

X-Ray Radiography Measurements of the Thermal Energy in Spark Ignition Plasma at Variable Ambient Conditions

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ABSTRACT

The sparking behavior in an internal combustion engine affects the fuel efficiency, engine-out emissions, and general drivability of a vehicle. As emissions regulations become progressively stringent, combustion strategies, including exhaust gas recirculation (EGR), lean-burn, and turbocharging are receiving increasing attention as models of higher efficiency advanced combustion engines with reduced emissions levels. Because these new strategies affect the working environment of the spark plug, ongoing research strives to understand the influence of external factors on the spark ignition process. Due to the short time and length scales involved and the harsh environment, experimental quantification of the deposited energy from the sparking event is difficult to obtain. In this paper, we present the results of x-ray radiography measurements of spark ignition plasma generated by a conventional spark plug. These measurements were performed at the 7-BM beamline of the Advanced Photon Source at Argonne National Laboratory. The synchrotron x-ray source enables time-resolved measurements of the density change due to glow discharge in the spark gap with 153 ns temporal and 5 μm spatial resolutions. We explore the effects of charging time, EGR-relevant gas compositions, and gas pressure on the sparking behavior. We also quantify the influence of the measurement technique on the obtained results.

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INTRODUCTION

The crucial role of the spark plug in spark-ignited (SI) engines is to initiate the plasma kernel that ultimately forms a self-propagating flame to drive the combustion process. In order to assure sustained operation, the sparking event must occur in a reliably consistent manner at all operating load and speed conditions that a vehicle is expected to encounter. While various concepts for spark ignition systems exist [1,2], the conventional ignition coil is still most commonly used today. With emissions requirements becoming increasingly stringent, lean combustion strategies, exhaust gas recirculation (EGR), turbocharging, and boost systems have been implemented to meet these progressive standards while striving to also improve fuel economy. As these methods are applied more aggressively, the combustion process becomes increasingly prone to cycle-to-cycle variability, incomplete burn, and misfires. To this end, exploring the effects of external factors such as EGR and cylinder pressure on the sparking event is important for understanding the operating limits of such strategies, and providing guidance for system improvement.

In a conventional ignition coil, current is provided to the coil primary windings for a specified charging time. When the current is switched off, the changing magnetic field creates a high voltage spike in the secondary windings, on the order of 15 kV [2]. As this voltage rises, it creates an increasing potential gradient between the electrodes.

Once the breakdown voltage is reached, an electrically conductive path is established between the spark plug electrodes, reducing impedance in the gap and allowing current to flow from cathode to anode, creating a spark. This breakdown voltage is a function of the environment surrounding the spark plug, as well as the gap distance, electrode material, and surface layers on the electrode [3]. The resulting sparking event may be categorized by three stages: breakdown, arc, and glow discharge phase. The breakdown process occurs at extremely short time scales - approximately 10 ns. The arc phase follows, during which the reactive species required for flame propagation begin to form [2]. A reduced voltage, the expansion of the kernel through mass diffusion and heat conduction, and microsecond timescales characterize this process. During the glow discharge phase, which lasts on the order of milliseconds, most of the heat transfer to the environment occurs. There is typically about 70% energy loss due to heating of the electrodes at this stage. Energy from glow discharge can be convected away from the electrode by a cross-flow, thus reducing heat loss to the electrodes and allowing for re-ignition to occur, consequently increasing the ignition probability in such systems [3]. The arc and glow phases govern the cooling period of the plasma kernel, and provide the time and supplementary heat for reactive species to avalanche into a self-sustaining process that is no longer supported by the energy from the breakdown phase. If the kernel does not reach its minimum required volume by the time its temperature falls to the to the normal flame temperature of the environment, ignition will not occur [4].

A variety of optical diagnostic techniques have been used to study various characteristics of the spark ignition process, including the temperature, gas concentration, turbulence field, and flame structure [3]. Conventional microscopy still photos, interferograms, and high-speed schlieren imaging allow visualization of the flame kernel and plasma [2, 4, 5]. Planar laser induced fluorescence (PLIF) and chemiluminescence imaging provide information on the concentrations of probed species [6]. Particle image velocimetry (PIV) quantifies flow velocities and the turbulence intensity [7]. In addition, a diode laser sensor has been successfully used for crank-angle resolved point measurements of the temperature near a spark plug [8]. Flow calorimetry may also be used to measure the amount of supplied energy that is deposited into the gas [9].

Previous computational endeavors have modeled the two-dimensional (2D) spark discharge by coupling chemical reactions, fluid dynamics, and transport models that account for the interaction of charged particles [10]. More recent work explores the effect of dilute and lean methane/air mixture on the sparking behavior [11]. Provided sufficient computational resources, models can resolve temporal and spatial timescales that are relevant to a sparking event, including the genesis of the arcing phase. However, they still require supplementary experimental data for model validation and robustness.

In recent years, x-ray radiography has been utilized to provide time-resolved measurements of the projected density for a range of multiphase flows [12]. The Advanced Photon Source (APS) at Argonne National Laboratory supplies an x-ray beam with the requisite photon flux and range of operational energies required for high spatial ($O(\mu\text{m})$) and temporal ($O(\text{ns})$) resolution in such measurements. Accordingly, facilities at the APS have been used to investigate properties of the fuel spray ejected by gasoline direct injection (GDI) [12, 13] and diesel injectors [15], [16], [17], [18], including shot-to-shot statistics [19]. Kastengren et al. (2016) have demonstrated the use of x-ray radiography to obtain temporally and spatially-resolved 2D maps of the gas displacement inside the gap of a conventional spark plug, mainly during the glow discharge phase [20]. The authors surveyed the effect of variable charging time and gas composition (air vs. argon) on the sparking behavior. At the energies required for these measurements, the primary interaction between the gas and the x-ray photons is through photoelectric absorption. The probability for multiple scattering is negligible, as is refraction of the x-rays due to temperature and pressure gradients in the measurement [21]. Consequently, x-ray radiography can provide a complementary diagnostic to quantify the amount of displaced gas in the vicinity of the spark plug at high spatial and temporal resolution. In this paper, we extend the work of Kastengren et al. (2016) to investigate the effects of charging time, gas composition, and ambient pressure on the sparking behavior produced by a conventional ignition coil system. Air was diluted with various concentrations of CO_2 in order to mimic EGR-relevant conditions. The displaced volume of gas and thermal energy in the vicinity of the spark gap were calculated. In addition, shot-to-shot statistics were measured to better understand the variability of the sparking event. Lastly, the effect of the x-ray beam on the measurement technique was investigated.

METHOD

Experiments were performed at the 7-BM beamline of the APS at Argonne [22]. A production M14 NGK-R OE iridium spark plug (IZFR6K11) with a 0.94 mm gap was horizontally mounted in a 500 cm^3 stainless steel pressure chamber that provided the ground path for the discharge. The chamber was pressurized between 3.4 - 10 bar gauge at room temperature with varying gas compositions, summarized in Table 1. These pressures correspond to density values ranging between 5 kg m^{-3} - 13 kg m^{-3} . Typically, for lean conditions, the timing is advanced so that sparking occurs earlier in the cylinder cycle, i.e. at lower cylinder pressure. Spark experiments in the lower density range mimic conditions expected in a naturally-aspirated GDI engine with up to 20% EGR during time of spark, while higher density conditions are more relevant to boosted operation. Mass flow controllers (MFCs) were used to deliver each gas from its respective cylinder into the chamber. For a mix of air and CO_2 , the outputs of two MFCs were connected with a tee and allowed to mix prior to entering the chamber by way of an elongated steel tube between the tee and chamber. Gas was continuously supplied from the cylinders into the chamber for each experiment. A backpressure regulator was used to maintain a steady chamber pressure. The gas was purged through the chamber at a rate of 1.5 standard L min^{-1} .

Table 1. Operating conditions for spark radiography experiments. Ultra-zero air was used in all experiments, composed of 20-22% O_2 and 2 ppm H_2O by volume, with less than 1 ppm of trace gases.

Condition #	Chamber Pressure (bar gauge)	Charging Time (ms)	Gas Composition (vol %)
1	3.4	2.5	100 % air
2	3.4	2.5	1% CO_2 , 99% air
3	3.4	2.5	2% CO_2 , 98% air
4	3.4	2.5	5% CO_2 , 95% air
5	5	1.5	100 % air
6	5	2	100 % air
7	5	2.5	100 % air
8	5	2.5	1% CO_2 , 99% air
9	7	2.5	100 % air
10	10	2.5	100 % air

Figure 1 schematizes the experimental setup and relevant coordinate system. The broadband emission from the APS bending magnet was filtered using a double multilayer monochromator to generate a 6 keV monochromatic x-ray beam (4.2% full width at half maximum bandpass) before entering the experimental station. Where possible, the beam path was evacuated to maintain photon flux. Downstream of the monochromator, the beam passed through a rotating two-slot chopper wheel at 3% duty cycle to minimize ionization of the ambient gas, which could influence the breakdown voltage and sparking behavior. An oscilloscope was used to ensure synchronization of the chopper gating with the sparking event, with proper timing set by a Stanford digital delay generator. For each sparking event, the x-ray beam pulse lasted 15 ms to capture the full evolution of the spark. The beam was focused to a $5 \times 6 \mu\text{m}$ spot using a pair of focusing mirrors, with the focal point at the center of the spark gap. The focused beam passed through two 0.1 mm transparent polyimide windows mounted on either side of the

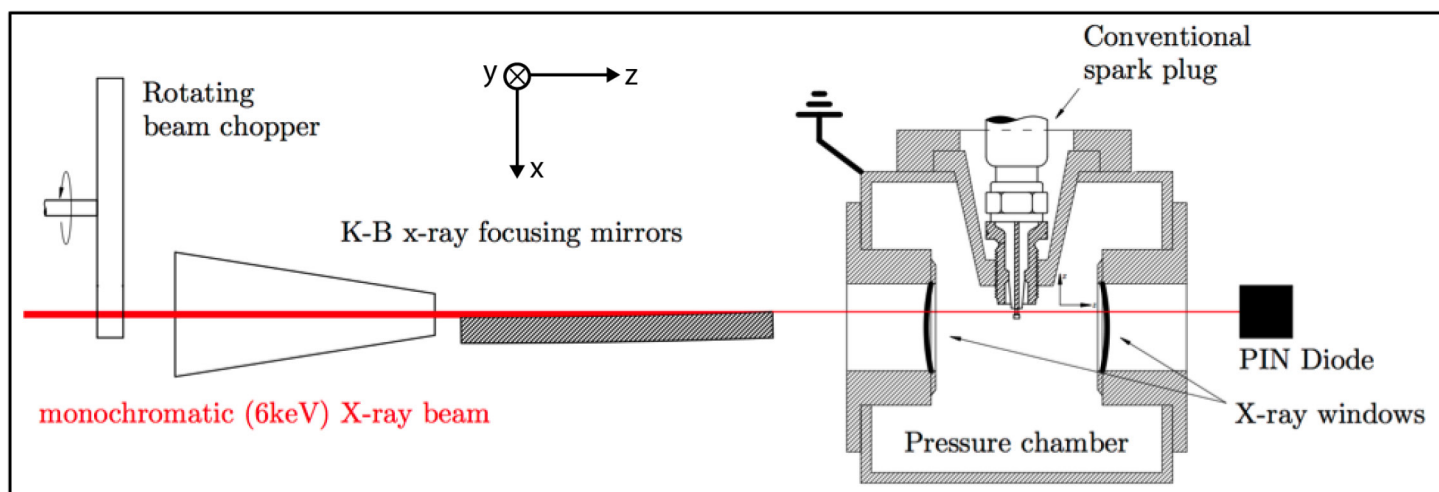


Figure 1. A schematic of the experimental setup used for x-ray radiography experiments. The depicted view is from above, looking down at the experimental setup. The x-ray beam is denoted in red, and is traveling from left to right in the image. The y-coordinate is positive into the page.

chamber. The spark plug was connected to a Motorcraft DG-562-CM5Z-12029-K (OEM: CM5E-12A366-CB) transistorized coil, powered by a Kepco 25 V, 20 A DC power supply. The spark plug was fired at 1 Hz. The transmitted x-ray intensity was measured downstream of the pressure chamber with a PIN diode.

As the beam passes through the spark gap, incident x-ray photons are absorbed by the surrounding gas through photoelectric absorption. This process is characterized by the absorption of an x-ray photon by an atom, which then transfers its energy to a core-shell electron. This transfer of energy expels the electron, leaving the atom ionized [21]. Absorption is related to the properties of the medium such as its density and atomic number, as well as the x-ray beam energy. Thus, the degree of absorption is related to the density of gas in the beam path. During an arcing event, the gas in the vicinity of the spark gap is heated, leading to a local change in density. If the gas density decreases, there is correspondingly less x-ray absorption, as the number density of gas molecules in the beam path has decreased. This leads to an increase in the recorded beam intensity relative to its initial state. The effective path length of gas in the beam path is described by the Lambert-Beer law [21],

$$l(x, y, t) = \frac{1}{\mu \rho_0} \log \left[\frac{I(x, y, 0)}{I(x, y, t)} \right], \quad (1)$$

where $I(x, y, 0)$ is the initial beam intensity before a sparking event occurs, $I(x, y, t)$ is the measured beam intensity, and μ and ρ_0 are the mass attenuation coefficient and the initial ambient gas density, respectively. The value of μ for each gas composition at 6 keV was found from lookup tables that take into consideration the mass fraction of each gas in the mixture [23]. Because $I(x, y, t) > I(x, y, 0)$ when the gas expands, the path length is represented by a negative value.

During experiments, the synchrotron operated in 24-bunch mode. The measured beam intensity was bunch-resolved with a temporal resolution of 153 ns, and subsequently binned over each synchrotron orbit to provide a final resolution of 3.68 μ s. The secondary voltage

signal was sampled at 8 ns. Each sparking event was recorded for 10 ms, with $t = 0$ ms corresponding to the time at which the ignition coil was commanded to start charging by a TTL trigger. On account of the short lifespans of the breakdown and arc phases, the temporal resolution achieved in these measurements only captures the transition to, and the full extent of, the glow discharge phase.

In order to build a 2D map of the path length of gas in the vicinity of the electrodes, the pressure chamber was translated in the x and y coordinates relative to a stationary beam. A total of 722 points were scanned. The beam intensity and secondary voltage were recorded for 30 sparking events at each (x, y) position. Figure 2 plots the raster-scanned measurement grid that was used for all conditions. The spacing outside of the spark gap was $150 \times 150 \mu\text{m}$ ($H \times V$), and $60 \times 50 \mu\text{m}$ inside the gap.

Three ignition coil charging times were explored: 1.5, 2.0, and 2.5 ms, with the longest duration corresponding to the saturation limit of the coil. The primary voltage supplied to the spark plug was held constant at 13.2 V DC. The total stored energy in the coil was 58.3, 90.2, and 126.9 mJ for a charging time of 1.5, 2.0, and 2.5 ms, respectively, calculated by integrating the primary current signal of the charging phase. The maximum obtained primary current was 6.5 A at 2.5 ms charging time.

ANALYSIS

To reduce high-frequency noise, the time-binned secondary voltage signals were passed through an 8th order Butterworth filter with a cutoff frequency set to 0.04 of the Nyquist frequency. The maximum breakdown voltage and its time of occurrence were then found from averaging 20 data points before the breakdown event. Figure 3 plots an example of the unfiltered secondary voltage profile as well as the filtered signal for one of the sparking events measured at 3.4 bar air with 1% CO₂ and 2.5 ms charging time. The voltage slope before breakdown is shallow relative to the timescale of breakdown, which is on the order of nanoseconds. Therefore, averaging over 160 ns will