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Time-Resolved Measurements of In-Cylinder Fuel Spray and Combustion Characteristics using High-Speed Visualization and Ionization Sensing

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Abstract

A time-resolved measurement technique combining the diagnostic tools of high speed flow visualization and high fidelity in-cylinder ionization sensing was implemented to evaluate the fuel air mixture formation and combustion characteristics in a single cylinder engine with optical access to the combustion chamber. In-cylinder spray and combustion images were taken at an acquisition rate of 10,000 frames per second with simultaneous recordings of both in-cylinder ionization and pressure signal traces within a complete engine cycle. The results reveal that, prior to the combustion event, the injector spray pattern and injection timings affect the fuel-air mixture formation, spray impingement on cylinder wall, and fuel distribution near the spark plug in the cylinder. After combustion is initiated, the synchronized combustion images with in-cylinder ionization measurements provide more cycle-resolved information about the combustion characteristics, from the onset of spark ignition to flame propagation and to flame quenching at the cylinder wall. Combining and synchronizing the high speed images with in-cylinder combustion ionization and pressure signals improve the understanding of fuel mixture distribution, combustion characteristics, flame propagation, and the quality of combustion in the engine combustion chamber.

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INTRODUCTION

Recent innovations on vehicles to improve fuel economy and reduce emissions have been primarily achieved through the use of sophisticated fuel injection hardware capable of adapting to more challenging injection control strategies. For spark ignition (SI) engines, gasoline fuel is atomized into fine fuel droplets and injected into either the intake port in port fuel injection (PFI) engines or directly into the combustion chamber for gasoline direct injection (DI) engines. Particularly for gasoline DI engines, fuel spray characteristics including the spray shape, penetration, drop size, dynamic flow stability and injection repeatability have been identified as key factors to enhance the engine combustion performance and reduce exhaust emissions from internal combustion engines [1]. In fact, fuel injectors are arguably one of the most critical components in ground vehicles. The fuel mixture preparation process in the engine significantly affects engine combustion and emissions performance. This is particularly true for exhaust emissions of hydrocarbon (HC) during engine cold-start and warm-up conditions [2]. If the quality of fuel injector spray can be properly verified, additional high engine exhaust emission problems relating to engine choking, misfire, and rough idle may be minimized [1,3].

In addition to controlling the air-fuel mixture formation, SI engine combustion can also be improved by precisely optimizing the ignition timing in a closed-loop manner, provided that the state of combustion in the cylinder can be closely monitored in real time. Historically, various closed loop ignition (spark) timing control schemes have been deployed based upon in-cylinder pressure measurements [4]. Recently, advances in electronics have allowed the same combustion information to be extracted from real-time analysis using the ionization current associated with combustion events [5-8]. Since combustion produces ions and free electrons, with a conventional spark plug and a modification of the ignition system, an electrical current proportional to the combustion induced ions and electrons can be measured, and it can be used to detect engine partial burn and misfire [8], engine knock [5, 8], and combustion stability [6]. Based upon the estimated engine knock, MBT (Minimal advance for the Best Torque) timing and combustion stability criteria, closed loop engine knock, MBT timing and combustion stability control has been introduced in SI engines [4, 5, 6]. In essence, a spark plug by itself is an actuator for the ignition, and an ionization sensing system expands the role of a spark plug as a sensor to detect the in-cylinder combustion process when a bias voltage is applied between the spark plug gap and ground electrodes. In fact, when the engine load is high, the ionization signal can be used to locate in-cylinder pressure peak [5, 7]. For SI engine, a typical ionization signal has two peaks: the first peak is due to the initial flame kernel development after the spark. When the flame front leaves the spark plug, the magnitude of the ionization signal reduces. As the pressure in the cylinder increases rapidly, the combusted mixture around the spark plug gap is ionized again due to the high temperature resulted from the combustion, that generates the second peak. Because the flame starts at the spark plug gap and gradually moves away from it, the ionization signal may provide more information about in-cylinder combustion than an in-cylinder pressure signals [6]. However, up to date, most of the ionization applications for either combustion quality detection or closed loop combustion controls are for PFI engines and very limited information has been reported for gasoline DI engines.

The objective of this work is to demonstrate the time-resolved measurements of in-cylinder fuel mixture formation and combustion in a gasoline DI engine with optical access to the combustion chamber. The measurement technique combines high speed imaging with high fidelity in-cylinder pressure and ionization detections. Even though different engine speed and load conditions are reported in this paper for fuel mixture and combustion tests, our primary focus is to illustrate the applicability of combining and synchronizing several measurement tools to obtain more information about the in-cylinder combustion processes.

EXPERIMENTAL SETUP AND APPARATUS

The visualization experiments are carried out in an optical single-cylinder engine [1]. The half block of the 5.4 liter V8 engine rig attached with the production intake manifold is shown in Figure 1. It has two intake valves and one exhaust valve. Implemented between the cylinder head and the reciprocating assembly are the quartz cylinder and piston with a quartz insert, in which both provide optical access to the inside of the engine cylinder from two different viewing angles. Three of the four cylinders on this half cylinder head bank have been deactivated by grinding off their lobes on the camshaft. The cylinder head was originally designed for PFI injector, but it has been modified to accommodate a side-mounted gasoline DI injector from the intake side. The cylinder head, mounted on top of a single cylinder crank case, has been re-stroked to 105.7 mm to match the crankshaft geometry of the engine and utilize the original connecting rod. The engine is held at constant speed by a 15 horsepower AC motor with a variable speed drive. An optical shaft angle encoder is used to trigger the fuel injection and image recording which is accomplished through the use of an integrated timing controller. A laboratory-grade nitrogen-fed fuel bladder was used to pressurize the fuel. Indolene was used as the test fuel at an injection pressure of 30 bar. For each test condition, the engine was first motored to reach the desired speed. Once the engine was stabilized, a signal from the controller was sent out to the fuel injector to trigger the start of injection (SOI) at a specific crank angle of piston location. The same signal was also used to trigger the high speed camera and start recording the image sequence.

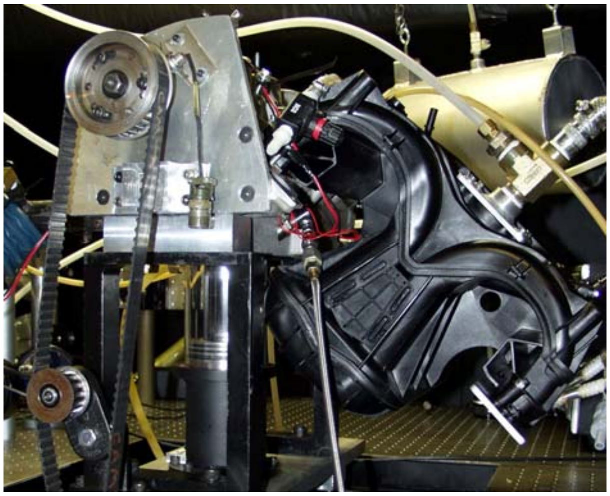

Figure 1. View of the single cylinder optical engine with production intake air manifold.

The high-turbulence fuel injectors used in the tests were specially designed with multi-hole nozzles. Multi-hole fuel injectors have advantages over swirl-type fuel injectors as the number of hole, hole pattern, hole orientation, and the internal flow cavity can be tailored to generate different overall spray patterns. This allows the high flexibility to optimize the fuel mixing in the cylinder, which has been reported in detail in a previous publication by the author [9]. In this study, three different injector spray configurations with 8-hole nozzles with spray angles of 40, 60 and 80 degrees and offset angles of 0, 5 and 10 degrees from the injector axis were used (denoted as 40/0, 60/5 and 80/10, respectively). The spray geometrical parameters such as spray angle, offset angle, and spray tip penetration had been verified from the Mie-scattered images and the drop size distributions of the spray were measured using Phase Doppler Interferometry [10].

The ionization detection system used for the combustion diagnosis is integrated with a coil-on-plug ignition system, where the ionization detection electronics with ignition coil driver is integrated into the ignition coil spark plug assembly. This ionization detection system is capable of detecting ionization current around 10 microamperes. The output of the ionization signal is a current source which is proportional to the measured ionization current. In addition, a pressure sensor (Kistler) was also installed in the cylinder head to monitor the in-cylinder pressure signals. The tip of the pressure sensor was located in between the intake and exhaust valves.

All fuel spray imaging tests were performed with the engine motored only. A Mie scattering technique was used to visualize the liquid phase of the fuel dispersion inside the combustion chamber through the quartz cylinder liner wall as well as the quartz piston insert. The fuel spray was imaged with a non-intensified high speed digital video camera (*Photron*, Model Fastcam APX RS). The camera was set to record at 10^4 images per second with a resolution of 512 pixels by 512 pixels to cover a spatial imaging area of approximately 120 mm by 120 mm. A high repetition rate pulsed copper vapor laser (*Oxford Lasers*, Model LS20-50), synchronized with the high speed camera and the fuel injection timing logic, was used to illuminate the liquid fuel dispersion via a fiber optics cable. The visible laser illumination was directed to the cylinder using a fiber optics cable through the quartz piston insert, as shown in Figure 2. The 20 Watt laser provided the high intensity short pulse duration of about 25 ns. Based on the previous test data of fuel flow and lambda calculation on this firing engine, the fuel injection duration was adjusted at each load condition to achieve a stoichiometric air-fuel ratio. For each imaging test, 300 consecutive frames from each injection cycle were recorded to visualize the fuel dispersion during the intake and compression strokes. Five injection cycles were normally recorded to allow for a quick assessment of cycle-to-cycle variation.

Figure 3 shows the view of the top of the combustion chamber through the quartz piston insert. For combustion visualization, the image sequence recording was started near the end of the compression stroke before the piston reached the top dead center. The images were reflected toward the camera via a UV-visible mirror mounted at 45° below the cylinder. Both in-cylinder pressure and ionization signals, collected using a dynamometer data sampling system for 300 cycles with one crank degree resolution, were synchronized with the high speed images. A lambda sensor is installed in the engine exhaust to allow for measuring the air-fuel ratio. Because of the large number of images acquired per experiment, automation of the image analysis was essential. Computer programs were written using Matlab to identify the flame propagation synchronizing with the in-cylinder signals of pressure and ionization.

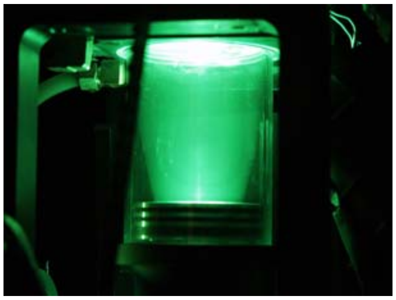

Figure 2. Illumination of the engine cylinder.

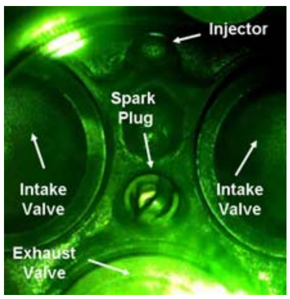

Figure 3. View of in-cylinder configuration through a quartz piston insert.

RESULTS AND DISCUSSIONS

The test condition reported in this paper was carried out at an engine speed of 2500 RPM with full load wide open throttle (WOT) condition. Additional information other engine test points and observations can be found in [1]. The SOI was set at 300º crank angle (CA) before top dead center (BTDC). Figure 4 depicts the three different spray mixture formations at this engine load condition. The images show that both the spray angle and offset angle were critical in affecting how the fuel spray was dispersed in the cylinder. Since the intake air was dominant when the engine was running at full load condition, the intake air diverted the spray slightly towards the direction of moving piston. The initial spray dispersion at an early CA of 262.5º BTDC seemed to be quite similar for all three sprays. However, as the cycle progressed to 225º BTDC, the liquid fuel of the 40/0 spray moved directly towards the opposite side of the cylinder wall. The 60/5 spray penetrated more towards the central region of the cylinder and less on the cylinder wall. The spray was tilted more towards the piston and it created a slightly better fuel dispersion within the cylinder. The impinging location of fuel on the cylinder wall was further away from the top of the cylinder along the stroke than the previous 40/0 spray.

It is evident that for this injector mounting orientation and cylinder geometry, a wider spray angle improves the fuel dispersion and the additional spray offset angle of 5º from the injector axis moves the spray even more towards the piston direction. As expected, the 80/10 spray directed the fuel dispersion even more towards the central region of the cylinder without any noticeable fuel impingement on the cylinder wall. At 197.5º BTDC, the fuel impingement of the 40/0 spray was very pronounced. At 150º BTDC, both intake valves were almost fully closed. The fuel dispersion of the 40/0 spray was quite localized in the upper half of the cylinder closer to the exhaust valve. Even though the 60/5 spray improved the fuel distribution slightly, the wide spray delivered by the 80/10 injector was able to provide the best fuel air mixing in the cylinder.

There are several key observations which are of interest in our fuel mixture visualization tests. First, the images confirm that the spray pattern has a dominant effect on how fuel is dispersed inside the cylinder. The narrow spray of 40/0 created a reduced core dispersion of fuel droplets in the central region of the cylinder. A narrower spray usually has a higher axial spray penetration. In contrast, a wider angle of fuel spray not only produced a more homogeneous fuel-air mixture by dispersing the mixture formation more in the upper to central region of the cylinder, it also reduced the penetration along its injector axis. Second, the mounting angle of the injector has a profound effect on the fuel homogeneity and wall wetting inside the cylinder. Since the spray penetration was along its injector axis which was mounted at an angle of 35º inclined from horizontal, the tip of the spray penetrated directly across the cylinder along the injector mounting axis and impinged on the opposite side of the cylinder wall at a location somewhere near the middle of the cylinder. This impingement location was found to be closely related to the geometrical mounting orientation of the injector. Finally, since the spray was designed to bend towards the piston by either 5º or 10º, the spray was able to propagate more directly towards the piston. Thus, adding an offset angle to the injector may enhance fuel homogeneity in the cylinder, particularly for application where side-mounting injector is required.

Figure 5 shows the time-resolved images of the combustion and flame propagation with the measurement of in-cylinder pressure and ionization signals. The engine was idling at 750 RPM with a lambda (λ) of 0.9 (fuel rich condition), where lambda is defined as the ratio of actual air-fuel ratio (AFR) to stoichiometric AFR for a given mixture. This condition was selected to demonstrate the feasibility of the measurements and analysis technique. The fuel spray selected for this demonstration test was from the 60/5 injector at an injection pressure of 30 bar. The SOI of the fuel was set at 300º BTDC.

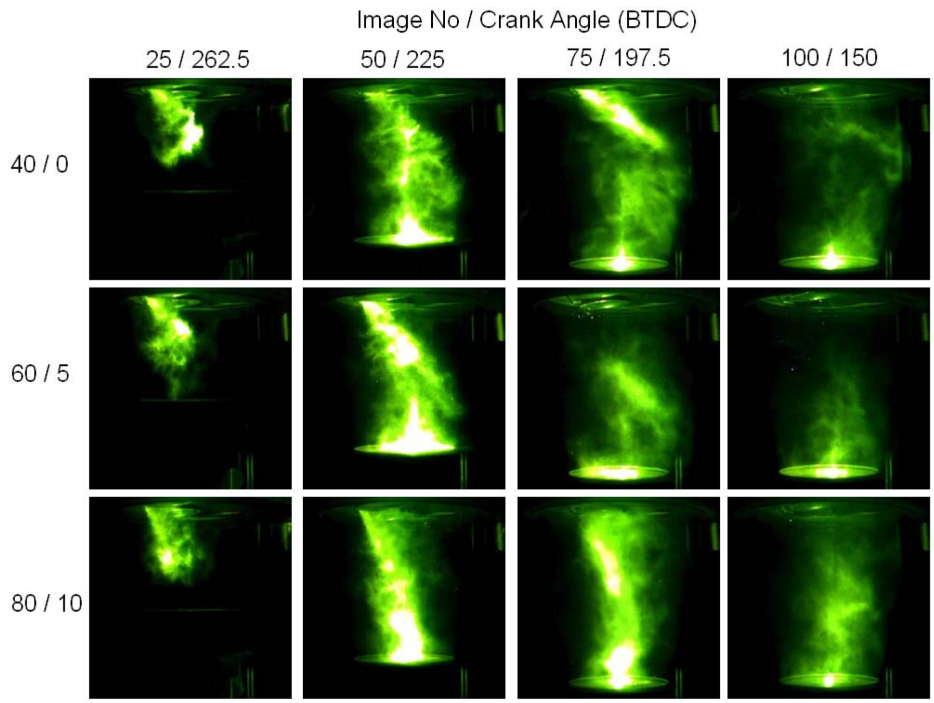

Figure 4. Crank-angle resolved images of in-cylinder fuel mixture formation through cylinder wall [1].

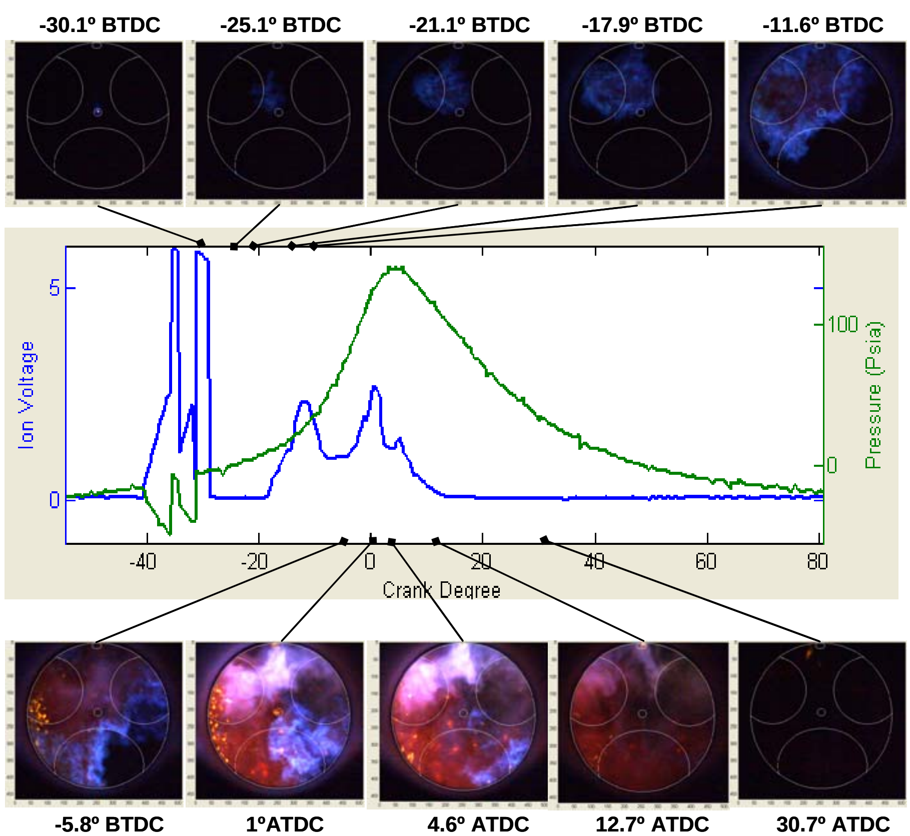

Figure 5. Crank-angle resolved images of in-cylinder combustion through quartz piston insert.

As shown in Figure 5, two spark ignition (dual spark) events were used in this test, as indicated by the two spikes in the ionization signal. The first spark was initiated at 35º CA BTDC, followed by a second spark occurred at a delay of about 5º CA. It can be clearly seen that immediately after the second spark, a very visible flame was then initiated near the spark plug region. At 21º CA BTDC, the flame expanded and it propagated radially outward. It occupied the upper part of the region towards the left side of the cylinder closer to the left intake valve. The flame continued to show a slight symmetry as it expanded into a larger region in the cylinder. Analyzing the optical images will show that the combustion process appeared to burn more to the left side of the combustion chamber. The flame reached the cylinder wall at about 11.6º CA BTDC. It is also important to note that several bright spots were seen mostly on the left side of the image. These orange color spots were the results of liquid fuel impinging on the top of the piston.

There also appears a white region in the upper part of the image. It is speculated that this region was occupied by the unburn fuel spray which did not participate in the combustion. It is likely due to the fuel rich condition in the combustion chamber. The peak pressure happened at around 5º CA after the TDC. At that instant, the flame appeared to slowly being quenched at about 12.7º CA after TDC as the pressure signal continued to decrease.

The first peak of the ionization signal did not happen immediately after the first spark. It was mainly due to two factors: low in-cylinder temperature of the optical engine and light engine load that has led to relatively low heat released by the flame when compared with the high load combustions. Nevertheless, as confirmed in other previous work on ionization sensing in gasoline engines, the ionization signal in this test clearly showed two peaks, with the first peak located on the rise of the pressure curve and the second peak almost coincided with the peak of the pressure signal. The profile of the ionization signal contained useful information about the combustion event which could be useful for real time control of spark ignition. In addition, it is worth mentioning that in many publications, the averaged ionization signals would be shown over a certain number of engine cycles (300 engine cycles have been reported in some cases). In our demonstration, the ionization signal depicted in Figure 5 was obtained in a single combustion event, which is relative noise free signal.

SUMMARY

In this paper, we have demonstrated the use of high speed imaging to visualize the time-resolved fuel mixture formation and combustion in a gasoline direct injection engine. In addition, in-cylinder pressure and ionization sensing had also been implemented to provide more diagnostic information about the state of combustion in the cylinder. Test data reveal that for a given cylinder head, piston configuration and intake air port flow characteristics, injector spray pattern plays a dominating role in how the fuel-air mixture is formed. It was found that the spray angle, offset angle, and injector mounting orientation had pronounced effects on the fuel mixture preparation. If an appropriate injector spray pattern is chosen, the in-cylinder fuel mixing can be enhanced by minimizing fuel impingement on cylinder wall, piston top, and intake valves, thus producing a more homogeneous fuel-air mixture prior to the ignition.

After ignition is initiated, the synchronized high-speed crank-angle resolved images of combustion with in-cylinder ionization measurements provide more information about the combustion characteristics, from the onset of spark ignition to flame propagation and to flame quenching at the cylinder wall at every crank angle resolution. Combining and synchronizing the high speed images with in-cylinder combustion ionization and pressure signals provide both qualitative and quantitative aspect of the combustion event, thereby improving the understanding of fuel mixture distribution, combustion characteristics, flame propagation, and the quality of combustion in the engine combustion chamber. Future work will be focused on understanding the fuel mixture and combustion in the DI engine with other renewable fuels such as ethanol and E-85 (85% ethanol and 15% gasoline) fuel blends.

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