Analysis of high-speed broadband flame chemiluminescence imaging in a SI engine

S Shawal1, 2,*, M S Meon1, J B Saedon1, M F Remeli1, N H Mohamad Nor1 and S A Kaiser2

1 Faculty of Mechanical Engineering, Universiti Teknologi MARA, Malaysia
2 IVG, Institute for Combustion and Gas Dynamics-Reactive Fluids, University of Duisburg-Essen, Germany

*Corresponding author: syahar6595@salam.uitm.edu.my

Abstract. This study investigates the characteristics of flame propagation in a gasoline S.I engine through a combined thermodynamic and optical approach. Two high-speed CMOS camera were used together with an endoscopic system to visualize the early flame in a spark-ignited engine. An unintensified high-speed (20 kHz) imaging of early flame kernel formation and turbulent flame propagation for hundreds of consecutive combustion cycles has been analysed and compared to pressure-derived heat release rates and mass fraction burn (MFB) profiles. At very low light levels, the patterned read-out noise on the detector becomes significant. Filtering in the Fourier domain was effective in suppressing this noise component to acceptable levels. In this paper, a previously-developed algorithm with automatic dynamic thresholding was used to separately detect spark ignition and flame kernel in the image sequences. The detected flame boundary was post-processed to compute basic flame characteristics such as flame area and turbulent flame speed based on spherical flame propagation assumption. Ignition and flame propagation are compared for fast combustion cycles and slow combustion cycles based on the optical flame speed and crank angle resolved mass fraction burned profile. The good burn (fast) cycles show higher spark stretch caused by local tumble flow-field, greater early flame growth rate, and nearly spherical flame propagation at the center of combustion chamber. In contrast, the poor (slow) cycles show slower flame kernel growth rate, and mostly asymmetric flame propagation near the spark-plug and pentroof of the combustion chamber. The analysis shows a good correlation between thermodynamics and optical data.

Keywords. Flame propagation, Chemiluminescence, Broadband imaging, S.I engine, Image processing

1. Introduction
Flame front development, in particular with respect to cycle-to-cycle variability has been investigated previously 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]. Some of these investigations show a strong correlation between the flame growth and pressure-derived heat release. Hence, flame-front imaging can be used as indication of reaction progress of combustion processes.
However, most of these studies were carried out in a research engine with large-scale optical access. The accompanying modifications to the engine limit the operating range in speed and load and change heat transfer. Also, the in-cylinder flow, with its influence on flame wrinkling and convective flame displacement, can be different from a production engine due to greatly increased crevice volumes. The large optical access in a research engine, on the other hand, allows low-light imaging through large-aperture lenses with good light-collection efficiency. 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. Endoscopic access has been used to image SI combustion, for example to obtain the spatio-temporally resolved flame temperature [7, 8] by two-colour visualization of 2-D soot luminosity and particle image velocimetry (PIV) [9], which are also techniques with relatively high levels of visible light. However, premixed combustion in spark-ignited (SI) engines emits relatively little light, much of it in the UV. However, previous development of a UV-transparent endoscope with relatively large aperture [10] enables the detection of much weaker signals, like those from premixed combustion [11,13] or laser-induced fluorescence in the UV [12].

In this paper we evaluate how well the premixed flame front can be detected from broadband CL imaging through such an endoscope system. Fourier-domain filtering is used for images from one of the cameras. In extension of our previous work [13], an improved algorithm was developed to simultaneously extract the shape of the early premixed flame and that of spark.

2. Experiments

2.1. Engine and operating conditions

Endoscopic imaging was performed in a production 4-cylinder engine with port-fuel injection and a mechanically variable intake-valve train (“Valvetronic”). The latter also controlled 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. In the current work, the engine operated at 2000 min⁻¹ and 75 Nm, the maximum torque at that speed being 176 Nm. Engine parameters and operation conditions are summarized in table 1.

| Table 1. Engine parameters and operating conditions. |
|-----------------------------|
| Engine parameters | N46B20 |
| Cylinders | 4, inline |
| Compression ratio | 10 |
| Displacement per cyl. [cm³] | 499 |
| Bore / stroke [mm] | 84 / 90 |
| Speed [min⁻¹] / load [Nm] | 2000 / 75 |
| Fuel | Gasoline |
| Relative fuel/air-ratio | 1.0 |
| Ignition timing [°CA] | -34.5 |
| IMEP [bar] | 4.4 |
2.2. Endoscopic imaging system

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 (not used here) and another one for observation. 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 1.

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 angle of view was about 60°, yielding a maximum field of view (FOV) with a diameter of about 40 mm in the center of the combustion chamber. The front endoscope projected a real intermediate image onto a field lens outside of the engine. A relay optic, isolated from the vibrations of the engine, projected this intermediate image onto the camera sensor. The original system design features a hybrid refractive-diffractive optical element, correcting chromatic aberration in the UV [10]. Since the CMOS-detectors used in this work are not UV sensitive, a commercial camera lens was used instead to re-project the intermediate image, accepting the chromatic aberrations incurred in the front endoscope. With this endoscope system, imaging was carried out with two different camera systems, whose characteristics are summarized in table 2.

![Figure 1. Engine and optics.](image)

| Camera          | Photron SA-Z                  | Phantom v7.3                        |
|-----------------|-------------------------------|-------------------------------------|
| Pixel size      | 20.0 μm²                      | 22.0 μm²                            |
| Read noise      | 29e− rms                      | 21e− rms                            |
| Sensor size     | 20.5 x 20.5 mm                | 17.6 x 13.2 mm                      |
| Exp. time       | 20 / 12 μs                    | 20 μs                               |
| Rep. rate       | 20 / 75 kHz                   | 11 kHz                              |
| Actual ROI      | 860 x 660 px / 552 x 384 px   | 608 x 456 px                        |
| Projected pixel size | 35 μm/px                      | 50 μm/px                            |
| Lens system     | 50mm f/1.2 + + 250 mm f/1.2 + + 250 mm CU | 250 mm CU |

Both cameras are active-pixel CMOS detector capable of kHz frame rates. Current CMOS detectors are most sensitive in a spectral range between 400 and 800 nm. In premixed flames, such broadband sensing in the visible mainly detects the luminescent species CH*, CO, CO2, and H2O. These may not be directly associated with the flame front, but our previous work had shown that nevertheless reasonable information on spark and flame could be extracted from broad-band imaging.
Vision Research’s Phantom v7.3 had been used in our previous work [13]. A Nikon 50 mm, f/1.2 lens combined with a close-up lens (Canon 250D) relay-imaged the endoscopic FOV onto a region of interest (ROI) of 608 x 456 pixels. At this resolution the sensor can be read out at 11 kHz (1.09°CA per image at 2000 rpm). In order to systematically evaluate the robustness of our image processing algorithm with respect to noise, datasets with different lens apertures, f/1.2, f/2.8, and f/5.6, were acquired. Decreasing the relative aperture decreases the signal while the physical object of interest – spark and flame – remains the same.

Since the Phantom v7.3 is about 10 years old as of 2018, we were interested how a more recent high-speed camera would perform. The available camera, Photron’s SA-Z, has a larger sensor, slightly smaller pixel size, and higher per-pixel read noise. The data throughput rate is about 6.5 times that of the older Phantom v7.3, allowing for a frame rate of 20 kHz at full resolution, 1024 x 1024 pixels.

The larger sensor was matched to the field lens by adding a second close-up lens to the previously-used combination of a Nikon 50 mm + Canon D250 close-up lens. Two data sets with different frame rates are considered here. First, the full sensor was read out at 20 kHz frame rate (0.6°CA per image). Here, the FOV was somewhat larger than in the experiments with the Phantom v7.3. For a more accurate comparison, we cropped the images in post-processing to an ROI of 880 x 660 pixels, matching the FOV (but still with increased resolution and different pixel-level characteristics). In a second experiment, only 552 x 384 pixels were read out, increasing the repetition rate to 75 kHz (0.15°CA per image). This high frame rate allowed more detailed analysis of the spark and very early flame kernel.

3. Results and discussion

In this section, we will show and qualitatively discuss example of two image series from unintensified high-speed endoscopic imaging. 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. In this experiment we also check if the optical measurements correlate with the pressure-trace analysis as expected.

3.1. Ignition and flame propagation imaging at kHz rate

Figure 2 shows two different sequences of flame propagation from the SA-Z endoscopic unintensified high-speed imaging at 20 kHz, which is corresponding to 0.6° CA per image. Figure 2(a) shows a series of flame propagation images for a faster burn cycle and Figure 2(b) shows a slower burn cycle from the Photron SA-Z at the maximum relay lens aperture f/1.2. Details of the spark events are clearly discernible, which could be a significant advantage over intensified imaging [1]. The good burn (fast) cycles show higher spark stretch caused by local tumble flow-field, greater early flame growth rate, and nearly spherical flame propagation at the center of combustion chamber. In contrast, the poor (slow) cycles show slower flame kernel growth rate, and mostly asymmetric flame propagation near the spark-plug and pent-roof of the combustion chamber.
After ignition timing, spark channel transfers the electric energy to the surrounding air-fuel mixture to initiate kernel formation. The flame starts to accelerate between $3^\circ$ to $10^\circ$ CAaIT before it becomes as fully turbulent and then propagates at constant velocity until it reaches the edge of endoscopic Field of View (FOV).

Both series confirm a key finding of previous research, [2, 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.