“Designer diagnostics” for developing direct-injection gasoline engines

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Abstract. The primary motivation for stratified-charge spark-ignited direct injection (SC-SIDI) engines is to maximize fuel economy by operating the engine with minimal (preferably no) throttling at part load. This requires control of the fuel-air mixing process to create a fuel cloud around the spark plug that is favorable for ignition and complete combustion in every engine cycle. This paper illustrates experimental techniques that have been developed to measure key aspects of the in-cylinder fuel-injection, ignition, combustion and emissions-formation processes. Most of these techniques rely on high-speed digital imaging and in-situ calibration in order to characterize dynamic in-cylinder phenomena that vary substantially from cycle to cycle.

1. Introduction
Most gasoline engines in production operate with a premixed, nearly homogeneous charge obtained by introducing fuel with a low-pressure injector upstream of the intake valve. Because robust ignition and flame propagation occur only for a comparatively narrow range of fuel-air ratios with gasoline, the engine load must be controlled by throttling, which necessarily incurs substantial thermodynamic (pumping) losses. It has long been recognized [1] that these pumping losses can be reduced or eliminated and fuel economy can thereby be substantially improved by injecting the fuel directly into the combustion chamber shortly before ignition so as to concentrate the fuel into an ignitable cloud around the spark plug at the time of ignition, allowing the engine to run unthrottled with the load dictated by the amount of fuel injected. It has also long been recognized that this process is extremely sensitive to small perturbations. Although simple in concept, this approach has proved sufficiently difficult in practice that only within the last decade have advances in fuel injectors, engine controls and exhaust-catalyst technology permitted such stratified-charge spark-ignited direct-injection (SC-SIDI) engines to reach commercial production (see [2] and references therein).

The first generation of commercial SC-SIDI engines have been primarily wall-guided (WG) designs (Figure 1, left) in which the interaction of the fuel spray with a contoured piston surface helps to form and stabilize the desired fuel-air distribution around the spark plug. The closer coupling of mixture preparation and ignition in spray-guided (SG) SIDI designs (Figure 1, right), now under vigorous development, substantially expands the speed-load range of stratified-charge operation.

Even for warmed-up steady-state operation, SC-SIDI engines of both types confront several interrelated development issues which do not significantly affect conventional premixed-charge engines: 1. repeatable formation and ignition of the stratified fuel-air mixture, sometimes with significant quantities of liquid fuel present;
2. robust flame propagation despite the heavy dilution by residual gases that is needed to minimize production of oxides of nitrogen (NOx);
3. mixing-limited burnout of locally rich regions under heavily diluted conditions;
4. engine-out soot emission due to locally rich combustion;
5. effects of liquid fuel films on the piston surface or spark electrodes
6. unburned hydrocarbon emissions due to regions of fuel-air mixture that are too lean to burn.

Contributing to a number of these issues is the in-cylinder environment itself, which is geometrically complex, time-varying in the mean, turbulent, and characterized by steep spatial gradients and rapid temporal fluctuations. The periodic motions of the piston and intake/exhaust valves lead naturally to a statistical description in terms of ensemble- or phase-averaged rather than time-averaged quantities, with engine crankshaft rotation angle taking the place of time. Despite the periodic nature of the mechanical boundary conditions, there is overwhelming evidence that engine flow and combustion processes vary substantially from cycle to cycle.

Computational fluid dynamics (CFD) codes currently used in practical engine design solve the ensemble-averaged equations of motion using a statistical-closure model for turbulence kinetic energy, but they have little or no predictive capability for concentration or temperature fluctuations [4]. Thus, although CFD is a valuable tool for understanding in-cylinder processes and designing engines (e.g., [5][6]), it can only partially or indirectly address some of the issues enumerated above (e.g., 1).

Clearly, then, experimental techniques to address practical SC-SIDI problems such as those listed above are important. Optical diagnostics have been used to understand important in-cylinder combustion processes since the pioneering work of Rassweiler and Withrow at GM in the 1930s [7]. In the 1990s, optical techniques began to contribute more directly to engine development [8]. Among the most prominent have been laser-based two-dimensional (2-D) planar techniques such as particle-image velocimetry and laser-induced fluorescence (LIF) of fuel and NO, as well as high-speed imaging of Mie scattering, combustion luminosity and soot incandescence.

This paper summarizes how several issues in SC-SIDI engine development have been addressed by delineating the major development issues, identifying the associated in-cylinder processes and corresponding observables, and designing, calibrating and systematically applying optical diagnostic techniques. The dynamic, cyclically varying in-cylinder environment places a considerable premium on diagnostics that can follow a key process continuously through the relevant portion of an individual engine cycle and accumulate such individual-cycle records over many engine cycles. Most of the techniques reviewed here are therefore based on high-speed digital imaging.

2. “Designer diagnostics”: approach

Summarizing the events involved in forming, igniting and burning a stratified fuel-air mixture in a SIDI engine helps identify the key issues to be addressed by experimental diagnostics. Fuel must be injected relatively late in the compression stroke to form a mixture distribution that supports robust ignition and flame propagation. This depends critically on the fuel-spray structure and penetration and on the interaction of the spray with the in-cylinder air motion, the piston surface, and the spark plug. These interactions may also deposit liquid fuel on the piston surface or the spark plug, leading, for example, to pool fires on the piston [9] and deposits on the electrodes. Reliable ignition clearly requires that ignitable fuel-air-residual mixture be present at the spark gap at the correct time in every cycle. Flow velocities or velocity...
gradients that are too high can impede ignition and flame-kernel growth. The presence of liquid fuel near the spark may also be of concern (e.g., extracting energy from the spark or flame kernel to vaporize droplets). Heavy charge dilution (~20–40% of the intake air is typically replaced by recirculated exhaust gas (EGR)) is employed to reduce the combustion temperature and minimize NOx production, but this also reduces the flame speed and makes reliable ignition, complete flame propagation and local rich-zone burnout more difficult. Locally rich combustion can also produce engine-out soot emissions if soot that is formed cannot be completely oxidized before in-cylinder temperatures fall too low. Regions of fuel-air mixture that are too lean to burn are a particular concern for unburned hydrocarbon emissions. In addition to optimizing all these processes on average, the cycle-to-cycle variation must be minimized to eliminate misfires, partial burns and emissions.

For each of six development issues selected from this summary, Table 1 indicates the associated phenomena or quantities to be observed or measured and the corresponding optical diagnostic technique, which will be discussed and illustrated after the experimental apparatus has been described.

Table 1. Selected development issues, observable quantities, and diagnostics techniques

| Development Issue          | Observable                                      | Diagnostic Technique                  |
|----------------------------|-------------------------------------------------|----------------------------------------|
| Fuel-air mixture preparation | Spray structure & penetration                    | High-speed (HS) Mie scattering         |
| Ignition                   | Vapor & liquid fuel concentration at spark plug | Spark-emission spectroscopy            |
| Flame propagation          | OH* chemiluminescence                           | HS spectrally resolved imaging         |
| Rich-zone burnout          | Thermal emission from soot                     | HS spectrally resolved imaging         |
| Soot formation & oxidation | Soot temperature and relative soot loading (KL); |                                      |
| Liquid fuel films          | Film thickness                                  | HS refractive-index matching           |
|                            | Pool fires                                       | Imaging (various)                      |

3. Apparatus

The experiments described here were carried out in single-cylinder wall-guided and spray-guided SIDI engines equipped for optical access to the combustion chamber. Both were four-valve, pent-roof configurations with bore × stroke of 86 × 86 mm (0.5 L displacement) and compression ratio of 10.3. As sketched in Figure 1, the WG engine has a centrally mounted spark plug while the fuel injector is positioned between the intake valves. The SG engine has a centrally mounted fuel injector, with the spark plug positioned obliquely between the exhaust valves. The experiments were carried out at an engine operating condition that represents a part-load cruise condition in which the charge is highly stratified to maximize fuel economy (2000 RPM engine speed, 10 mg fuel injected per cycle (about 30% load), and essentially wide-open throttle (0.95-bar manifold inlet pressure)]. Charge dilution by EGR was simulated by replacing up to 40% of the intake air with nitrogen. Along with optical imaging, simultaneous cylinder-pressure data (digitized once per crank-angle degree) and in some cases spark voltage and current (digitized at 100 or 500 kHz) were acquired.

Figure 2 shows the WG-SIDI engine and optical apparatus schematically. A quartz window forms the bottom of the piston bowl and provides optical access, along with endoscope probes mounted at the ends of the roofline of the cylinder head. The SG-SIDI optical engine does not have endoscope access, but has quartz windows at the gable ends of the cylinder head.

Table 2 collects characteristics of the high-speed digital camera systems used in this work.
Table 2. High-speed digital camera systems.

| Camera System          | Sensor(s)       | Wavelength Range (nm) | Image Formats Used (pixels) | Frame Rates Used (frames/s) |
|------------------------|-----------------|-----------------------|----------------------------|-----------------------------|
| Kodak 4540             | 1 NMOS          | 250–800               | 256 × 256 (full frame)     | 4500                        |
|                        |                 |                       | 256 × 128                  | 9000                        |
|                        |                 |                       | 128 × 128                  | 13500                       |
| Photron Fastcam Spectra| 3 Intensified NMOS | 250–400 (1)          | 256 × 256 (full frame)     | 40500                       |
|                        |                 | 400–800 (2)           | 256 × 128                  |                             |
|                        |                 |                       | 64 × 64                    |                             |

4. “Designer diagnostics”: illustrations

4.1. High-speed, high-resolution Mie-scattering imaging

Fuel spray structure, penetration and cyclic variation in the firing spray-guided engine were characterized by planar Mie-scattering imaging using a thin (~0.5 mm) sheet of light from a pulsed copper vapor laser (Oxford Lasers LS-20, 30 ns pulse duration, 2 mJ/pulse, wavelengths 511 and 577 nm) synchronized to a Kodak 4540 high-speed camera, operated here at 9000 half-height frames (256 × 128 pixel image format) to provide images every 1.33° crank angle. The laser sheet entered vertically through the piston window along the injector axis. The camera viewed the scattered light at right angles through one of the cylinder-head windows. A K2 long-distance microscope provided high magnification (9-mm high field of view).

Figure 3 shows a few images selected from sequences obtained with a high-pressure (11 MPa) injector that produces eight spray plumes in a circular pattern with a 70° angle between opposite plumes. Near the injector exit, all the spray plumes are within the laser sheet. Individual-cycle images show non-uniform scattered-light intensity on the scale of 1–2 mm (comparable to the 1.5-mm spark gap). Mie-scattering intensity is proportional to total liquid surface area rather than to liquid mass or droplet number, but it provides a useful measure of liquid inhomogeneity as the spray plume approaches the spark plug. Variations in the spray plume angle within individual cycles and from cycle to cycle [10] have also been meas-
ured from these image sequences. Also seen for some injectors are secondary injections and large, slow-moving droplets and ligaments that emerge from the injector as it closes.

An example of the spray/spark-plug interaction is shown in Figure 4. In this extreme case, the spark plug ground electrode faces the oncoming spray plume. Although the electrode shields the spark gap from the spray plume and reduces the local velocity at the time of spark, the wake causes strong fluctuations and degrades ignition stability.

4.2. Spark-emission spectroscopy
The minimum requirement for reliable ignition is that the spark encounter readily ignitable fuel-air mixture every cycle. This section describes a technique to measure the individual-cycle fuel concentration at the spark gap from the light emitted by the spark itself [11][12]. Previous studies using, e.g., planar LIF in various SC-SIDI engines have shown that the fuel concentration can vary widely near the spark gap, both within an individual cycle and from cycle to cycle [8][13]. Unfortunately, stray-light problems and interference by the electrodes create difficulty for LIF measurements right at the spark gap. Using chemiluminescence from the spark reduces the requirements for optical access (the technique has subsequently been implemented using a fibre-optic spark plug [14][15]), eliminates the need for a high-power pulsed laser, and insures that the measurement is spatially confined to the spark discharge. Unlike earlier spark-
emission approaches that were devised for premixed-charge engines and that are accurate only for near-stoichiometric combustion [16][17], the approach developed here works well over a wide range of fuel concentrations (fuel-air equivalence ratios from 0 to >3).

To develop the spark-emission spectroscopy technique, spark-discharge emission that passed through the piston window in the wall-guided SIDI engine was analyzed with a 0.25-m imaging spectrometer coupled to an intensified CCD camera. Pointed electrodes insured that the spark breakdown always occurred within the limited spectrometer field of view (Figure 2).

For high-energy coil ignition systems, the spark event consists of three primary phases: breakdown (~10 ns duration), arc (typically a few µs duration, although sometimes up to ~100 µs) and glow discharge (up to a few ms duration) [18]. Extensive dissociation and ionization occur during the breakdown phase. Spectra recorded during breakdown contain a large and cyclically fluctuating continuum contribution. During the arc phase, atomic recombination leads to radiation from excited diatomic molecules (e.g., NO*, OH*, CN*, C2*). Radiation persists with decreasing intensity through the glow discharge. Figure 5 shows a typical spark-emission spectrum recorded early in the glow discharge, which optimizes the spectrum signal-to-noise ratio for diatomic emissions.

As discussed in detail in Ref. [11], the integrated intensity under the CN* peak is proportional to the local fuel concentration for otherwise fixed operating conditions. Expressing fuel concentration in terms of carbon-atom number density accounts for changes in gas density, temperature and pressure with operating condition and allows the CN* intensity to be calibrated on homogeneous fuel-air mixtures (either propane or vaporized liquid fuel), as illustrated in Figure 6. For fixed fuel concentration, the spark energy during the measurement interval (typically of 100–150 µs duration delayed 30–100 µs after the spark breakdown) is strongly correlated with the CN* emission intensity. Normalizing the individual-cycle CN* intensity by the simultaneously measured spark energy from time-resolved spark current and voltage data) reduces the measurement uncertainty from 15–20% to 8–10% for calibration measurements in the engine on homogeneous mixtures.

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**Figure 5.** Typical near-ultraviolet spark-emission spectrum from a single cycle in the WG-SIDI engine, labeled with the features corresponding to the major diatomic emitting species. The integrated intensity of the CN* band at 385–388 nm is proportional to the fuel concentration.

**Figure 6.** Spark-emission spectroscopy: calibration of CN* emission intensity (normalized by spark energy during the measurement interval) vs. fuel concentration expressed as carbon number density. The calibration is slightly non-linear. Skip firing (injecting and firing 1 out of 12 cycles) eliminates residual gases from the cylinder. Burst firing produces a normal level of residuals.
and minimum cyclic variation in IMEP) is significantly rich on average (φ as before while the CH* and C_2* emission intensities were essentially zero. When liquid fuel was present in the SG-SIDI engine with premixed propane-air, the peak CN* intensity tracked the fuel vapor number density from liquid dissociated by the spark is much more likely to produce C_2* and CH* than CN* because the more liquid fuel in and near the spark gap than in the WG-SIDI engine. Statistically, fuel vapor formed getting of the spray at or near the spark plug and the short time between injection and ignition lead to much certainty. Also shown (right axis) is time-resolved spark energy. (b) Correlation of individual-cycle engine output [indicated mean effective pressure (IMEP)] with measured equivalence ratio φ.

Figure 7 illustrates the use of spark-emission spectroscopy to study ignition stability as spark advance (ignition crank angle) is varied in the WG-SIDI engine [12], which uses a high-pressure (8.5 MPa) swirl injector. The end-of-injection (EOI) command is fixed at the optimum 70°BTDC. Fuel concentration is expressed here as fuel-air equivalence ratio φ assuming that the gas temperature, density and oxygen distributions are uniform throughout the combustion chamber.

Note that the equivalence ratio for the optimum spark timing of 30°BTDC (based on maximum IMEP and minimum cyclic variation in IMEP) is significantly rich on average (φ = 1.5–1.6). Note also that the range of φ for the spark timings of 40° and 30°BTDC is much wider than the range (=0.6–1.6) usually considered to define the bounds of ignitability for gasoline. Two interacting factors are at work here. First, Solomon has shown that even when the spark gap was immersed in a cloud of fuel droplets and rich vapor, a nascent flame kernel can persist until the mixture becomes lean enough to sustain flame propagation [19]. Second, the ~1–2 ms glow-discharge duration allows substantial time (~12–24°CA) for fuel transport and mixing, so that the spark can encounter ignitable mixture if none was present early in the glow discharge when φ was measured [12][20]. (The 50°BTDC ignition timing is an extreme case: for most cycles, the fuel cloud has not yet arrived at the spark gap at the time of the measurement, and hence the measured φ is not strongly correlated with combustion performance.) However, as ignition is retarded past the optimum timing, the spark is less and less likely to encounter fuel-air mixture that is strong enough for good ignition and rapid flame propagation before the glow discharge dies out if such mixture was not present during or immediately after the spark breakdown.

In the spray-guided engine, the spark-emission spectroscopy technique was extended using spectrally resolved imaging [5] with the three-intensified-camera Photron Fastcam Spectra system (Table 2; see the next section for more detail) by imaging the spark at 40500 frames/s through interference filters to select emission at the CN*, CH* (431 nm) and C_2* (516 nm) band wavelengths. In the SG-SIDI engine, the targeting of the spray at or near the spark plug and the short time between injection and ignition lead to much more liquid fuel in and near the spark gap than in the WG-SIDI engine. Statistically, fuel vapor formed from liquid dissociated by the spark is much more likely to produce C_2* and CH* than CN* because the local concentrations of C and H are much higher than those of N or O. In calibration experiments in the SG-SIDI engine with premixed propane-air, the peak CN* intensity tracked the fuel vapor number density as before while the CH* and C_2* emission intensities were essentially zero. When liquid fuel was present in the spark gap, the CH* and especially the C_2* intensities were much higher. The C_2* intensity tracked
the expected behavior of liquid fuel as a function of fuel type (substantially less with isooctane than with gasoline) and the relative timing of injection and spark. In the presence of liquid fuel, the CN* intensity is therefore taken to measure the concentration of vapor-phase fuel as in Figure 6, and the C2* intensity is tentatively taken as a relative indicator of the amount of liquid-phase fuel either in the spark gap or on the electrodes.

Experimental results for ensemble-averaged vapor and relative liquid fuel concentrations are compared with CFD results in Figure 8 [5]. Note that the intervals between injection and spark are much briefer here than for the wall-guided engine in Figure 7. The earliest SG spark timings are during injection. The optimum spark timing (CA = -40°ATDC = 40°BTDC) is only 8° after EOI and leads to a very rich mean equivalence ratio (\(\phi = 2.8\)). Note also the large rms cycle-to-cycle variations in the measured fuel vapor data. Quantitative agreement between CFD and experimental mean values is fairly good for the vapor fuel, and both show the same trend for the liquid fuel.

4.3. Spectrally resolved high-speed imaging

The Photron Fastcam Spectra system (Table 1) has been used extensively for spectrally resolved imaging of combustion in both the wall-guided engine [12][21] and spray-guided SIDI engines [5][6]. The system consists of three image-intensified high-speed cameras that view the same scene through dichroic beamsplitters and narrowband filters that define the wavelengths detected by each camera.

To investigate flame propagation and rich-zone burnout in the SG-SIDI engine, one camera detected OH* chemiluminescence near 306 nm, which has been shown to be an excellent indicator of flamefront location for a variety of flames [22][23], although the OH* intensity cannot be taken as a quantitative measure of heat release rate because of the wide range of pressure and local temperature and composition encountered here, and because of uncertainties about the OH* formation mechanism [24][25]. The other two cameras detected light near 430 nm (CH* chemiluminescence in the early flame; later, CO-O recombination radiation and thermal emission from soot) and 750 nm (thermal emission from soot). Optical access was through the piston window.

Excerpts from three individual-cycle image sequences recorded with two levels of intake-charge dilution at 9000 half-frames/s are shown in Figure 9. Without dilution (left column), the flame propagates across and around the piston bowl so rapidly that locally rich combustion shows vestiges of the individual spray plumes (e.g., CA=12°). With 30% N2 dilution (center column), the initial partially premixed flame is much slower, allowing more time for fuel-air mixing and bulk fuel transport around the bowl, leading to an almost symmetric “phoenix-wing” pattern for the OH* emission (blue false color). The slower combustion requires 15° earlier injection and ignition in order to obtain the proper location of peak cylinder pres-
The total image exposure (intensifier gain × exposure duration) was increased by two orders of magnitude to show the 0% and 30% N₂ results on similar intensity scales.

The right column of Figure 9 shows an almost total misfire for the 30% N₂ case. The initial spark luminosity is significantly weaker than for the normal-combustion example in the center column, and nothing resembling normal flame propagation can be seen, although a very small region of weak burning can just be discerned to the left of the spark site in the images at CA = −11°, −3° and 5°.

**Figure 9.** Excerpts from 9000-frame/s sequences of spectrally resolved individual-cycle combustion images in SG-SIDI engine for 0% (left column) and 30% N₂ dilution (center and right columns). The images are shown on a logarithmic false-color scale (Blue: 306 nm; Green: 431 nm; Red: 750 nm). The first image in each case is at 5° after spark breakdown. Succeeding images are spaced at 8° intervals.
4.4. Quantitative high-speed refractive-index-matching imaging

As shown by the true-color endoscopic images in Figure 10 [9], pool fires that track the impact location of the fuel spray on the piston appear in wall-guided SIDI engines and persist late in the engine cycle. Two questions immediately arise: (1) how much fuel is actually deposited on the piston, and (2) are the pool fires an appreciable source of engine-out soot or hydrocarbon emissions? Early CFD simulations and some experiments suggested that even for light-load, warmed-up conditions, the fuel film on the piston contained ~10% or more of the total fuel injected. Prior to development of the refractive-index-matching (RIM) technique [26] summarized here, a number of techniques including LIF had been used to visualize fuel films in intake ports and in engine cylinders (see [9] for a review of earlier experiment and CFD), but a quantitative technique capable of measuring the formation and evaporation of thin films in an engine over a range of operating conditions was not available.

The key to the RIM technique is a roughened surface on the quartz piston window, which is illuminated with white light using a fibre-optic light guide. Figure 11 shows a surface height profile obtained with an interferometric microscope. When illuminated and viewed from below (Figure 2), the dry, rough surface scatters light diffusely due to the refractive index mismatch between the quartz \(n=1.45\) and the air \(n=1.0\) above the surface. Diffusely scattered light that is directed toward the camera creates a bright image of the surface [Figure 12(a)]. When a fuel film wets the surface (shaded areas in Figure 11), light transmission through the surface increases because the refractive index of the fuel \(n\approx1.39–1.41\) reduces the index mismatch and because the liquid film creates a locally smoother surface. The result is that the wetted surface appears darker than the dry surface, as illustrated in Figure 12 (b). In situ calibration relates the local change in transmission of light through the window surface \(\Delta T = 1 - I_{inj}/I_{ref}\) (where \(I_{inj}\) and \(I_{ref}\) are the intensities of the injected and calibration and reference images, respectively) to the local liquid-film thickness [Figure 12 (c) and Figure 13.]

**Figure 10.** Endoscopic images of fuel spray from high-pressure swirl injector and pool fire on piston surface in WG-SIDI engine. The pool fire location tracks the impact location of the spray on the piston. The pool fires persist late in the engine cycle after any useful heat release has ended.

**Figure 11.** Surface height profile of roughened quartz window used for RIM measurement of fuel film thickness. Shaded areas indicate liquid fuel. Note that the depth (vertical) scale is greatly expanded.

**Figure 12.** (a) Reference image of dry piston window illuminated and viewed from below as in Figure 2. (b) Calibration image with known volume of liquid fuel on piston. (c) Change in light transmission through piston window.
In the WG-SIDI engine, the RIM technique was implemented with the Kodak 4540 high-speed camera at 4500 frames/s. Each camera pixel corresponds to an area of \( \sim 0.5 \times 0.5 \text{ mm}^2 \) and hence integrates over hundreds of pits in the rough window surface. Although rough compared to a smooth quartz window or a newly machined metal piston, the surface roughness is comparable to that of a piston that has been fired for several tens of hours. Since piston temperature is important for fuel-film formation and evaporation, motoring or skip-firing was used to maintain the same piston surface temperature (140–150°C) in the optical engine as in a continuously fired, all-metal WG-SIDI engine. Typically, 50 images were recorded for each injected cycle. A corresponding set of reference images was taken on the preceding non-injected cycle to account for changes in the lighting and viewing conditions as the piston moves and for changes in surface cleanliness over the course of an experiment.

The individual-cycle fuel-film thickness images in Figure 14 and the ensemble-average data in Figure 15 show that, for the high-pressure swirl injector, indolene (a full-boiling-range test gasoline of controlled composition) leaves much more fuel on the piston than does isooctane (a single component fuel with boiling point of 99°C at atmospheric pressure). Figure 15 also shows that the multihole injector with gasoline leaves about the same fuel-film thickness and volume on the piston as the swirl injector does with isooctane. In all cases, only a very small fraction of the injected fuel forms a film on the piston: just over 1% for indolene with the swirl injector, and < 0.1% for isooctane with the swirl injector and for indolene with the multihole injector.

Figure 16 correlates RIM measurements of fuel film mass in the optical engine for a variety of injection timings to corresponding engine-out soot measurements from an all-metal engine of the same design under the same operating conditions. These results strongly suggest that pool fires supported by the fuel film on the piston are dominant source of engine-out soot for these part-load, warmed-up conditions. In contrast, the fuel-film mass is too small to account for more than a very modest fraction of the measured unburned hydrocarbon emissions. Hydrocarbon emissions are dominated by overmixing, which forms regions that are too lean too burn on the fringes of the fuel cloud [9].

Figure 14. RIM images of individual-cycle fuel-film thickness at 31°BTDC for two fuels (note the different thickness scales). EOI = 65°BTDC. The dark boundary indicates the periphery of the wetted area identified by the image analysis. The ellipse shows the edge of the piston window.
paratively weak soot radiation (due to the lower soot concentrations and temperatures) in SIDI engines much easier to control and calibrate than photographic film, and have adequate sensitivity for the chemiluminescence images to indicate reacting regions. The high-speed image-intensified cameras are sequences of soot-radiation images at 650 and 750 nm wavelengths, together with simultaneous OH* the optical WG-SIDI engine, the Photron Fastcam Spectra system was used to capture individual-cycle integrating along a narrow path or over a large portion of the combustion chamber. For measurements in quantitative imaging or, for continuous time-resolved measurements, have sacrificed spatial resolution by can be given here; see [6][28] for more detail.

色 pyrometry [27], which evaluates line-of-sight-averaged soot temperature and relative soot loading can be given here; see [6][28] for more detail.

4.5. High-speed two-color pyrometric imaging
Engine-out soot emission originates from competition between complex soot formation and oxidation processes, which depend on the local composition, temperature, pressure and mixing. For wall-guided SIDI engines, two primary sources of engine-out soot have been identified (see [9] and references therein): (1) rich combustion in the bulk gases and (2) the pool fires discussed in the previous section. To quantifying how spray structure and operating conditions affect soot formation and oxidation in these two modes, high-speed spectrally resolved imaging has been used to modernize the classic technique of two-color pyrometry [27], which evaluates line-of-sight-averaged soot temperature and relative soot loading from the intensity of thermal radiation by soot at two wavelengths. Only a brief summary of the approach can be given here; see [6][28] for more detail.

Previous IC engine applications of two-color pyrometry (mostly in diesels) have used either single-shot quantitative imaging or, for continuous time-resolved measurements, have sacrificed spatial resolution by integrating along a narrow path or over a large portion of the combustion chamber. For measurements in the optical WG-SIDI engine, the Photron Fastcam Spectra system was used to capture individual-cycle sequences of soot-radiation images at 650 and 750 nm wavelengths, together with simultaneous OH* chemiluminescence images to indicate reacting regions. The high-speed image-intensified cameras are much easier to control and calibrate than photographic film, and have adequate sensitivity for the comparatively weak soot radiation (due to the lower soot concentrations and temperatures) in SIDI engines.
compared to diesels. The soot-emission wavelengths were selected to avoid contribution from interfering molecular band emissions (CH*, C2*) and the CO–O recombination continuum, which extends up to about 600 nm. A tungsten lamp was used to calibrate the imaging system for absolute light intensity measurements at 650 and 750 nm over the temperature range 1500–3000 K.

At each soot-emission wavelength $\lambda$, the soot radiance $I_\lambda(T)$ can be expressed in two ways:

$$I_\lambda(T) = \varepsilon_\lambda I_{\lambda b}(T) = I_{\lambda b}(T_a).$$

In the first equality, $\varepsilon_\lambda$ is the soot emissivity (<1 for any physical radiator) and $I_{\lambda b}(T)$ is the radiance from a perfect blackbody at the same temperature $T$, given by the Planck distribution. In the second equality, $I_{\lambda b}(T_a)$ is the radiance from a perfect blackbody at an apparent or brightness temperature $T_a < T$. The soot emissivity is approximated by the time-honored semi-empirical model [27]

$$\varepsilon_\lambda = 1 - \exp(-KL / \lambda \alpha),$$

where $K$ is an absorption coefficient proportional to the soot concentration, $L$ is the optical path length, and $\alpha = 1.39$ for visible wavelengths. The $KL$ factor thus provides a relative measure of total soot loading along the optical path. The equations above, together with the Planck distribution, provide two non-linear equations that are solved iteratively pixel by pixel for $KL$ and the actual soot temperature $T$ using as input the two apparent soot temperatures given by the calibrated high-speed images at the two wavelengths.

Two-color pyrometry is subject to systematic errors due to the line-of-sight character of the measurement and the model of the soot emissivity. Biases associated with spatial distribution and temperature of the soot, attenuation of the soot radiation along the optical path, the soot particle size distribution, and the soot’s complex index of refraction have been assessed [21][28][29], as well as effects of camera noise and dynamic range [21]. Nevertheless, as illustrated next, the soot temperature and $KL$ factor are useful for studying the temporal evolution, spatial distribution and cyclic variability of soot formation and oxidation, and for comparing the effects of different injectors and operating conditions.

Figure 17 follows the evolution of combustion and the soot temperature and $KL$ distributions in one engine cycle. A partially premixed flame propagates from the spark into locally rich regions near the spark plug and later ignites pool fires. For the eight-hole injector used here, only the two spray plumes with the shortest distance to the piston leave significant fuel films, as shown by the individual-cycle RIM fuel-film image in the lower right corner of the figure. Because the pool fires can be distinguished both spatially and temporally from the earlier rich combustion emanating from the spark plug region, soot properties from these regions are quantified separately in Figure 19, which presents a more global picture in which the spatially averaged soot temperature and spatially integrated $KL$ factor have been ensemble averaged. The heat-release rate evaluated from the cylinder pressure is also shown.

During early flame development (e.g., 15°BTDC), only OH* emission from partially premixed combustion can be detected with the filters and camera exposure used for Figure 17. Detectable soot luminosity, which first appears near the spark plug about 10°BTDC, increases in size and intensity as the partially premixed flame expands to fill most of the field of view. The maximum soot radiance and soot temperatures occur a few degrees before the peak heat-release rate, which comes just before TDC. During this period the soot temperature and/or concentration are high enough to saturate the detectors over an appreciable portion of the locally rich region. Note also in Figure 19 that the ensemble-averaged, spatially integrated $KL$ factor in the partially premixed combustion region near the spark plug reaches its maximum after the soot temperature has begun to decrease (about 10–15°ATDC).

Although soot forms earliest in rich zones during partially premixed flame propagation (Figure 19), rapid turbulent mixing with surrounding hot lean regions leads to rapid soot oxidation and apparently complete burnout by ~50°ATDC. This soot burnout is consistent with the observed OH* emission (see the far-right images in Figure 17 for 33° and 49°ATDC).
Soot from the pool fires evolves very differently. Weak pool-fire soot luminosity can be detected as early as TDC, but does not become significant until about 10–20°ATDC, when the heat-release rate has fallen substantially and ~80% of the total heat release has occurred (Figure 18). In Figure 17, the pool fires reach their maximum extent around 33°ATDC, after which they shrink. Overall (Figure 18), the pool-fire KL reaches a maximum around 50°ATDC and is accompanied by a secondary peak in the spatially integrated OH* intensity, which seems reasonable in view of the leading role of OH-radical attack in soot oxidation [30]. The disappearance of the soot luminosity (vestiges can be seen until about 120°ATDC for this condition) and the decreasing KL are largely due to soot oxidation and complete consumption of the fuel film on the piston, which contains no more than ~0.1% of the total 10 mg of fuel injected per cycle for this operating condition [9]. However, soot dispersion, convection out of the field of view (seen in some single-cycle image sequences), and soot-emission intensities below the threshold for meaningful analysis can also decrease the observed KL.

Piston wetting and engine-out soot emissions are an order of magnitude larger for the swirl injector than for the multihole injector (Figure 15 and Figure 16). Correspondingly, Figure 19 shows that the in-cylinder soot loading (KL) is an order of magnitude larger for the swirl injector with the same injection timing (EOI = 50°BTDC). For fixed spark timing with the swirl injector, the wall-film mass and soot loading decrease with earlier injection, which increases the injector-to-piston distance and allows more time for fuel-air mixing. For the two heaviest-sooting cases, net soot production (evidenced by the KL peaks) continues until about 80°ATDC. For these two cases, soot luminosity can be observed and soot temperature and KL can be determined until the exhaust valve opens (144°ATDC). Overall, the two-color pyrometry results strongly support the conclusion that pool fires are the dominant soot source in the WG-SIDI engine under warmed-up, part-load conditions.
Summary and Conclusions

This paper has reviewed a suite of optical diagnostic techniques (largely based on high-speed imaging, spectrally resolved optical emissions, and in-situ calibration) that are designed to address specific issues in developing stratified-charge spark-ignition direct-injection gasoline engines. For the wall-guided SIDI design, in particular, these techniques have provided an unusually complete and quantitative characterization of mixture preparation (fuel concentration at the spark gap at the start of ignition measured using spark-emission spectroscopy), combustion (spectrally resolved imaging of partially premixed flame propagation and rich-zone burnout), formation and evaporation of liquid fuel films on the piston (refractive-index-matching imaging of fuel-film thickness), and in-cylinder soot formation and oxidation (soot temperature and relative soot loading measured by high-speed two-color pyrometry). Two results of particular practical significance are (1) the average fuel-air ratio $F/A$ at the spark gap must be rich in order to avoid misfires and partial burns associated with the large cycle-to-cycle variations in $F/A$ and (2) pool fires supported by thin liquid films on the piston are the dominant source of soot emissions from the WG engine under warmed-up, part-load, conditions. Early in the development of wall-guided SIDI engines [2], it was thought to the contrary that the optimum fuel-air ratio at the spark plug would be stoichiometric or slightly lean to minimize rich combustion, that rich combustion in the bulk gases was the primary soot

![Figure 19](image_url)

**Figure 19.** In-cylinder soot loading late in the engine cycle shown by the ensemble averaged, spatially integrated $KL$ factor vs. crank angle for swirl and multi-hole injectors as injection timing is varied. The $KL$ values are normalized to the maximum $KL$ value for the multi-hole injector in Figure 19. Although the $KL$ values are integrated over the entire field of view, only the pool fires contribute appreciably after about 60° ATDC, as illustrated in Figure 19.

5. Summary and Conclusions

This paper has reviewed a suite of optical diagnostic techniques (largely based on high-speed imaging, spectrally resolved optical emissions, and in-situ calibration) that are designed to address specific issues in developing stratified-charge spark-ignition direct-injection gasoline engines. For the wall-guided SIDI design, in particular, these techniques have provided an unusually complete and quantitative characterization of mixture preparation (fuel concentration at the spark gap at the start of ignition measured using spark-emission spectroscopy), combustion (spectrally resolved imaging of partially premixed flame propagation and rich-zone burnout), formation and evaporation of liquid fuel films on the piston (refractive-index-matching imaging of fuel-film thickness), and in-cylinder soot formation and oxidation (soot temperature and relative soot loading measured by high-speed two-color pyrometry). Two results of particular practical significance are (1) the average fuel-air ratio $F/A$ at the spark gap must be rich in order to avoid misfires and partial burns associated with the large cycle-to-cycle variations in $F/A$ and (2) pool fires supported by thin liquid films on the piston are the dominant source of soot emissions from the WG engine under warmed-up, part-load, conditions. Early in the development of wall-guided SIDI engines [2], it was thought to the contrary that the optimum fuel-air ratio at the spark plug would be stoichiometric or slightly lean to minimize rich combustion, that rich combustion in the bulk gases was the primary soot
source, and that fuel-films on the piston were a major if not dominant source of hydrocarbon emissions [31].

The experimental approaches reviewed here do not characterize all the relevant in-cylinder processes, but they do provide important information not available otherwise. Combined with corresponding measurements in all-metal engines and CFD simulations (e.g., [5][6]), they offer a sound scientific basis for SC-SIDI engine design optimization.

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