ILASS – Europe 2010, 23rd Annual Conference on Liquid Atomization and Spray Systems, Brno, Czech Republic, September 2010

High Speed Shadowgraphy of a Combusting Air Blast Atomizer Spray at Elevated Pressure

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Abstract

This contribution demonstrates the use of a compact high repetition rate pulsed high power LED light source in combination with a high speed camera to obtain high speed shadowgraphs of an airblasted spray in a fired research combustor at medium pressures. The temporally resolved structures are subjected to conventional spectral analysis and exhibit very dominant fundamental frequencies throughout the visualized spray structures. The image data is further compared to time series of drop-sizing measurements made by a phase Doppler instrument. The periodicity is attributed to a spiraling spray release from the nozzle lip that is believed to be induced by a precessing vortex or vortices orbiting around the burner axis.

Introduction

In gas turbine combustion of liquid fuels, the fuel placement is of primary importance for the ensuing combustion characteristics. Current knowledge shows that the time dependent behavior of the flow as well as that of the atomization process of the liquid fuel itself exhibit coherent structures, which can have an influence on macroscopic features of combustion [1, 2]. Therefore, high speed visualization of the emerging spray and its mixing into the burner air flow is a useful tool to gain a quick overview on the unsteady phenomena which might be of importance throughout the operation range of the combustor. High speed imaging has seen a very rapid development in recent years with increasing camera performance at decreasing prices. Yet simple to use, low-maintenance, high speed light sources remained scarce until the recent introduction of high power LED [3]. In this contribution an application of a pulsed LED light source for high speed imaging is exemplified. The temporally resolved structures of the spray are compared with time series of drop-sizing measurements made by a phase Doppler instrument.

Materials and Methods

The facility, an optically accessible, single sector combustor, is described in detail in [4]. The general arrangement of the high speed shadowgraphy imaging setup was already described in [5] to study the atomization of a single kerosene jet issuing into an isothermal cross-flow. For the present application however a new high power LED source enabled the illumination of a significantly larger field of view allowing the full spray field downstream of the burner to be imaged at frame rates of 20 kHz. Details of the pulsed LED light source and experimental procedures will be presented next.

Figure 1 shows a photograph of the pressurized combustor facility in operation with the pulsed LED light source and high speed camera positioned on opposite sides. The components of the in-line illumination arrangement are schematically shown in figure 2. The light source is a high power light emitting diode (CBT-120, Luminus Devices) with a peak luminous flux of > 2000 lm at $\lambda_o = 526$ nm and a spectral width of about 40 nm (FWHM). Contrary to other high power LED devices that use a multitude of light emitting elements, this device emits light uniformly from a single die of 4.6×2.6 mm^2 area. The diode is driven with pulsed currents of $I_f = 10$ A for $\tau_p = 2$ μs using a laser diode driver (LDP-V 50-100 V3, PicoLAS GmbH). The emitted light is collimated using a combination of condenser lens ($f = 30$ mm) and Fresnel lens ($f = 100$ mm, $f_\# = 1.0$) and illuminates the optical accessible region downstream of the spray nozzle. A high speed CMOS camera (APX-RS, Photron) on the opposite side of the combustor focuses onto this region. Due to the strong flame luminosity (soot radiation) an interference filter ($\lambda_o = 532 \pm 5$ nm) was placed in front of the lens ($f = 105$ mm, $f_\# = 2.8$, Micro Nikkor, Nikon) to reduce the contribution of the flame luminosity and thereby enhancing image contrast.

With the camera frame rate set to 20 kHz the effective image area is reduced to 512×256 pixel which corresponds to a field of view of 65 mm wide by 32 mm high (magnification $\approx$ 8 pixel/mm). The camera is operated in a non-shuttered mode since the stroboscopic illumination by the LED ($\tau_p = 2$ μs) essentially freezes the motion of the spray during the 50 μs exposure time of each frame. Image intensity is optimized by adjusting the drive current of the LED.

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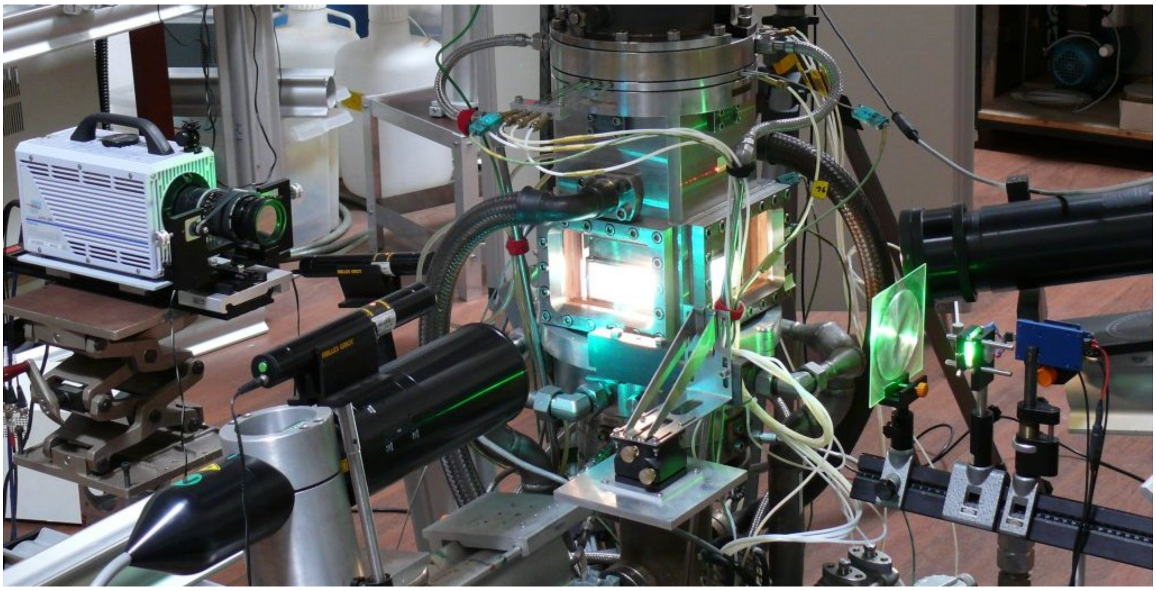

Figure 1. High speed shadowgraphy set up on the optically accessible single sector combustor facility during operation at 4 bar. The LED light source and collimating optics can be seen on the right while the camera is located on the opposite side to the left of the facility. PDA delivery and receiving optics are also visible

Results and Discussion

The compact, pulsed LED light source enabled the visualization of the global characteristics of the unsteady spray in the presence of combustion. The combustor operating conditions are summarized in table 1. Figure 3 shows an example of the evolving spray structure obtained at 20 kHz. Here dark regions are associated with high kerosene droplet concentrations. The field of view is about 65 mm wide by 32 mm high (512 × 256 pixel). The plane of the swirl burner orifice is located about 5 mm below the lower edge of the image. The visualized spray exhibit a zig-zag of concentration bands inclined about 30° above normal and can be explained with the imaged projection of a helical spiral of spray moving upstream into the combustor. The spray persists long enough to enter the combustion zone in which the spray is eventually completely evaporated.

The spiraling mode is even more apparent in animations of the image sequences. Extracting image intensities at a fixed location shows a clear periodicity (figure 4). The two traces were obtained at positions to either side of the burner axis and show a clear 180° phase difference. This is substantiated by the negative correlation between the signal at time lag zero (figure 4, bottom). The time trace data can be readily used to calculate frequency spectra. For the following examples image sequences of 1000 frames corresponding to a duration of 50 ms were analyzed. The spectra show a dominant frequency near $f_0 = 2.08$ kHz and harmonics thereof, summarized in table 1. The

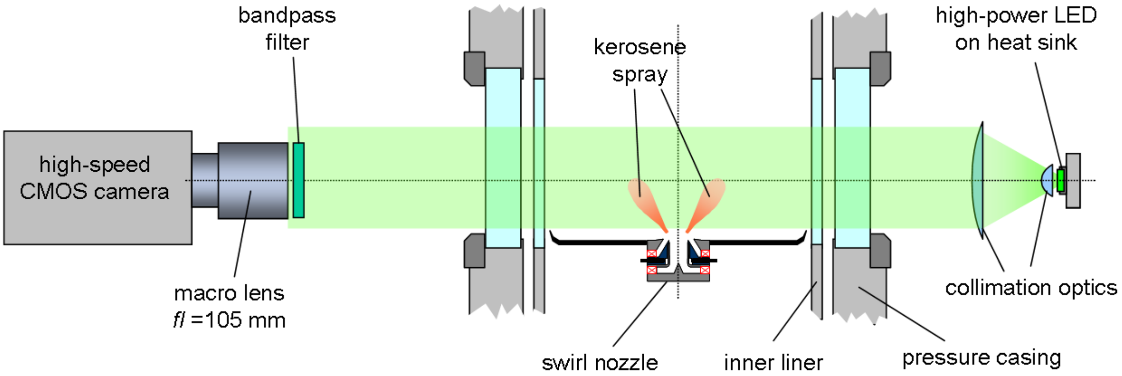

Figure 2. Schematic of shadowgraph imaging arrangement

Table 1. Operating conditions and measured dominant frequencies f_i

	PDA	Shadowgraphy No.1	Shadowgraphy No.2
	$p = 4$ bar	$p = 4$ bar	$p = 8$ bar
	$T_3 = 550$ K	$T_3 = 550$ K	$T_3 = 650$ K
f_0	2056 ± 1 Hz	2080 ± 20 Hz	2260 ± 20 Hz
f_1	4120 ± 1 Hz	4160 ± 20 Hz	4460 ± 20 Hz
f_2	-	6240 ± 20 Hz	-

fundamental frequency is representative of the periodic detachment of the helical spray structure from the burner exit into the combustion chamber. The higher harmonics are caused by the non-sinusoidal form of the time traces caused by the cessation of spray production for the time immediately after film breakup and cluster formation.

Phase Doppler measurements were performed in parallel to these visualizations [4]. A time series of 50000 samples acquired in about 0.9 seconds was used to calculate the spectrum of the axial velocity shown in figure 6. The velocity spectrum shows nearly the same dominant frequency at $f_0 = 2.06$ kHz as the spray visualization data suggesting a direct correlation between velocity field and spray distribution.

Following the observations of Becker & Hassa [1] it seems likely that a periodic fluctuation of radial velocity at the filmer lip from outward to inward movement is caused by a vortex convected with the mean swirl velocity, that is often found in swirling flows [6, 2]. This fluctuation in turn ruptures the liquid film by causing alternate elongations in the positive and negative radial directions. This results in a periodic release of a liquid parcel at any given location on the circumference of the filmer lip. In [2] such vortices were identified by particle image velocimetry (PIV) for a burner with a single swirling flow from radial swirlers and an inner body. Two vortices with 180$^{\text{o}}$ phase lag were found for the case of an inner jet and one vortex for the case without inner jet.

Conclusion and Perspective

To our knowledge this is the first application of high frame rate shadowgraphy to pressurized kerosene atomization in combustion, made possible through the use of high power pulsed LED light source and a high speed camera. The simplicity of the setup, its variability in terms of trigger frequency and pulse duration along with the absence of speckle artifacts (a common drawback of lasers) are just of few attractive features of this visualization technique.

The shadowgraph imaging configuration presented here was intended as a proof-of-concept and can be improved in several ways. The instantaneous LED emission can be increased by roughly a factor of 20 by overdriving the device with high currents. As demonstrated in [3] pulsed drive currents exceeding $I_{\text{f}} = 200$ A at $\tau_{\text{p}} = 2$ μs are feasible without damaging the device. Further improvements are possible with adequate interference filter used to block the flame radiation. At present a significant part of LED light was lost due to its limited bandwidth and transmission ($< 50\%$ at $\lambda_{\text{o}} = 532$ nm). Here it should be kept in mind that overdriving the LED results in a significant shift of emitted light toward shorter wavelengths by up to 30 nm [3]. Image contrast can be further improved by operating the camera in shuttered mode synchronized to the LED strobe flashes. At the given frame rate (20 kHz) and pulse width $\tau_{\text{p}} = 2$ μs this would result is a suppression of ambient light by a factor of 25.

The current imaging setup did not involve a diffusing screen as is common in shadowgraph setups. While this made the setup very light sensitive it also visualized small scale temperature gradients in the turbulent flame above the burner due to the associated light refraction. Given the possible margins of improvement allows a scattering screen to be added is which case the acquired images will exhibit less temperature gradient induced Schlieren.

The temporally resolved image sequences acquired with the imaging setup allow the efficient extraction of dominant frequencies in the ejected kerosene spray. Future work will concentrate on the coupling of unsteady atomization with the unsteady characteristics of the gas flow. The flow field information provided by phase-locked or time resolved PIV measurements in a plane normal to the burner axis is believed to shed light on presence of precessing vortices or similar cyclic features in the vicinity of the nozzle.

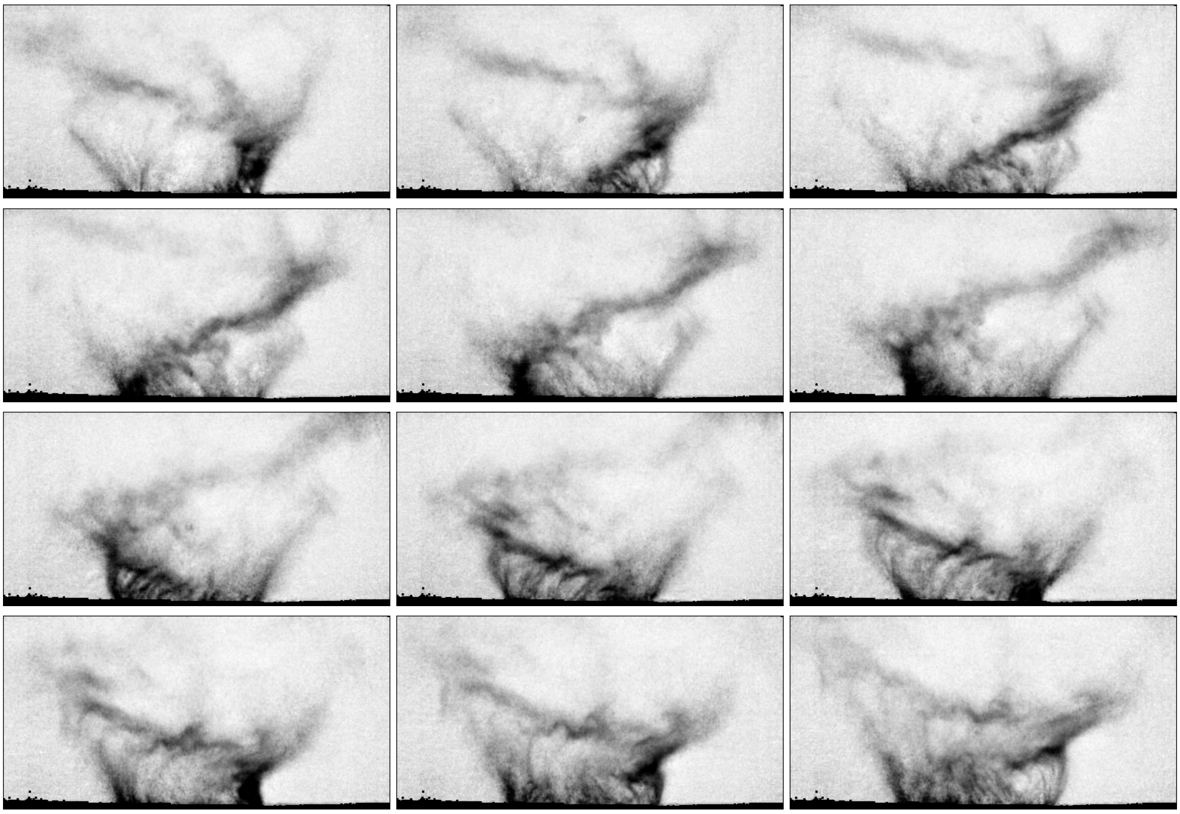

Figure 3. Successive shadowgraph images of the airblast spray at pressure $p = 4$ bar obtained at 50 μs time separation (20 kHz). LED illumination was limited to 2 μs to freeze the motion of the structures

References

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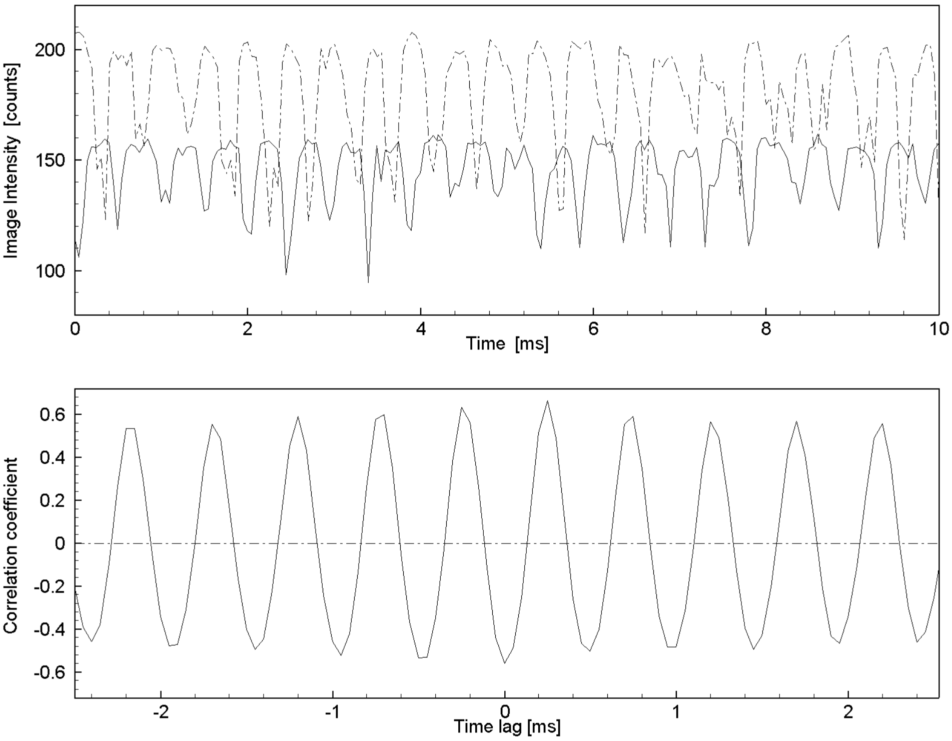

Figure 4. Time traces (top) and corresponding cross-correlation plot (bottom) obtained at $x = 15$ mm above the spray nozzle on opposite sides of the burner axis ($y = \pm 14$ mm)

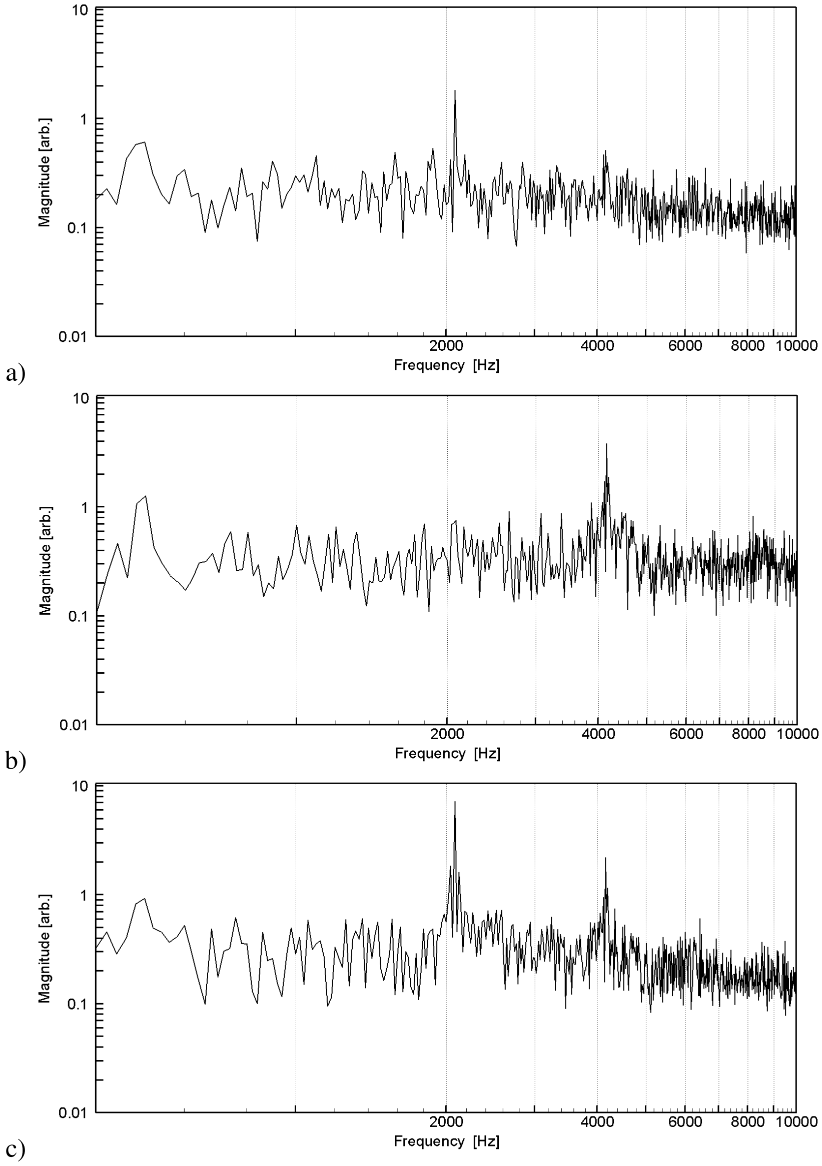

Figure 5. Frequency spectra obtained at 3 different locations using a sequence of 1000 images: a) near the outer edge of the spray, b) at the center line, c) at an intermediate position

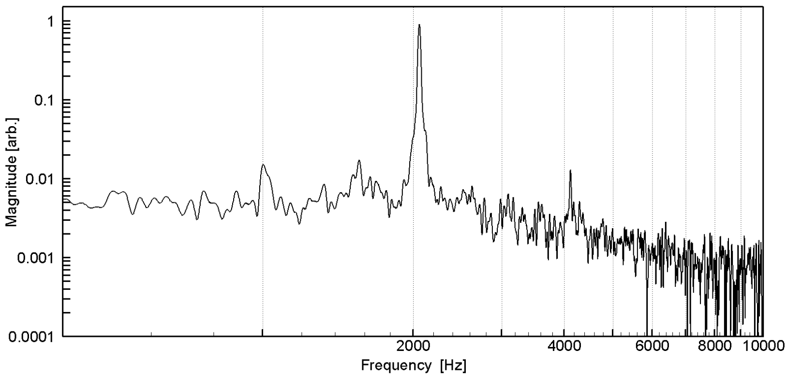

Figure 6. Frequency spectrum calculated from a PDA time trace of 50,000 samples obtained at $x = 12$ mm above the spray nozzle at a radial distance of $z = 7$ mm