

Endoscopic Imaging of Early Flame Propagation in a Near-Production Engine

Martin Goschütz, Christof Schulz, and Sebastian A. Kaiser
University of Duisburg-Essen

ABSTRACT

UV-chemiluminescence from the excited hydroxyl-radical (OH^*) has been used as a marker for the high-temperature reacting zone in spark-ignited engines for quite some time. In research engines with large optical access, sensitive camera systems make it possible to obtain images of the flame that can be used for, e.g., determining the flame-front's propagation speed [Aleiferis et al., Combust. Flame 136 (2004) 283-302]. However, on one hand such optical engines are limited in their speed and load range, on the other, typical UV endoscopes make wide-field imaging at low light levels challenging.

Here, a large-aperture UV endoscope is used to capture sequences of OH^* chemiluminescence during early flame propagation in a nearly unmodified production engine. We compare three imaging systems: phase-locked single-shot imaging, phase-locked double-frame imaging, and "high-speed" cinematography at kHz repetition rates. The four-cylinder spark-ignition engine can be operated at speeds and loads significantly exceeding the limits of most fully optically accessible engines. During the first 20° crank-angle after ignition, the phase-locked endoscopic images almost match the image quality reported from experiments in a dedicated optically-accessible engine. For later acquisition timings, the flame often exceeds the field of view. From phase-locked imaging the instantaneous size of the apparent burnt area (ABA) can be identified by thresholding after filtering. Its single-shot variant allows only computation of the multi-cycle average of the apparent flame speed (AFS). Acquisition of two successive frames in a single cycle enables determining the instantaneous AFS. High-speed imaging can follow a single cycle and thus the time-resolved ABA can be estimated, but the instantaneous shape of the flame cannot be imaged with much detail, because the detector hardware is less mature.

CITATION: Goschütz, M., Schulz, C., and Kaiser, S., "Endoscopic Imaging of Early Flame Propagation in a Near-Production Engine," *SAE Int. J. Engines* 7(1):2014, doi:10.4271/2014-01-1178.

INTRODUCTION

Flame propagation and its connection with early flame development (in particular with respect to cycle-to-cycle variability) have been investigated previously by imaging of chemiluminescence from excited OH - and CH -radicals [1, 2, 3] or sodium added to the fuel [4], by schlieren techniques [5], or by OH - and formaldehyde LIF [6, 7], most frequently in optical engines. Some of these investigations show a strong correlation between the flame growth and the crank angle at which 5 % of the mass fraction is burned, CA5. Hence, flame-front imaging can be used as indication of reaction progress. However, research engines with large-scale optical access have limitations because less mechanical strength, reduced cooling, and altered thermal conductivity reduce the operating range in speed and load. Furthermore, the in-cylinder flow, which has a strong influence on flame expansion and convective flame displacement, can be different from a production engine due to modifications needed to create optical access, for example, greatly increased crevice volumes.

Visualization with an endoscope requires only a small access port, enabling a wide operating range with minimal influence on in-cylinder flow and heat transfer. However, conventional endoscopes, especially UV-transparent models, have small relative apertures, which limit their use in optical combustion diagnostics to processes generating much detectable light like Mie-scattering from sprays [8, 9] or flame luminosity and soot formation in diesel engines [10, 11, 12, 13, 14]. Further techniques applied with endoscopic optical access were two-color visualization of 2-D soot luminosity to obtain spatially and temporally resolved flame temperature [15, 16] and particle image velocimetry (PIV) [17], which are also techniques with relatively high levels of visible light.

In previous work we demonstrated the progress that can be made with a large-aperture UV-transparent refractive-diffractive endoscope [18]. This modular system has been used for UV imaging in a near-production engine [19, 20]. Initial work on visualizing the flame in a spark-ignited (SI) engine is documented as well [21]. Here, we expand on these preliminary investigations and demonstrate that the image

quality achievable with such endoscopes enables quantitative investigation of early flame propagation, an important aspect of combustion in SI engines. In addition to phase-locked and cinematographic “high-speed” imaging, explored in a previous investigation [22], we transferred the technique of phase-locked double-frame imaging, which had been applied in a fully optically accessible engine [1, 2], to our endoscopically accessed production engine.

EXPERIMENTS

Engine

The experiments were performed in a production 4-cylinder engine from BMW (N46B20) with port-fuel injection, and a mechanically variable intake-valve train (“Valvetronic”). 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. The engine was equipped with pressure transducers in each cylinder and a crankshaft encoder. Details of the engine operation are listed in [Table 1](#).

Table 1. Engine geometry and operation

Displaced volume	1995 cc
Bore	84.0 mm
Stroke	90.0 mm
Compression ratio	10.0 : 1
Number of valves per cylinder	4
Intake valve lift	0.3 – 9.7 mm
Exhaust valve lift	9.7 mm
Fuel	Iso-Octane, C_8H_{18}
Equivalence ratio	1.0

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 (optional) laser input and another for observation. Only the latter, the detection endoscope shown in [Figure 1](#), was used here. To enable optical diagnostics in 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 (inset in the upper left of [Figure 1](#)).

A schematic drawing of the mechanical arrangement and endoscopic imaging system is shown in [Figure 2](#). 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 40 mm in the center of the combustion

chamber (the exact magnification varied between the three imaging systems used here). A relay optic, isolated from the vibrations of the engine, projected this intermediate image onto an intensified camera. The relay optic corrected the system's inherent chromatic aberration in a refractive-diffractive element (but this was of minor importance in the current spectrally narrow detection scheme). All lenses in the endoscope were manufactured from UV-grade fused silica. Details of the optical design can be found in [18]. The front-most lens was uncoated while the other lenses had a broad-band anti-reflective coating with reflectance of less than 1 % per surface between 200 and 600 nm. The system was designed in a previous project and is now commercially available from LaVision GmbH, Germany.

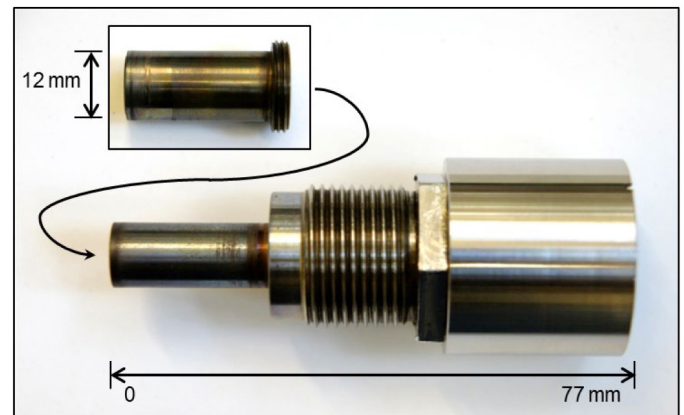


Figure 1. Front endoscope and titanium bushing

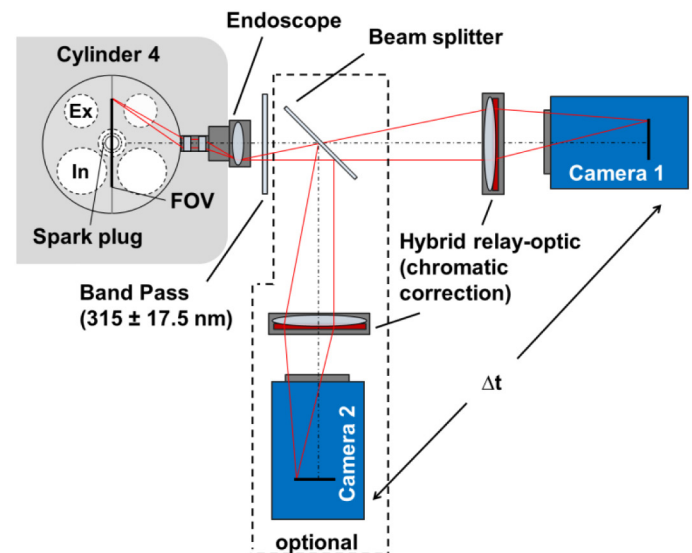


Figure 2. Schematic drawing of engine geometry and endoscopic imaging system. The dashed box encloses the components used only for phase-locked double-frame imaging.

With this endoscope system, UV chemiluminescence from the excited hydroxyl-radical (OH^*) at 308 nm was detected within a band pass at 315 ± 17.5 nm. A narrower filter may have blocked radiation from species emitting broad-band chemiluminescence more efficiently, but since such additional

signal would stem from within the burnt-gas region, it should not impact the interpretation of the data described below. We did not completely omit a band-pass filter because the chromatic correction was not designed for the entire spectral range the flame might have emitted.

With this endoscope system, imaging was carried out with three different camera systems:

"Phase-Locked" Single-Shot Imaging

In a first step, imaging was performed with a single camera, an image-intensified CCD with an S20 photocathode with an effective detector area of 119 mm². 2 × 2 binning yielded a discretization of 520 × 688 pixels. In a compromise between motion blur and signal level, the exposure time was set to 10 μs. Due to the low repetition rate of the ICCD, this camera system permits only one image acquisition per cycle, typically at the same crank-angle. After the acquisition mode it was used in, we will thus refer to this system as "phase-locked".

"High-Speed" Cinematography

In the "high-speed" configuration, visualization was performed with an active-pixel sensor CMOS camera (Phantom v7.3), lens-coupled to an image intensifier (S20 photocathode). The full array of 800 × 600 pixels was read out, corresponding to an effective detector area of 229 mm², enabling a repetition rate of 6688 Hz. Based on pixel number, this detection scheme would be expected to yield better spatial resolution than phase-locked imaging, but in fact the high-speed image intensifier degrades the actual resolution much more than its low-repetition-rate counterpart, as will be seen in the results. The images were gated to have an exposure time of 20 μs. Thus, compared to the phase-locked system, more blurring due to flame motion was incurred, but this was judged acceptable because the resolution of the high-speed system was significantly worse, making the additional blur unperceivable. On the other hand, that system's greater detector noise demanded for increased light input.

"Phase-Locked" Double-Frame Imaging

This variant of phase-locked OH*-imaging previously has been employed by [1, 2] in a fully optically accessible engine. Two identical intensified CCDs were used, each receiving 50% of the OH*-Signal from a beam splitter positioned between front endoscope and hybrid relay optic, as shown in [Figure 2](#) (with the dashed-box sub-system included). This enabled the acquisition of two successive frames with arbitrary inter-frame timing in a single cycle. Here, the first image was phase-locked onto a reference crank angle after ignition timing (CA aIT), and the second image was taken with a delay of 2 - 4°CA. As a result of splitting the OH* chemiluminescence, the signal each detector receives decreased by 50% with a corresponding decrease of the signal-to-noise ratio. To partially compensate for the lower signal the exposure time was set to 15 μs (compared to 10 μs for the single-shot variant).

Data Acquisition

With both phase-locked systems, a parameter sweep was performed varying the load from 25 Nm to 125 Nm at a constant engine speed of $n = 2000 \text{ min}^{-1}$. At this engine speed the maximum torque is 176 Nm, but this could not be reached because the dynamometer was somewhat undersized. Also, at a constant load of 50 Nm we varied the speed from 2000 min^{-1} to 4000 min^{-1} , for the single "phase-locked" camera system up to 5000 min^{-1} (the difference in upper speed limit was due to technical problems with the engine test bed).

In these parameter sweeps the ignition time was automatically adjusted by the ECU. For ignition timings closer to TDC the pressure at ignition increases due to compression by the piston. The ignition timings (as read from the ECU) and the inter-frame delays for double-frame imaging are listed in [Table 2](#). For orientation, at 2000 min^{-1} , 2°CA correspond to 167 μs.

Table 2. Ignition timing (IT) and inter-frame delay setting

	IT / delay	IT / delay	IT / delay
speed / load	2000 min ⁻¹	3000 min ⁻¹	4000 min ⁻¹
25 Nm	-54.00° / 2.0°CA	-	-
50 Nm	-41.25° / 2.0°CA	-43.00° / 3.0°CA	-45.75° / 4.0°CA
75 Nm	-34.50° / 2.0°CA	-	-
100 Nm	-28.50° / 2.0°CA	-	-
125 Nm	-21.50° / 2.0°CA	-	-

At each operating point, phase-locked data sets were taken in steps of 2°CA from 4 or 6°CA to 20°CA after ignition timing (aIT), each set consisting of at least 200 images. For each cycle with image acquisition the crank-angle resolved cylinder pressure was recorded. High-speed imaging was performed at a single operating point with $n = 2090 \text{ min}^{-1}$ and $M = 75 \text{ Nm}$. At this engine speed, the frame rate of 6688 Hz corresponds to 1.875°CA between two images. Since the high-speed camera was operating on a time-basis, the image sequence for each cycle was synchronized with the spark timing in image post-processing by an automated routine detecting the first appearance of the spark.

RESULTS AND DISCUSSION

Phase-Locked Single-Shot Imaging

This arrangement is the most simple of the three used here and was explored first, since the effort for achieving proper timing and optical alignment was modest. In the following, we will first show a few series of typical images to give a general impression of the image quality, then procedure and initial results of morphological analysis are presented.

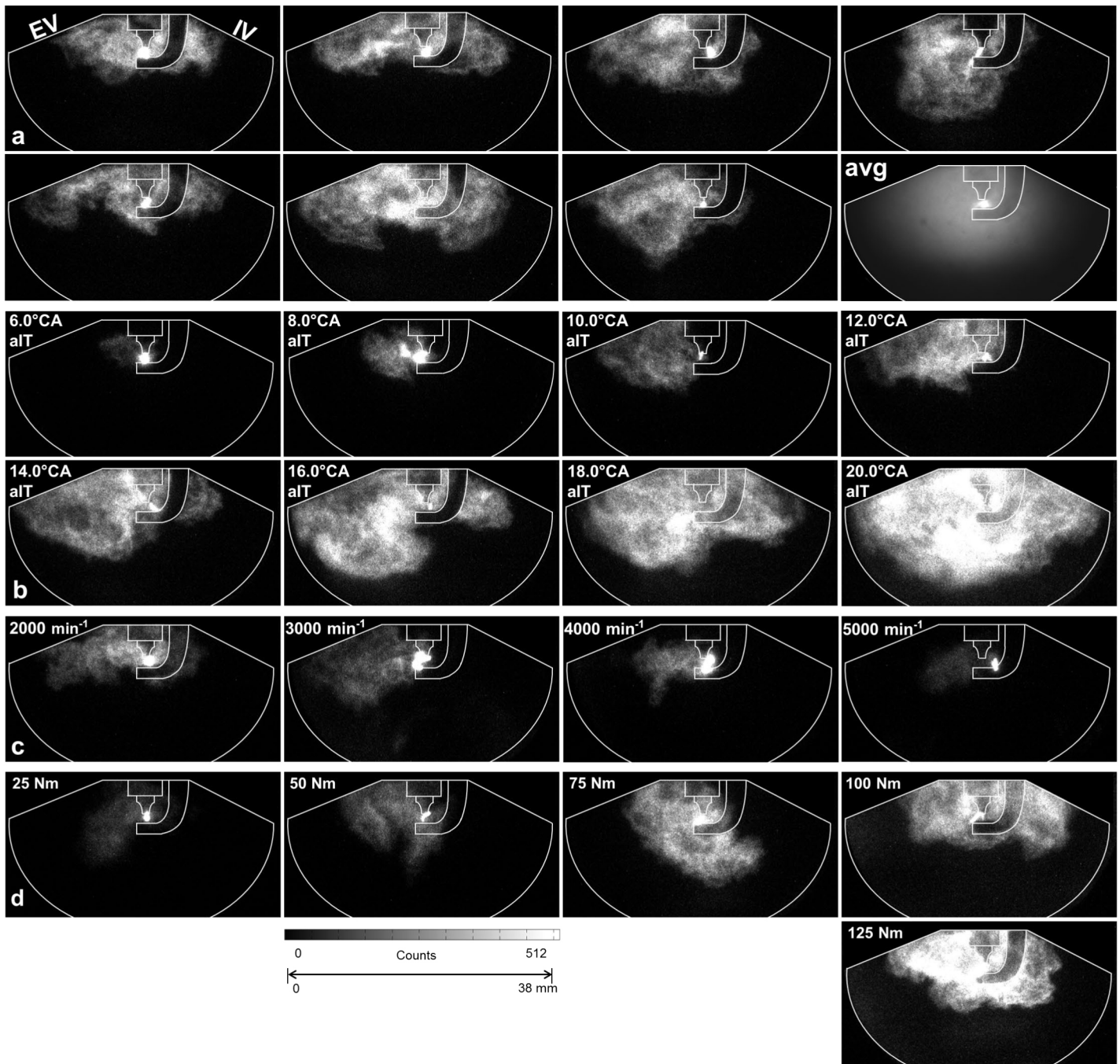


Figure 3. Phase-locked imaging: single-shot, single-cycle images of OH*. EV: exhaust valve, IV: intake valve (a) Seven cycles at a fixed timing ($n = 2000 \text{ min}^{-1}$, $M = 75 \text{ Nm}$, 14°CA aIT) and (last image) phase-locked average of all 200 cycles. (b) Pseudo time-series of flame propagation composed of images from separate cycles at the same operating conditions ($n = 2000 \text{ min}^{-1}$, $M = 75 \text{ Nm}$). (c) Fixed timing after ignition, varying engine speed ($M = 50 \text{ Nm}$, 14°CA aIT). (d) Fixed timing after ignition, varying engine load ($n = 2000 \text{ min}^{-1}$, 14°CA aIT)

Typical Images

In Figure 3 a, a selection of OH*-images is presented. These images were taken with fixed timing of 14°CA aIT with the engine operating at 2000 min^{-1} and a load of 75 Nm . With 300 counts, the maximum of the color scale is deliberately chosen to emphasize low values and white areas do not necessarily indicate saturation of the detector. However, the ignition spark did actually saturate the detector. The images in Figure 3 a show typical cycle-to-cycle variation in size and orientation in the flame development. In most cycles, the flame propagates

more towards the sides than downwards, but there are exceptions. The average of 200 cycles, presented in the last image of Figure 3 a, indicates that on average, flame propagation is slightly preferential towards the exhaust valves.

Figure 3 b shows the development of the flame for $6.0^\circ\text{CA} - 20.0^\circ\text{CA aIT}$ as a “pseudo flame propagation”, composed from separate cycles at the same operating condition ($n = 2000 \text{ min}^{-1}$ and $M = 75 \text{ Nm}$). During the initial phase of the spark event, until 5°CA aIT , no images were acquired since only the

spark could be observed. Although much can be learned from imaging the spark channel [3, 23], which has spectral characteristics quite different from the subsequent flame, the ignition event itself was not our primary interest here. Consistent with imaging in an optical engine [3, 7], the first flame kernel can be observed at around 5°CA - 6°CA aIT. This initial flame then grows towards the pent roof and spreads to the sides. Convection towards the exhaust valves, located on the left, indicates the presence of residual tumble flow. This is consistent with the ignition spark bending to the left at 8°CA aIT. Flame growth is accompanied by an increase of intensity. The last image was taken at 20°CA aIT, because at this time the flame had propagated close to the edge of the endoscope's field of view.

Figure 3 c shows images at 14°CA aIT with the engine speed ranging from $n = 2000$ to 5000 min^{-1} . Across this speed sweep, the ECU adjusted ignition timing from 41.25°CA before top dead center (bTDC) at $n = 2000 \text{ min}^{-1}$ to 48.75°CA bTDC at $n = 5000 \text{ min}^{-1}$. In all images the flame propagates towards the exhaust valves, but (at this fixed CA aIT) with decreasing flame size and intensity for higher engine speed. Flame speed in an SI engine's premixed combustion is a function of turbulent velocities [24, p.121] in the combustion chamber and thus in first approximation scales with the mean piston speed [25, p.341]. However, during early flame propagation the flame may not be fully turbulent and therefore may propagate slower than this scaling would indicate. Also, the scaling of turbulent flame speed with turbulent velocity fluctuations may be sub-linear, depending on Damköhler number (among other factors) [24].

The last sequence of images, shown in Figure 3 d, corresponds to a variation of engine load at fixed image timing, 14°CA aIT, and constant engine speed of 2000 min^{-1} . Visible is an increase in the flame size and intensity with higher engine load. Furthermore, for higher loads the gradient of the apparent flame front seems more defined. Also, the flame shape is more regular and remains centered.

The primary reason for the increase in OH*-emission with increasing load is clear: Higher load corresponds to higher pressure and density throughout the cycle. Also, to account for the faster burn, the ECU is parameterized to adjust ignition timing with increased engine load. At $M = 25 \text{ Nm}$, ignition starts at 49.5°CA before top dead center (bTDC), while for $M = 125 \text{ Nm}$ it is shifted to 21.0°CA bTDC. These two changes, less throttling and later ignition, correspond to an increase of pressure at ignition from 3.26 bar to 16.9 bar for $M = 25 \text{ Nm}$ and $M = 125 \text{ Nm}$, respectively. Increased mixture density, all else equal, yields higher density of OH* in the flame. Also, like that of any short-lived reaction intermediate, the concentration of OH* can be expected to be dependent on temperature and reaction rate, see below.

The reason for faster flame propagation at higher loads is more subtle. Laminar flame speed actually decreases slightly with increasing pressure [26]. For an increase in load, this is offset by increased charge temperature after intake-valve closure due

to less throttling and hotter walls. Flame initiation during ignition also may be faster for higher gas density. Since throttling is accomplished in this engine by changing intake-valve lift, it is difficult to make general statements about trends in velocity magnitudes and turbulence, which influence turbulent flame speed.

Quantitative Analysis

Since the quality of the OH*-images from the endoscopic system is only somewhat worse than that of comparable images obtained in fully optically-accessible engines (as, for example, in [1,2]), we explored if meaningful extraction of the apparent flame shape were possible. Such morphological (shape-based) post-processing is the first step in quantifying various aspects of early flame propagation.

Post-processing was performed in MATLAB. First, the average background was subtracted from all images. This background was determined for each operating point as the ensemble average of images immediately prior to ignition. In these background-subtracted images, a mask excluded the area outside of the endoscope's FOV. Subsequent 5×5 median filtering reduced noise with little impact on gradients. Finally, thresholding was applied, defining all pixels with intensity less than the threshold value as unburned, and conversely, with greater intensity as burnt. An example for input and output of binarization is shown in Figure 4.

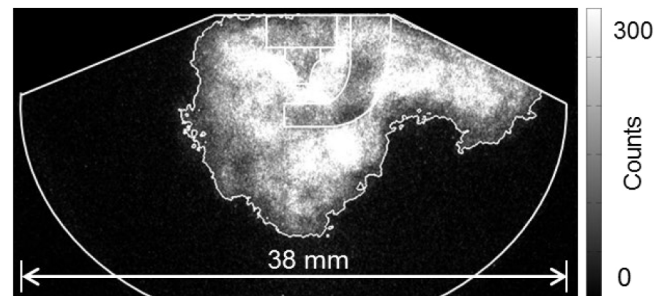


Figure 4. Example raw image from the ICCD with the flame front detected by thresholding indicated by the white, corrugated line ($n = 2000 \text{ min}^{-1}$, $M = 75 \text{ Nm}$, 16°CA aIT).

In Figures 3 and 4, a spatial scale has been assigned to image based on the spark plug's dimensions, the electrodes being clearly visible in many images. However, the front endoscope causes barrel distortion in the intermediate image [18]. Therefore, this scaling derived from a feature near the image center becomes inaccurate towards the edges of the FOV. For the analysis presented in this section (and the high-speed imaging further below) we will neglect the error introduced by distortion, but will return to the issue before the more extensive evaluation of the double-frame images.

A critical question in binarization is that of the appropriate threshold value. In most binarization tasks there is some arbitrariness to this choice, which needs to be minimized such that the physics of interest can be quantified with minimal bias. We therefore performed a sensitivity analysis. The dependence