

High-Speed Imaging of Early Flame Growth in Spark-Ignited Engines Using Different Imaging Systems via Endoscopic and Full Optical Access

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ABSTRACT

This work investigates the image quality achievable with a large-aperture endoscope system and high-speed cameras in terms of detecting the premixed flame boundary in spark-ignited engines by chemiluminescence imaging. The study is an extension of our previous work on endoscopic flame imaging [SAE 2014-01-1178]. In the present work, two different high-speed camera systems were used together with the endoscope system in two production engines to quantify the time-resolved flame propagation. The systems were cinematography with a CMOS-camera, both with and without an intensifier, the latter variation being used in a four-cylinder automotive engine as well as in a single-cylinder motorcycle engine. An algorithm with automatic dynamic thresholding was developed to detect the line-of-sight projected flame boundary despite artifacts caused by the spark and the large dynamic range in image brightness across each time series. A fundamental problem in evaluating the systems' efficacy is that it is not clear what constitutes "correct" detection of flame boundary. To help clarify this question, the endoscopic results are compared among each other and to a "best-case scenario", which was unintensified high-speed imaging with a large-aperture commercial camera lens in an engine with full optical access. We find that for the part-load operation examined here, broadband unintensified imaging through the endoscope yields useful and physically plausible results during all of the early flame propagation. Imaging is most challenging during inflammation, when the spark ignites the first small volume of mixture. For the conditions examined here, the chemiluminescence of the flame then is just at the level of the camera's background-corrected read-out noise, while the spark in the immediate vicinity can still be very bright.

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INTRODUCTION

Early flame-front propagation has been investigated in research engines with optical access for quite some time, partly because this stage of combustion is closely associated with cycle-to-cycle variability. Combustion can be detected by imaging of chemiluminescence (CL) from excited OH- and CH-radicals [1, 2] or sodium added to the fuel [3], by schlieren techniques [4], or by OH- and formaldehyde LIF [5,6,7]. (This collection of examples is far from exhaustive.) Each of these techniques delivers two-dimensional (2D) images, or time sequences thereof, but since their signal generation is based on different principles, they deliver information on different aspects of the complex three-dimensional (3D) time-dependent phenomena of premixed turbulent flame propagation. In particular, methods that are based on thin laser-light sheets show a 2D section through the enflamed volume of gas, while "passive" visualization and schlieren techniques yields a line-of-sight (LOS) integrated 2D projection of the 3D volume. In general, the former class of techniques is more suitable for small-scale quantification of physio-chemical properties like flame speed, local convection, and flame wrinkling. An excellent recent example is the detailed

examination of local flame propagation velocity in an engine in [7]. The latter class of measurements, in particular CL imaging, is much simpler in its implementation but correspondingly yields less detailed results, principally, because of the loss of information that accompanies the LOS projection.

Nevertheless, much useful information about early combustion and even flame-front propagation in optically accessible spark-ignited (SI) engines can and has been obtained with all of these techniques. Even some of the LOS-integrated investigations show a strong correlation between combustion imaging and pressure-derived heat release [1, 2] [4]. Hence, such imaging can be used as indication of reaction progress. However, in research engines with large-scale optical access, less mechanical strength, reduced cooling, and altered thermal conductivity reduce the operating range in speed and load. Furthermore, the in-cylinder flow, with its influence on flame wrinkling and convective flame displacement, can be different from a production engine due to modifications needed to create optical access, for example, greatly increased crevice flows.

The emphasis in endoscopic access is on minimizing the impact on operating conditions, i.e., keeping thermodynamics, heat transfer, and speed/load range as close as possible to that of an all-metal engine. Therefore, engines with endoscopic access never yield the same degree of freedom in terms of optical diagnostics. Additionally, most endoscopes employed for in-cylinder imaging were not originally designed for such use but are essentially modified medical instruments. Their light-collection efficiency is modest and most cannot be used in the ultraviolet (UV). This limits their use to processes generating much detectable light like Mie-scattering from sprays [8, 9] or flame luminosity and soot formation in diesel engines [9,10,11,12,13]. Also demonstrated were two-color visualization of 2-D soot luminosity to obtain the spatio-temporally resolved flame temperature [14, 15] and particle image velocimetry (PIV) [16]. These are all techniques that can rely on high levels of light in the visible spectrum. However, premixed combustion in spark-ignited (SI) engines emits relatively little light, much of it in the UV. Endoscopic access has been used to image SI combustion, for example to reconstruct the three-dimensional movement of the flame [17], flame visualization under very high thermal load in a racing engine [18], and more recently to identify pre-ignition kernels [19]. Each of these investigations met its goals, but the spatial resolution of the custom-built imaging systems was rather limited -maybe still best in [17], but the equipment was very specialized.

The recent development of a now commercially available UV-transparent endoscope with relatively large aperture [20] enabled the detection of weak signals from premixed combustion [21] or laser-induced fluorescence in the UV [22] with the good resolution obtainable by off-the-shelf scientific cameras. Using this endoscopic system in two production engines, in the present paper we compare premixed “flame-front” detection via different detector options with measurements in an optical engine. This study is in direct extension of our previous work on endoscopic flame imaging [21]. However, while in that earlier paper we mostly focused on phase-locked snapshot imaging with intensified CCD cameras, the current work is based entirely on cinematographic CMOS high-speed imaging, both with and without an intensifier. The kHz repetition rate of CMOS camera systems allows following the flame development in each single cycle with sub-crank-angle temporal resolution. Together with the corresponding cycles’ pressure traces, a wealth of detailed information on combustion can be acquired in little time. However, CMOS cameras that are designed for these very high frame rates exhibit much more (and in some cases less repeatable) read-out noise than cameras based on CCDs or noise-optimized “slow” CMOS detectors. Similarly, image intensifiers for kHz repetition rates degrade image resolution, dynamic range, and photometric accuracy even more than their “slow” counterparts for applications with typical video rates of up to 100 Hz [23]. In view of these limitations that high-speed camera systems currently have, the present work explores how well premixed combustion imaging can be performed with the relatively small optical access granted by endoscopes.

EXPERIMENTS

Engines

Endoscopic imaging was performed in two production spark-ignition engines from BMW, an automotive 4-cylinder engine and a single-cylinder motorcycle engine, both port-fueled for premixed stoichiometric combustion. Although the data examined here are from part-load operation, both engines could still be operated over their full speed and load range with the endoscopes in place. At throttled part-load, however, combustion imaging is more challenging than at high loads because the chemiluminescent light emission from the flame in the less dense air/fuel-mixture is less intense [21]. In addition to endoscopic imaging the two production engines, we also acquired similar image series in a fully optically accessible single-cylinder research engine (AVL, Graz), utilizing that engine’s large optical access for “conventional” lens-on-camera imaging. Parameters and operation conditions for both optical and production engines are summarized in Table 1.

Table 1. Engines parameters and operating conditions.

Engine	4-cylinder automotive (endoscopic)	Single-cylinder motorcycle (endoscopic)	Research engine (full optical access)
Cylinders	4, inline	1	1
Compression ratio	10	10.8	10
Displacement [cm ³]	499	652	499
Bore [mm]	84	100	84
Stroke [mm]	90	83	90
Speed [min ⁻¹]	2000	1500	1500
Fuel	Iso-octane	RON 95	Iso-octane
Rel. fuel/air-ratio	1.0		
Ignition timing [°CA]	-34.5	-45	-45
IMEP [bar]	4.4	3.8	2.2

4-Cylinder Automotive Engine

The automotive engine, operated at the Institute for Combustion and Gas Dynamics (IVG) of the University of Duisburg-Essen, was the BMW 4-cylinder model N46B20. It features a mechanically variable intake-valve train (“Valvetronic”), controlling the load by reducing the valve lift and opening duration in part-load operation. The engine speed was controlled by the dynamometer, while the load was set by an analogue input to the OEM engine control unit (ECU), which then determined all other parameters like fuel injection, ignition timing (IT), as well as valve lift and valve timings. It was not possible to actively change the ECU’s parameterization, but all relevant values could be read out. In the current work, the engine operated at 2000 min⁻¹ and 75 Nm, the maximum torque at that speed being 176 Nm. To achieve this load, 4.4 bar IMEP, at 1000 mbar intake pressure, the ECU set a maximum intake valve lift of 2.2 mm. Note that the low valve lift may cause an in-cylinder flow substantially different from that with conventional valve operation, which in turn may influence flame propagation.

Single-Cylinder Motorcycle Engine

Additional endoscopic imaging was done in a production single-cylinder engine produced by BMW/Rotax for the F650 motorcycle series. The engine at the Institute for Combustion Engines (IFKM) of KIT had phase shifters for intake and exhaust. Engine speed was controlled by a dynamometer, while load, cam phasing, injection and ignition parameters were controlled with the prototype engine control system ADWin Pro II. The valve lifts for intake and exhaust were 10 mm and the engine was throttled to intake pressures of 700 mbar at 1500 min⁻¹. Despite the modest throttling, the engine's indicated mean effective pressure (IMEP) was only just under 4 bar, presumably due to valve timings optimized for high-rpm performance.

“Optical” Research Engine

At the IVG, similar experiments were then also performed in a fully optically accessible single-cylinder gasoline engine (AVL Graz) with a pent-roof four-valve head and a flat piston top. The engine was operated on premixed air/fuel charge, throttled to an intake pressure of 700 mbar. Additional throttling by reduced lift of the intake valves (3.0 mm) and the exhaust (3.5 mm) valves resulted in a part-load condition with even less IMEP than that in the endoscopic experiments.

Imaging

Endoscope System

In the 4-cylinder automotive engine, the main modifications to the engine were two additional ports in the fourth cylinder (by the gear box), creating optical access via two endoscopes with 10 mm diameter each, one for laser input (optional, not used here) and another for observation. To enable optical diagnostics over the full operating range of the engine, the front section of the endoscope was protected from the combustion chamber's pressure and temperature by a 3 mm-thick sapphire window, mounted in a titanium bushing with an outer diameter of 12 mm. A schematic drawing of the endoscopic imaging systems is shown in [Figure 1a](#). The single-cylinder motorcycle engine was modified to receive the same endoscope, which protruded through the timing belt's casing.

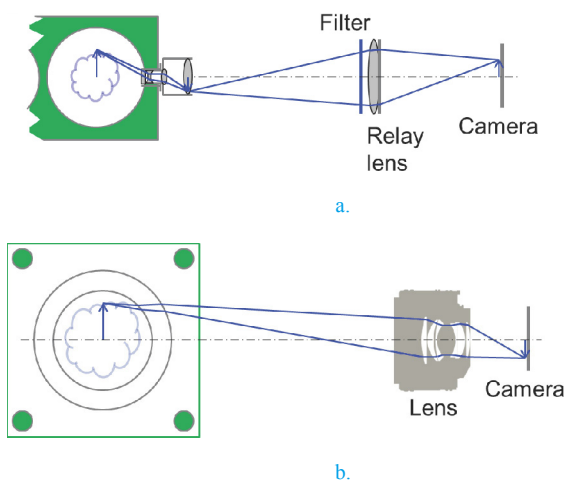


Figure 1. Schematic diagram of imaging with (a) endoscopic access and (b) large optical access

The optical system utilized a two-stage concept. A front endoscope with wide-angle characteristics was mounted directly in the engine, creating an intermediate image on a field lens. The maximum angle of view was about 60°, yielding a field of view (FOV) with a diameter of about 30 to 45 mm (depending on the engine bore) in the center of the combustion chamber. All lenses in the endoscope are made from UV-grade fused silica. The collection efficiency of this endoscope is about equivalent to that of a 105 mm f/4.5 UV-Nikkor lens [20], which is quite poor compared to commercial lenses for typical low-light imaging applications in the visible, but actually very good for an endoscope system.

A relay optic, isolated from the vibrations of the engine, projected this intermediate image onto the camera. For imaging in the UV, the relay optic was a dedicated hybrid refractive-diffractive optical (R-DO) element, correcting the system's inherent chromatic aberrations [20] (but in the present narrow-band application these are not expected to be significant). For imaging in the visible, a commercial camera lens was used instead to re-project the intermediate image. The system was designed in a previous project and is now commercially available from LaVision, Germany. With this endoscope system, imaging was carried out in three different experiments, whose detection-train characteristics are summarized in [Table 2](#). Additionally, imaging with a high-speed CMOS camera and a commercial large-aperture lens was performed in the optical research engine, as detailed in a section below.

Table 2. Main parameters of the imaging systems

Imaging system	Endoscopic, intensified (HS-OH*)	Endoscopic, unintensified (HS1)	Endoscopic, unintensified (HS2)	Full optical access, unintensified (HS)
Engine	4-cylinder automotive	4-cylinder automotive	Single-cyl. motorcycle	Research engine
Camera type	ICMOS	CMOS	CMOS	CMOS
Repetition rate (Hz)	6688	11019	9009	18018
Exposure time (μs)	20	20	29	15
Spectral window (nm)	300 – 335	400 – 800		400 – 800
(Relay) lens system	Hybrid R-DO	50 mm f/1.2 + 250 mm close-up lens		50 mm f/1.2
Region of interest (pixels ²)	800 x 600	608 x 456		512 x 312

The schematic diagram of flame and combustion chamber in [Figure 1](#) can also help to discuss the line-of-sight nature of our imaging technique and to define some of the terminology. The premixed turbulent flame in a spark-ignited engine is wrinkled and often highly three-dimensional. The imaging systems each project chemiluminescence from a range of species in and at the edge of that volume onto the two-dimensional detector. This line-of-sight (LOS) projection will be called the “projected burnt area” (PBA) and its outer perimeter in the images the (projected) “flame boundary”, the latter to distinguish it from the physical three-dimensional flame front. Similarly, the true turbulent flame speed is inaccessible through our LOS imaging, while the imaged 2D expansion of the PBA in time is termed “flame growth rate”. An even simpler scalar metric of this expansion is the “equivalent flame radius”, which will be introduced in a section below.

Intensified High-Speed Cinematography (HS-OH*)

Since the electronically excited hydroxyl radical OH* is usually considered to be a good marker of the high-temperature zone in premixed combustion, our initial experiments were aimed at using this species' UV chemiluminescence for flame-front visualization [21]. In the "intensified high-speed" configuration, OH* visualization was performed with an active-pixel sensor CMOS camera (Phantom v7.3), lens-coupled to an image intensifier with a UV-sensitive S-20 photocathode (LaVision). A bandpass filter transmitting from 300 - 335 nm preferentially transmitted OH*-chemiluminescence from the strong bands at about 310 nm. The detector's full array of 800×600 pixels was read out at a repetition rate of 6688 Hz, approximately corresponding to one image per 1.8°CA at 2000 rpm. Based on pixel number, among the ones considered here this detection scheme would be expected to yield the best spatial resolution, but in fact the high-speed image intensifier degrades resolution significantly, as will be seen in the results. The intensifier was gated to yield an exposure time of 20 μs . This experiment in the 4-cylinder engine will be designated "HS-OH*".

Unintensified High-Speed Cinematography (HS1 & HS2)

These measurements were performed with the same CMOS camera, but without the intensifier and the band pass filter. The CMOS detector itself is not UV-sensitive, but instead most sensitive in a spectral range between 400 and 800 nm. Such broadband sensing in the visible mainly detects the luminescent species CH*, CO, CO₂, and H₂O, not all of which are directly associated with the flame front. A Nikon 50 mm, f/1.2 lens combined with an achromatic close-up lens (Canon 250D) relay-imaged the endoscopic FOV onto 608×456 pixels. Reducing the readout area (ROI) of the detector allowed increasing the repetition rate. For experiment "HS1" in the 4-cylinder automotive engine, it was set to 11019 Hz (approx. 1.1°CA per image) at 2000 rpm, while for "HS2" in the single-cylinder motorcycle engine 9009 Hz correspond to 1.0°CA per image at 1500 rpm. Note that the seemingly odd numbers are due to the fact that the camera could only operate with stable read-out characteristics at certain fixed combinations of repetition rate and ROI. We increased the exposure time from 20 μs for HS1 to 29 μs for HS2, since results from HS1 had indicated that detecting the flame boundary in the unintensified images was more limited by the low signal-to-noise ratio than by motion blur.

Imaging with Large Optical Access (HS)

In the optical engine (experiment "HS"), the entire upper part of the cylinder was from fused silica, which enabled viewing the pent-roof combustion chamber and the complete width of the bore to about 29 mm down from the fire deck. Again the CMOS-camera was used without intensifier and filter, like in HS1 and HS2. However, the same commercial f/1.2-lens now directly projected the FOV onto 512×312 pixels, as shown in Figure 1b. The exposure time was set to 15 μs . At 1500 rpm, the repetition rate of 18 kHz corresponds to one image per 0.5°CA .

Pressure-Trace Analysis

The crank-angle resolved pressure in intake, exhaust, and cylinder was recorded in all experiments. For the current work, the results of pressure-trace analysis only will be presented for HS2 in the single-cylinder motorcycle engine. The analysis at the IFKM was based on a zero-dimensional model. The in-cylinder mass was determined in a gas exchange calculation, in which the residual gas mass was computed with the thermodynamic conditions of intake port, exhaust port, and cylinder and the separately determined flow coefficients of intake and exhaust valves. From the pressure trace, the burn rate and the burned fuel mass fraction were calculated using a two-zone model. The wall heat transfer was modeled with the theory of Hohenberg [24] because it gave the best fit in compression phase. Blow-by was assumed to be 0.4% of the cylinder charge.

RESULTS AND DISCUSSION

In this section, we will first show and qualitatively discuss example image series from intensified and unintensified high-speed cinematography in the 4-cylinder automotive engine HS1, then compare these endoscopic images to those obtained from the less challenging case of full optical access. The case HS2 is discussed last. We then present an algorithm to binarize the images to obtain the instantaneous location of the projected flame boundary and thus the projected burnt area. Identification of this boundary allows calculating the projected flame growth rate in terms of the equivalent flame radius, which we compare between all four experiments, and other derived statistics, a few of which are presented for the case HS2. For this experiment we also check if the optical measurements correlate with the pressure-trace analysis as expected.

Example Images Series

Intensified High-Speed Cinematography (HS-OH*)

Images from and qualitative discussion of this experiment were already included in [21], but are partially reproduced here for completeness. Figure 2 shows two series of OH* CL images from intensified high-speed endoscopic imaging. To reach kHz repetition rates, compromises have to be made in the design of image intensifiers, and similarly CMOS cameras optimized for extremely fast read-out are noisier than "slow" CCD or CMOS detectors. In particular, the strong emission from the spark impacts parts of the image that are several millimeters away. The spark's luminosity is probably in large parts not due to OH* [2, 3], but other species that either emit within the transmission band of the filter or have emission strong enough to "leak" through the filter in its spectrally blocked range. This strong signal is then "smeared" by the high-speed image intensifier, creating the seemingly large spatial extent of the spark. The tendency of high-speed intensifiers to smear bright regions is a particularly negative aspect of their relatively poor spatial resolution, which again comes from design choices that enable the high repetition rate.

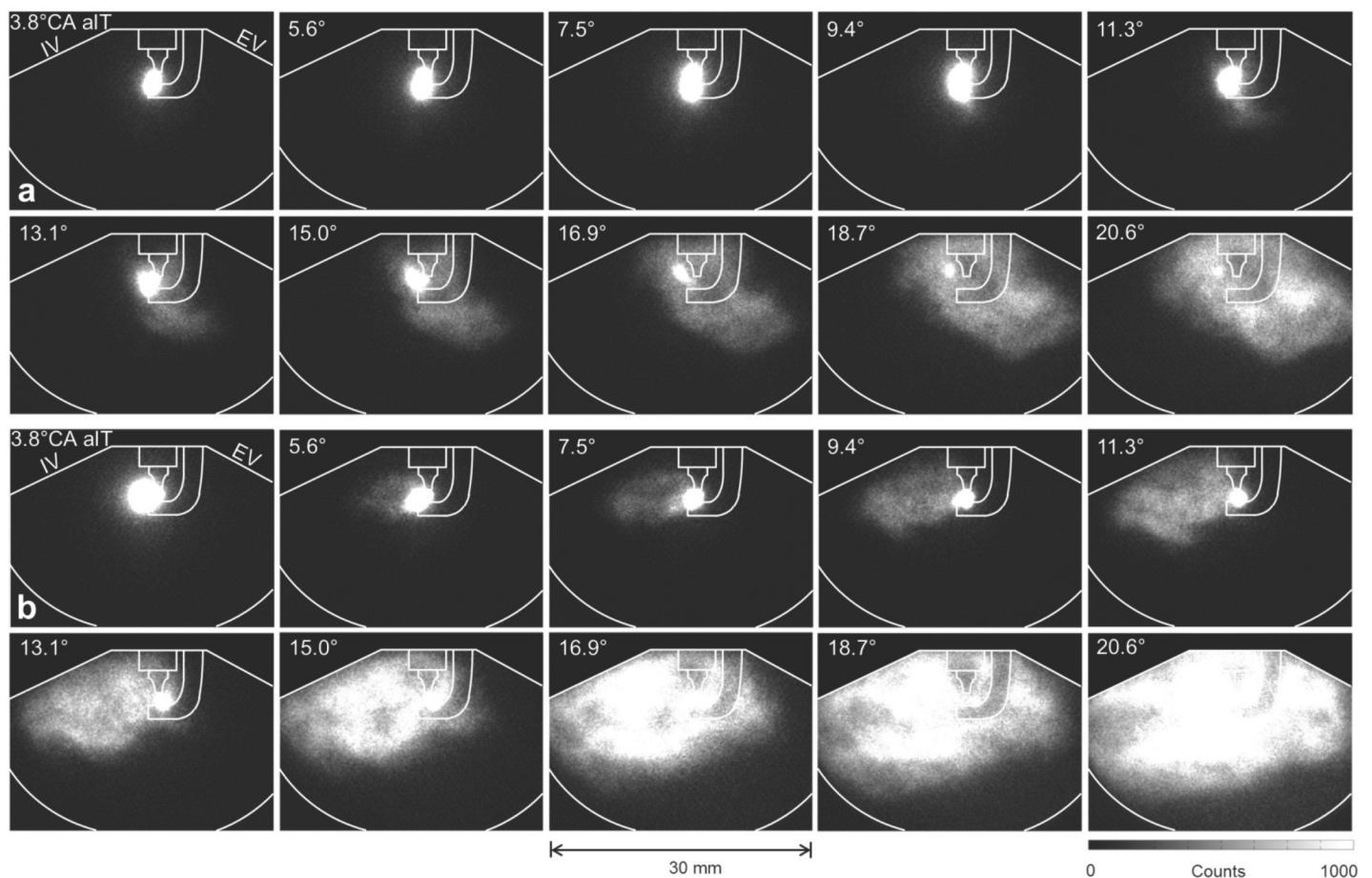


Figure 2. OH* chemiluminescence in endoscopic intensified high-speed cinematography (HS-OH*): (a) slower cycle, (b) faster cycle. Every second image from each time series is shown.

Despite the limited spatial resolution of the images, a few qualitative observations can be made. The delay between spark initialization and the onset of discernible flame propagation differs between the two sample sequences. In the first series during about the first 10°CA aT only the spark can be seen, while in the second one an irregularly-shaped flame emerges from the saturated part of the image at 5.6°CA aT. Correspondingly, by the end of the second sequence the burned area fills a much greater portion of the FOV. Overall, the early flame develops faster in cycle (b) than in cycle (a). Both series confirm a key finding of previous research, [1, 3] that flames keep their shape while growing. The main direction of convective displacement in these sequences is evident as well and is different between the two sequences, a clear indication of significant cycle-to-cycle variability in the flow field near TDC.

Unintensified High-Speed Cinematography (HS1)

Figure 3 shows two sequences of flame propagation from endoscopic unintensified high-speed cinematography in the 4-cylinder automotive engine, HS1. As opposed to the images in Figure 2 details of the spark are discernible here. Although the ignition event itself was not our primary interest here, much can be learned from imaging

the spark channel [2, 3], therefore this could be a significant advantage over intensified imaging. The lack of an intensifier-induced “halo” means that the flame kernel can be distinguished from the spark earlier. However, without the analog amplification of the intensifier upstream of the CMOS-detector the signal is much closer to the read-out noise of the detector. The CL in the visible part of the spectrum detected here may also not be as strong as the UV-emission of OH* detected by the bandpass-filtered intensifier (Figure 2).

This particular camera shows a pattern in the read-out noise that is spatially shifting with time. To obtain the lowest noise floor in those images that capture the weakly luminescent nascent flame kernel, we subtracted the mean of the last 10 images in each cycle before the spark from each subsequent image. Both sequences in Figure 3 show that this works quite well for the first few crank angles after ignition, but later the pattern has shifted too much and cannot be fully compensated. As a result the edge of the burned area is “ragged”. For later crank angles, the increase in signal partially compensates the concurrent increase in residual background noise. As for Figure 2, also for Figure 3 we have chosen a faster and a slower cycle, which again differ both in crank-angle of first flame emergence and the projected burnt area at the end of the sequence.