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HIGH SPEED IMAGING OF FUEL SPRAYS USING A LOW-COST ILLUMINATION SOURCE

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ABSTRACT
The recent availability of (affordable) high frame rate electronic imaging with large frame counts now allows for parametric, time-resolved investigations of the liquid break-up processes that dominate the atomization. In previous investigations high-speed background shadowgraphy was used to observe the liquid sheet breakup process downstream of prefilming airblast atomizers. Here the choice of illumination was one of the challenges and ultimately employed a high-power continuous light source. A careful trade-off between sufficient camera exposure time and tolerable motion blur yielded images of adequate contrast to successfully complete the investigation. As an alternative to high power continuous light sources the article explores the use pulsed light illumination for imaging applications of this type. In particular recent efforts utilizing pulsed light-emitting diodes (LEDs) are described. Images acquired in an in-line illumination arrangement exhibit high contrast and practical absence of frame-to-frame intensity fluctuations, and thus are well suited for statistical and time-spectral image processing.

INTRODUCTION

The performance and emission behavior of aero-combustors depends strongly on the efficient atomization of the liquid fuel in the premixing zone. Jet-in-cross-flow and film layers are both fuel delivery concepts that exploit strong shearing between the fuel and surrounding air flow to ideally create uniform sprays. The process of spray formation and subsequent evaporation is and has been subject of various ongoing scientific investigations and is only partially understood for realistic combustor configurations, as they exhibit a combination of high speed, turbulent and swirling flows at elevated temperatures and pressures [1-4]. This environment can be partially reproduced in dedicated spray channels with optical access allowing the application of optical diagnostic techniques. Here phase Doppler anemometry provides information on droplet size and velocity of the developed spray while shadowgraphy offers insights in the early development stages of atomization.

The recent availability of (affordable) high frame rate electronic imaging with large frame counts now allows for parametric, time-resolved investigations of the liquid break-up processes that dominate the atomization. In previous investigations high speed background shadowgraphy was used to observe the liquid sheet breakup process downstream of prefilming airblast atomizers [3,4]. Here the choice of illumination was one of the more critical challenges and ultimately employed a high-power continuous light source. A careful trade-off between sufficient camera exposure time and tolerable motion blur yielded images of adequate contrast to successfully complete the investigation. Obviously pulsed light illumination is the method of choice for imaging applications of this type and recent efforts on this behalf are the central subject of this article.

Two types of light sources are commonly used for pulsed light illumination: high-speed (Xenon) flash lamps or lasers. The former offer pulse lengths in the microsecond range but are not readily available for pulse rates in the 100 kHz range. While sub-microsecond pulses are readily generated by lasers their cost and especially undesired effects arising from laser speckle have to be considered.

A further alternative is offered by light emitting diodes (LEDs) which have undergone a considerable development in recent years making them viable alternative to existing light sources in many application areas. While LEDs are commonly used in a continuous mode, they can also be operated in pulsed mode at significantly higher currents and light output. This was demonstrated already in the mid-80's by Stasicki et al. [5,6]. More recent investigations are reported for instance in [7] as well as for Schlieren imaging [8], shadowgraph particle image velocimetry (PIV) [9,10] and micro-PIV [11].

EXPERIMENTAL APPARATUS

The spray investigations presented here were conducted in the LPP (Lean Premixed Prevaporiser) spray test facility of the DLR Institute of Propulsion Technology. The LPP test facility is designed to carry out research on two-phase, non-reacting flows at high pressures and temperatures simulating near real gas turbine inlet conditions to the combustor. The test facility can be operated at a maximum static pressure of p=20 bar and static temperature of 850 K. The test section is made of optical quality glass windows. For the visualizations presented in the following the kerosene is introduced wall-normal through single circular orifices of D = 0.3 – 0.5 mm in the middle of the test section.

In the present investigation the aim was to use sub-microsecond illumination from the LED to avoid motion blur in a high magnification shadowgraphy configuration. As shown in Fig. 2 a 3W red LED (Lumileds, Luxeon III, λ=627 nm) with separate condenser lens was arranged in an in-line configuration. The LED was supplied by current pulses of 230 ns duration from a high-speed MOSFET driver stage that was synchronized with the frame rate of the high-speed CMOS camera (Photron APX-RS). A f = 105 mm macro lens imaged the investigated jet-in-cross-flow at about 1:2 magnification (69.4 pixel/mm) using apertures of $f\#$ =5.6 – 8.

One major difference to previously conducted high speed spray imaging (i.e. [3,4]) was the absence of diffuser screens in the in-line optical arrangement. This increased both the overall light availability and image contrast. In effect the luminous area of the LED was projected onto the sensor by the condenser lens.

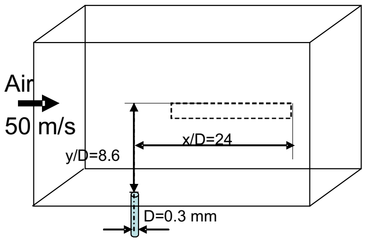

Fig. 1 : Schematic of jet in cross-flow arrangement in spray facility along with imaged region.

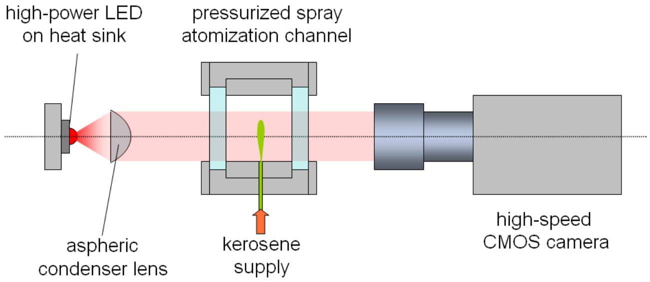

Fig. 2 : Shadowgraph imaging set-up for the jet-in-cross-flow investigation

Fig. 3 : Single shadowgraph image of the kerosene spray entering an oncoming flow of U_∞ = 50 m/s from the left. LED illumination pulse was 230 ns. The field of view is 11 mm wide (Flow parameters: D=0.3 mm, U_∞= 50 m/s, p=4 bar).

SAMPLE RESULTS & POST-PROCESSING

Fig. 3 provides one example of an image acquired with the described pulsed LED shadowgraphy setup. The rather short illumination – 230 ns vs. 10 µs with continuous illumination – significantly reduced motion blur. This along with the sharply focused droplets and considerable image contrast are characteristics that were previously unattainable with strobelights (Nanolight) or continuous illumination. In part the good quality can be attributed to the reduced chromatic aberration from the narrow banded red LED illumination (about 20 nm FWHM).

Fig. 4 shows a subset of 14 consecutive images obtained at 100 kHz in the upper portion of the evolving spray field. To achieve a high framing rate the image resolution was reduced to 384 x 48 pixels.

The high frame rate allows tracking of features over many frames. Although the images are rather small, shadowgraph PIV or PTV is feasible on these images. In a first attempt conventional PIV processing was successfully applied on 100 images to extract the mean droplet velocity shown in Fig. 5. Prior to processing several image contrast enhancing steps were necessary. First the image was inverted to obtain bright droplets on a dark background. Second, high pass filtering enhanced the intensity gradients to which the correlation analysis of PIV is most sensitive. The PIV processing itself utilized sampling windows of 24x12 pixels (340 x 170 µm^2) on a grid of 6x6 pixels. Measurements of this type are believed to augment more precise PDA/LDA measurements further downstream.

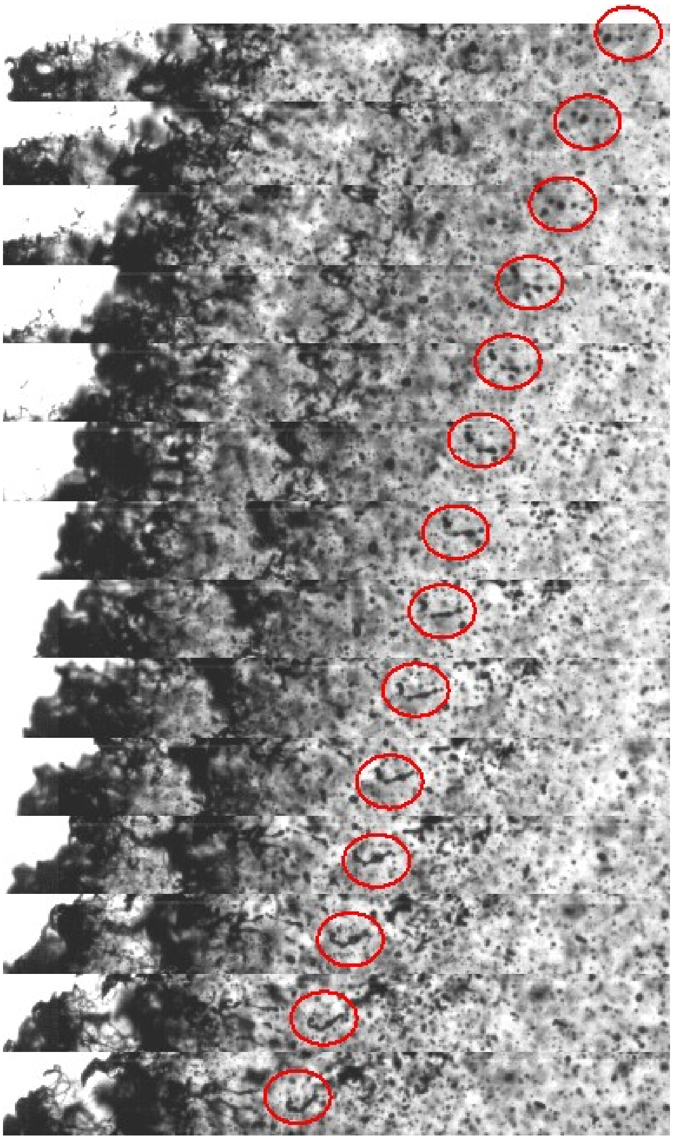

Fig. 4 : Sequence of shadowgraph images obtained at a frame rate of 100 kHz. The imaged region is about y/D=8.5 above the wall (see Fig. 1). Time is from bottom to top. (Flow parameters: D=0.3 mm, U_∞= 50 m/s, p=4 bar).

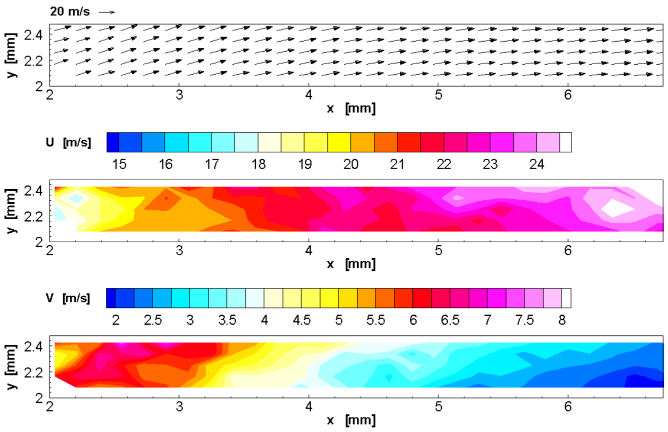

Fig. 5 : Mean droplet velocity downstream of the jet break-up. Contour maps represent the horizontal velocity component (middle) and vertical component (bottom).

In a second set of experiments the complete jet was imaged at 105 kHz and a resolution of 128x80 pixels. Here the motivation was to use a large number of images to estimate the mean penetration depth of the kerosene spray into the flow. Prior to computing image statistics, flat field intensity correction was applied to account for non-uniformities of the illumination source as well as fixed pattern noise and gain variations on the sensor side (Fig. 6).

Both the mean and standard deviation images provided in Fig. 7 show very good convergence and suggest that statistical analysis based on large image sequences obtained with the presented image hardware is feasible, even at rather low image resolutions.

As indicated in Fig. 7 (bottom, right) image feature extraction can also be used to estimate the jet breakup position and penetration depth. The long, continuous image sequences also lend themselves to spectral analysis and are subject of current investigations.

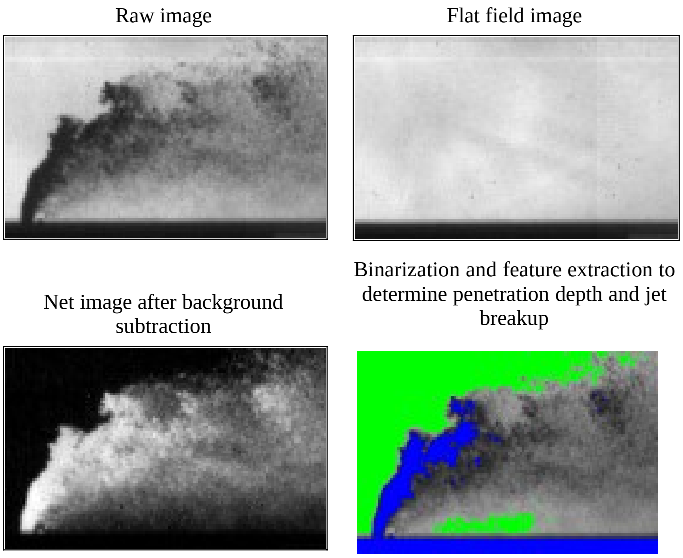

Fig. 6 : Image processing steps for estimating the jet penetration depth and jet breakup location.

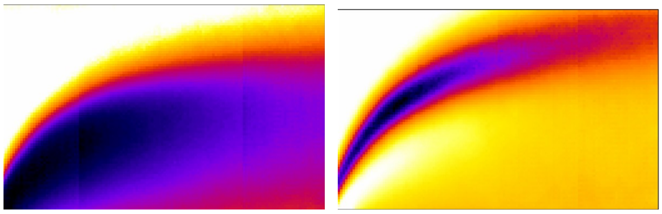

Fig. 7 : Mean (left) and standard deviation (right) of the gray values derived from 10.000 frames as an indicator of the vertical jet penetration depth (Flow parameters: D=0.5 mm, U_∞= 100 m/s, p=4 bar, q = 6)

CONCLUSIONS AND OUTLOOK

A high speed camera together with a low cost, pulsed LED illumination source demonstrated that high quality shadowgraph image data of atomization fuel sprays can be obtained. High image contrast, low motion blur, constant light flux and the absence of speckle effects are very appealing advantages of LED based shadowgraphy. While not shown here shadowgraph PIV images at full camera resolution can be achieved using frame straddling approaches that are commonly used in conventional PIV allowing detailed measurements of the projected droplet velocity field.

Due to the in-line configuration the LED could be operated at a rather low current leaving considerable head room for possible off-axis investigations. Further application potential of pulsed LED illumination is expected for background oriented Schlieren (BOS) or potentially even as a light source for fiber-delivered PIV.

The development of high powered LED technology for use in automotive and lighting applications is expected to rapidly continue over next years. Optical diagnostics, such as the high-speed droplet shadowgraphy presented here, are very likely to take profit of these advances.

NOMENCLATURE

Symbol	Quantity	SI Unit
λ	wavelength of light	nm
D	diameter of fuel jet orifice	mm
p	pressure in test section	bar
q	liquid-to-air momentum flux ratio	-
u	droplet or ligament velocity	m/s
U_∞	free stream velocity	m/s
FWHM	full-width, half mean	

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