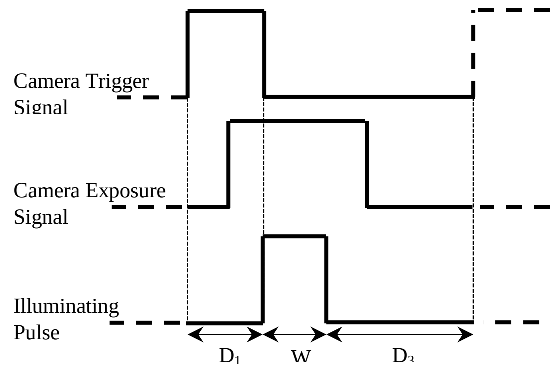


Fig 3. Pulse sequence produced by the microcontroller

This optical methods can be utilized to study the test sections with different refractive indexes compared to the reference medium. Temperature and concentration are two key factors to change the refractive index. Therefore, the refractive optical methods are usually applied to measure the temperature as well as the concentration in the transparent medium.
The superposition of two collimated electromagnetic waves from a coherent light source is namely interference. The light distance changes through crossing a transparent medium with different refractive index. The interference of the deflected light beam and the original beam forms a sequence of dark and bright lines known as fringes. Since the fringe size is in the length scale of the light wavelength, interferometry is a highly sensitive to the environment vibration and the stability of light source.
The light beam deflection makes schlieren method to be formed while the deflection and displacement of the light rays effect on the shadowgraph technique.
As explained, schlieren is applied to study the medium with variable refractive index. The light rays lag through passing a dense medium compared to a dilute one. As shown in Fig 4, it makes the deflection in the front of the light wave. The cumulative deflection angle is calculated as follows, where the surrounding medium is air

$$\alpha = \int_0^L \frac{\partial n}{\partial y} dz \qquad (1)$$

This angle is in the order of 10^{-6}-10^{-3} radians [13]. Based on these explanations, the Z-type setup of the schlieren method is illustrated in Fig.5. In this arrangement, the light is condensed by a lens to a pinhole. The pinhole acts as a point light source located on the focal length of a concave mirror. The test section is in the region between tow concave mirrors. In addition, a knife is set on the location of pinhole image to cutoff the light. After the knife, a camera records the schlieren images.

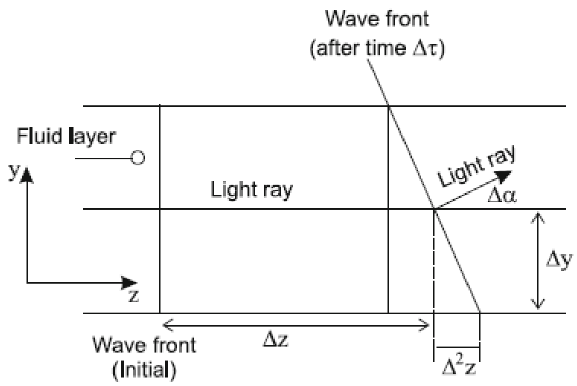


Fig 4. Schematics of light beam deflection [12]

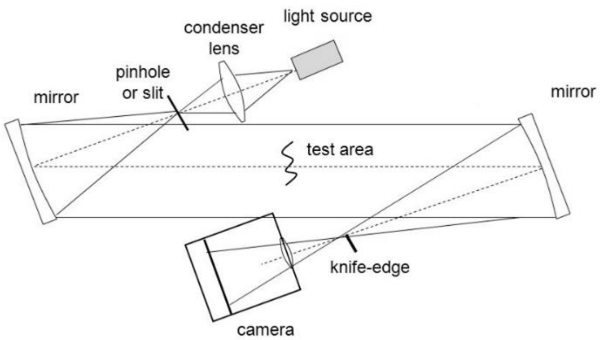


Fig 5. Z-type setup of the schlieren method [12]

The adjustment of the knife-edge plays a significant role in the quality of the schlieren image. Beside, disturbances to a schlieren setup include floor vibrations because of heavy machinery, and also the movement of laboratory personnel in the vicinity. The schlieren technique, however, is not nearly as vibration-sensitive as interferometry, where motion amplitudes of the order of a light wavelength are visible in the form of fringes. Since schlieren depends primarily on geometric, rather than principles of wave-optics, it is superior to interferometry in its resistance to shock and vibrations. If the sensitivity of the schlieren setup is deliberately reduced, either by a lower intensity cutoff by the knife-edge, or by replacing the knife-edge with a graded (gray-scale) filter, vibration errors would be truly minimal [14].

Experimental Setup

The main goal for schlieren imaging in this work was a candle flame in the atmospheric conditions (besides other experiments were illustrated as well). Images are captured by the Nikon D7200 camera with a 24 megapixel CMOS sensor equipped with AF-S NIKKOR 55-200 mm 1:4-5.6 lens. A point light source was created with a 100-micron pin hole. Two concave mirrors with a focal length of 83.71 cm and a diameter of 26.4 cm were used for this experiment. The distance between two mirrors was adjustable between 2 meters. Also, a razor blade located on a optical bench was applied as a knife.

The light source is an equipment named S-PhotoFreezer v1.00 [15]. S-PhotoFreezer is a LED based high power pulsing light source. The output power of S-PhotoFreezer is about 25 Watts and exposure time was set to 500 nanoseconds.

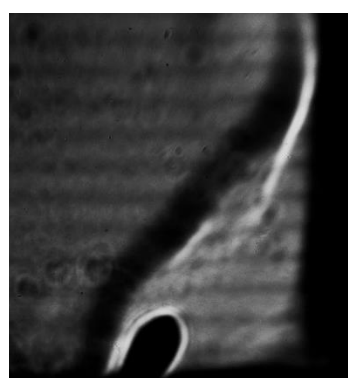
For high-speed imaging, the camera was synchronized with the light source through the S-PhotoFreezer timing section. The imaging speed (frame per second) of the schlieren system can adjust according to the camera specifications.

Fig 6. S-PhotoFreezer v1.00

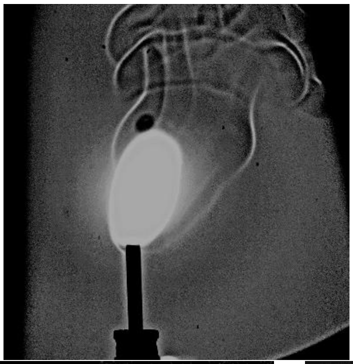
Results and Discussion

In the schlieren imaging, three factors affect the image quality:

1- Given that the flame is a transient phenomenon, it is necessary to reduce the exposure time to capture the sharp edges. As described, using a high power pulsing LED light source, the amount of light required for schlieren imaging is provided. In this work, although a conventional camera is used, but by using the S-PhotoFreezer synchronizer circuit, the images were recorded at around 250 nanoseconds. In Fig. 7, a comparison between the exposure time of a candle flame and a research burner [16] is shown.

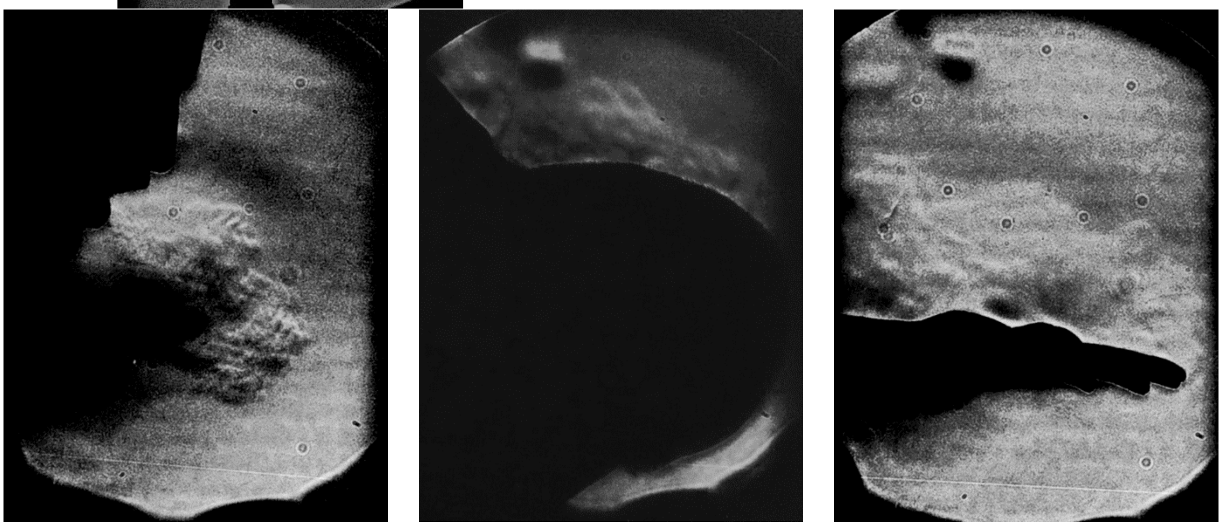


(a) Schlieren of a candle flame in long exposure time



(b) Schlieren of a burner flame in short exposure time [16]

Fig 7. The effect of the exposure time on the schlieren image quality



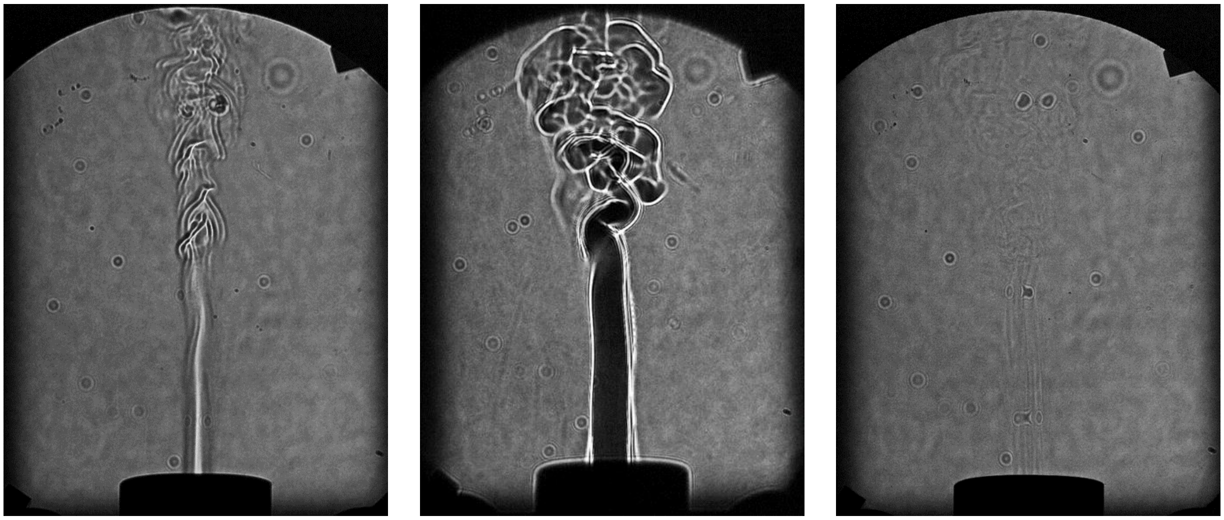
(a) breath (b) head (c) hand

Fig 8. Schlieren imaging of natural convection due to the heat body

Image is recorded using a continuous light source for a long exposure of shutter in Fig 7(a). While the image of research burner flame -Fig 7(b) is captured in a short exposure pulsing time. Comparison of these two images shows that, although the flame velocity in the research burner is far more than the flame velocity of the candle, the temperature gradient contours created in the schlieren image are much sharper in the burner flame.

2- Another striking feature for high-quality schlieren images is the sensitivity and ability to detect low temperature gradients. A schlieren setup is acceptable if it can capture the air motion caused by the difference in temperature between the human skin and the room temperature. In Figure 8, the air motion caused by human breathing (a), the temperature of the human head (b) and, finally, the palm of the hand (c) are demonstrated. In this figure, the temperature gradient contours are more distinct in the images of respiration, human head and palms, respectively.

3- A schlieren image will be perfect when the knife is really sharp and in position. To adjust the location of a knife, you need an optical bench. Figure 9 shows a comparison between the schlieren images for different knife locations.



(a) knife set on the correct place **(b) knife set on the wrong place** **(c) knife set on the wrong place**

Fig 9. Effect of knife location on the image quality

In Fig. 9(b), the knife is located ahead of the focal point of the second mirror, and in Fig. 9(c), the knife is located farther from the focal point of the second mirror. While in Fig. 9(a), the knife is positioned exactly on the focal point of the mirror.

Finally, the results of experiments (Figs. 7, 8 and 9) confirm that the present schlieren setup equipped by pulsed LED light source has an acceptable capability in combustion research. Finally, in Fig. 10, the temperature gradient contours above the candle flame are shown. In this figure, the candle flame is not observed. What is seen in this figure is the movement of the air stream caused by the difference in temperature and the resulting difference in the air density. In this figure, the image is captured at 30 frames per second.

The movement of air in these sequential photos is able to track due to the high speed imaging. It should be noted that the movement of air is not visible through the naked eye. Also, there is no significant temperature difference at the top of the flame. The pseudo-three-dimensional images shown in this figure indicate that perfect schlieren has occurred, and that the schlieren setup has been carefully embedded.

Conclusion

Light Emitting Diodes (LED) are powerful and controllable light sources that make it possible to implement a cost effective high-speed schlieren imaging system. Due to the structure of the LEDs, it is possible to record images at high frequency and short pulse widths by designing a circuit. This circuit also has the task of synchronizing LED and the camera at high frequency, we call this novel equipment as S-PhotoFreezer v1.00. A schlieren setup equipped with S-PhotoFreezer can detect low temperature gradients and identify natural convection flow due to the difference in temperature between the human body and the surrounding environment. Also, the results indicate that the schlieren system can be used to study the thermal plum created around the flame to identify the combustion structure.

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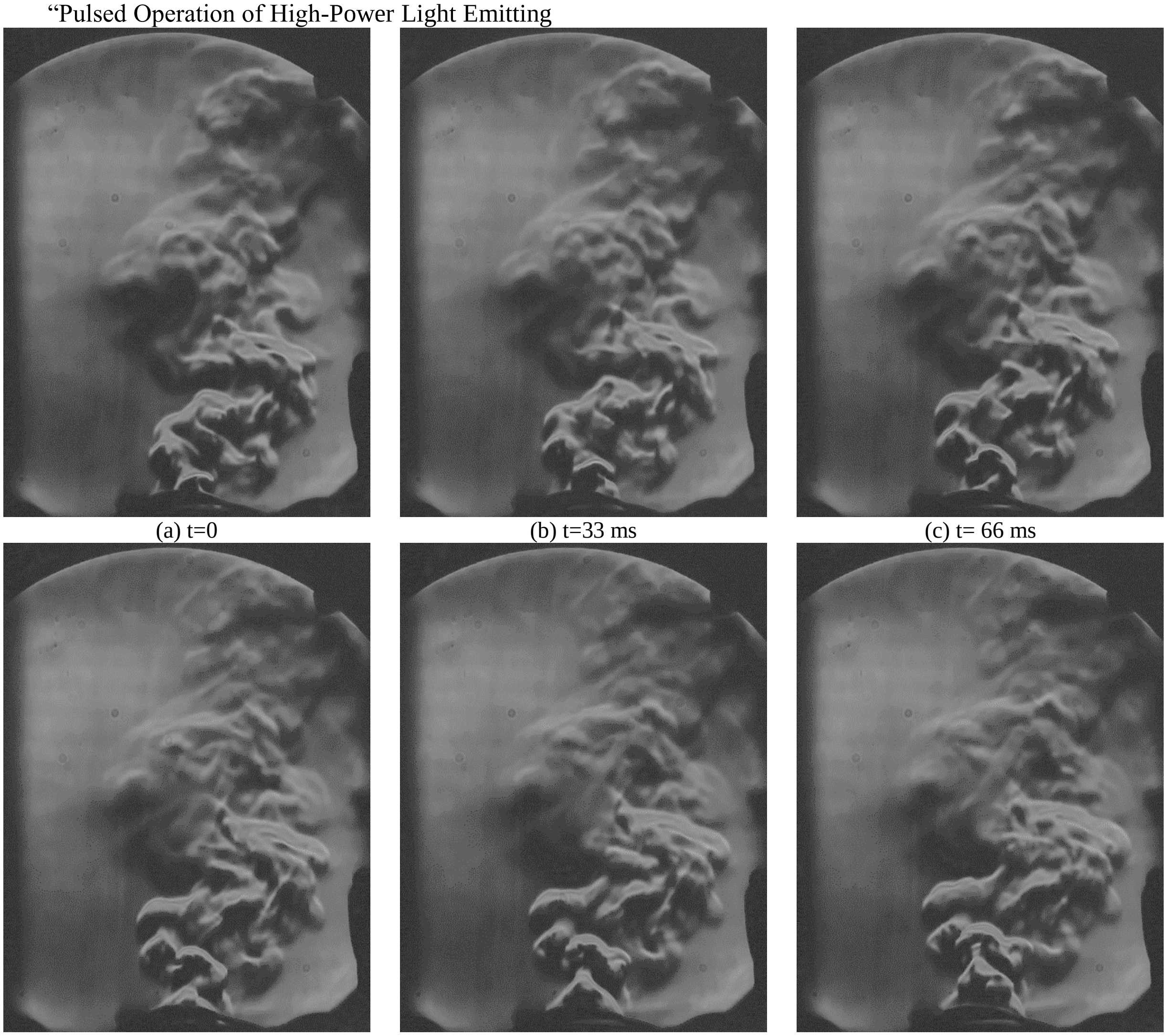

(a) t=0 (b) t=33 ms (c) t= 66 ms

(d) t= 99 ms (e) t=132 ms (f) t=165 ms

Fig 10. Schlieren imaging of the heat plume above a candle flame