

Investigation of Impacts of Spark Plug Orientation on Early Flame Development and Combustion in a DI Optical Engine

Yanyu Wang, Jiongkun Zhang, Xin Wang, Paul Dice, Mahdi Shahbakhti, and Jeffrey Naber
 Michigan Technological University

Michael Czekala, Qiuping Qu, and Garlan Huberts
 Ford Motor Company

ABSTRACT

The influence of spark plug orientation on early flame kernel development is investigated in an optically accessible gasoline direct injection homogeneous charged spark ignition engine. This investigation provides visual understanding and statistical characterization of how spark plug orientation impacts the early flame kernel and thus combustion phasing and engine performance.

The projected images of flame kernel were captured through natural flame chemiluminescence with a high-speed camera at 10,000 frames per second, and the ignition secondary discharge voltage and current were measured with a 10 MHz DAQ system. The combustion metrics were determined using measurement from a piezo-electric in-cylinder pressure transducer and real-time engine combustion analyzer.

Three spark plug orientations with two different electrode designs were studied. The captured images of the flame were processed to yield 2D and 1D probability distributions. Charge motion interaction with kernel development was characterized. The data was segregated according to the initial flame kernel convection directions and investigation was conducted to understand how the different spark plug orientations influence the flame kernel propagation cycle-to-cycle.

The results revealed that the two electrode designs produce the same trend for the cycles whose initial flame kernels are convected to the exhaust side of the cylinder: the 90° index orientation (crossflow) produces the largest and fastest growing flame kernels while the 0° index orientation where flame kernel is convected onto the ground strap produces the smallest and slowest growing flame kernels. For the cycles whose initial flame kernels are convected to the intake side, 0° index orientation, however, exhibits slight advantage over the other two index orientations.

CITATION: Wang, Y., Zhang, J., Wang, X., Dice, P. et al., "Investigation of Impacts of Spark Plug Orientation on Early Flame Development and Combustion in a DI Optical Engine," *SAE Int. J. Engines* 10(3):2017, doi:10.4271/2017-01-0680.

INTRODUCTION

Automotive engines are in transition from port fuel injection (PFI) to direct injection (DI) for that DI offers more precise fuel metering, cylinder charge cooling and the potential to achieve lean combustion by stratification. However, in the United States, all direct injection spark ignition (DISI) gasoline engines still operate in stoichiometric homogenous charge conditions with various levels of exhaust gas recirculation (EGR) except during the cold startup period, due to the limitations of the three-way catalyst and high particulate matter produced at stratified conditions. While technologies are being investigated to achieve commercialization of lean and stratified combustion of DI gasoline engines in the United States[1], there is still a need to further optimize the DISI engine in homogenous charge conditions.

One common and widely studied method to reduce gasoline engine NOx emission and to increase thermal efficiency (by dethrottling) is to introduce EGR, either through external EGR or through internal EGR via cam phasing[2]. The residual burned gas increases the charge heat capacity, lowers the peak in-cylinder temperature, thus reducing the production of NOx. As EGR level increases, the combustion stability decreases, eventually to the point that the engine can no longer operate. The physics behind this phenomenon is that as EGR level increases, the combustion becomes increasingly sensitive to the variations in in-cylinder conditions such as charge motion, charge composition, and thus the combustion stability is compromised.

Ignition, as the start and trigger of the combustion process, has been proved to have a dominant role in determining the quality of the entire combustion process. Prior studies[3, 4, 5, 6, 7] found that spark discharge duration has a strong impact on the initial flame

kernel size and growth rate, leads to shorter ignition delay and combustion duration and extended lean combustion limit. Nakai's work[3] suggested that 5ms discharge duration could effectively shorten the combustion delay and reduce cycle-by-cycle variations in combustion delay. Chen's work[8] on a production Ford Ecoboost engine and Zhang's work[9] in a constant volume combustion chamber both indicate that, under high charge flow motion, the timing and scheduling of the energy deposit into the gap could influence the initial flame kernel formation and thus affect the engine performance. The discharge duration and pattern were not the only factors found to impact the variations in combustion metrics[10, 11]. The orientations of the spark plug were found to impact the engine performance as well. Aleiferis et al.[12] found that crossflow orientation produces lowest cycle-by-cycle variation in terms of indicated mean effective pressure (IMEP); they also found the ground strap upstream performs the worst in terms of coefficient of variation of IMEP (COVimep). However, previous study by Anderson and Asik[13] suggested that upstream position performs better than downstream position.

The current work described by this paper tackles this question by investigating how the initial flame kernel is affected by the orientation of the spark plug in a homogeneously charged single cylinder optical engine instrumented with a long discharge high energy ignition coil. By varying the spark plug orientations of two different electrode designs, size and location of early flame kernel was investigated.

Though much work has gone into designing the piston, combustion chamber, intake system to control the tumble inside gasoline ignition engines[14], the charge flow condition across the electrodes at the timing of ignition is still variable cycle by cycle. This is observed in this study. Cycles are categorized into two groups based on the initial flame kernel convection direction, either to the exhaust side of the combustion chamber in concurrence to the designed tumble direction or to the intake side counter to the designed tumble direction. Analysis is done for the two groups separately to gain a clear understanding how the relationship between electrode orientation and flow influences the flame kernel development.

In the following sections, the setup of the engine, test-bed, and optical instrumentation is described, followed by the introduction of the calculation methods of 2D and 1D probability distribution. Next, the results are discussed in group of cycles whose initial flame kernels are convected to the exhaust side in concurrence to the designed tumble direction and in group of cycles whose initial flame kernels are convected to the intake side counter to the designed tumble direction for the two spark plugs respectively. A comparison is then made between the two spark plugs. At last, summary and conclusions are presented.

EXPERIMENT SETUP

Optical Engine

The single cylinder optically accessible engine utilized in this research was designed and modified from a Ford four cylinder 2.0L gasoline direct injection (GDI) engine by Mahle Powertrain

(Figure 1)[15]. The cylinder head is elevated to accommodate the Bowditch piston extension on cylinder number 2, which is the operating cylinder. The bottom of the Bowditch extension is bolted on the original number 2 piston, and on the top of the Bowditch extension is mounted a flat top piston with a 62mm diameter sapphire (single-crystal aluminum oxide Al_2O_3) window insert allowing optical access through the piston. The elevated piston is separated from the crankcase and the oil circulation system, so self-lubricating piston rings made from torlon are used. The torlon pistons cannot tolerate high temperature for too long, so skip-firing operation strategy has to be applied during testing. A quartz liner providing optical access to the tumble plane is held against the cylinder head via a hydraulic clamping plate. The hydraulic clamping plate is raised to push the optical liner holder that holds the quartz liner against the cylinder head during engine operation via a hydraulic system; the quartz liner can be conveniently lowered and removed for cleaning and maintenance by releasing the hydraulic system pressure.

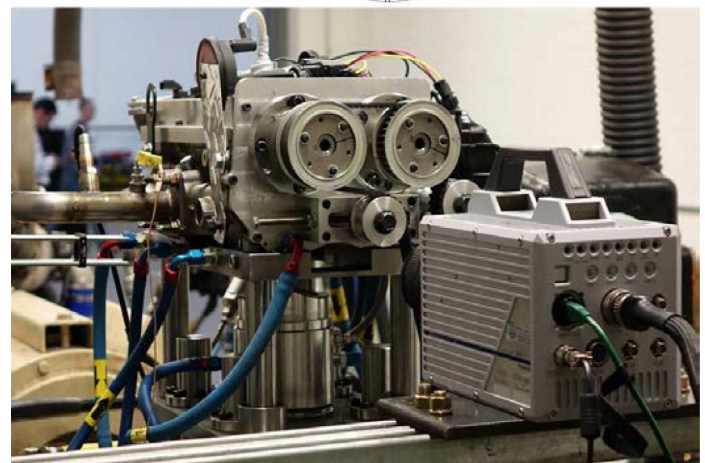
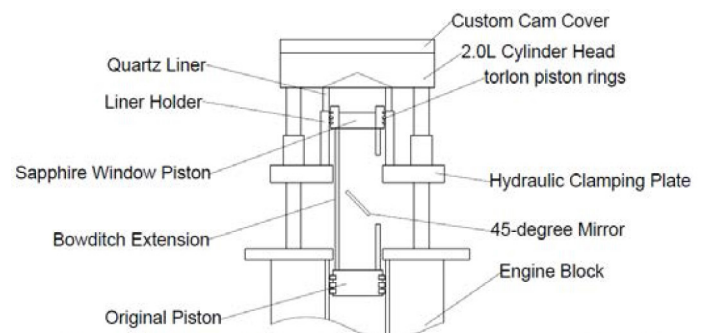


Figure 1. Top: schematic of the optical engine; bottom: optical engine with high-speed camera pointing to the tumble plane.

The production intake manifold for the original base engine is used to maintain the charge motion. A custom exhaust pipe is used along with the original integrated exhaust manifold. The original exhaust pipe is not used since it was designed to work with the turbocharger system. The optical engine has tumble ratio of about 1 at 2000 rpm. In the current study, the tumble ratio would be lower since the tests were done at 1000 rpm.

During testing, the fuel is pressurized to 4.5MPa by an external high pressure fuel pump, and delivered to a production Bosch multi-hole GDI injector, which is installed on the edge of the pent-roof cylinder head below the two intake valves. The start of injection (SOI) occurs at 300 crank degrees before top dead center (dBTDC). The injection pressure and SOI were chosen based on the production engine calibration at the same operation conditions. The spark plug is located in the center of the pent-roof cylinder head, and the spark energy is supplied by a high energy coil (110mJ, 3.2ms nominal discharge duration). The specifications of the optical engine are summarized in Table 1.

Table 1. Specifications of the optical engine.

Optical Cylinder Displacement (Liter)	0.6
Bore (mm)	87.5
Stroke (mm)	100.0
Compression Ratio	10.01 : 1
Fuel	RON 87
Injection Pressure	4.5 Mpa
Start of Injection (SOI)	300 BTDC
Injector	Bosch 6-hole GDI injector
Ignition Coil	high energy long discharge coil
Spark Plug	double fine wire and oval-J spark plugs
Piston	flat top piston
Intake	Ford 2L Ecoboost intake manifold
Exhaust	custom exhaust manifold

Spark Plug Electrode Designs

Two spark plug electrode designs were used in this study: the double fine wire and the oval-J plug, as illustrated in Figure 2.

The double fine wire spark plug features standard double fine wire electrodes, and the oval-J spark plug also features two fine wire type electrodes; however, the ground electrode lies horizontally instead of vertically.



Figure 2. Left: double fine wire spark plug; Right: oval-J spark plug.

The specifications of each spark plug are summarized in Table 2. Notice for the oval-J spark plug, the exact index angles are 0°, 100° and 170°.

Table 2. Specifications of the studied spark plugs.

Spark Plug	Index Orientation (deg)	Gap Size (mm)	Internal Resistance (kΩ)
Double Fine Wire	0	0.65	4.83
	90	0.65	4.04
	180	0.65	4.23
Oval-J	0	0.65	4.21
	100	0.65	4.59
	170	0.65	5.24

Definition of Spark Plug Orientation

Conventionally in literature, the spark plug orientation is termed as crossflow, upstream or downstream. However, this type of definition can be confusing in consideration that the flow direction at the moment of ignition can vary cycle-by-cycle. Therefore, index orientation defined by angle is used and explained as follows.

As shown in Figure 3, looking from top of the engine, 0° is defined as spark plug gap facing the intake side; 180° is defined as the spark plug gap facing the exhaust side; while 90° is defined as spark gap facing the front end of the engine where the high-speed camera is located. Negative degrees are defined as the spark gap facing the rear end of the engine where the view of the camera is partially blocked by the ground strap.

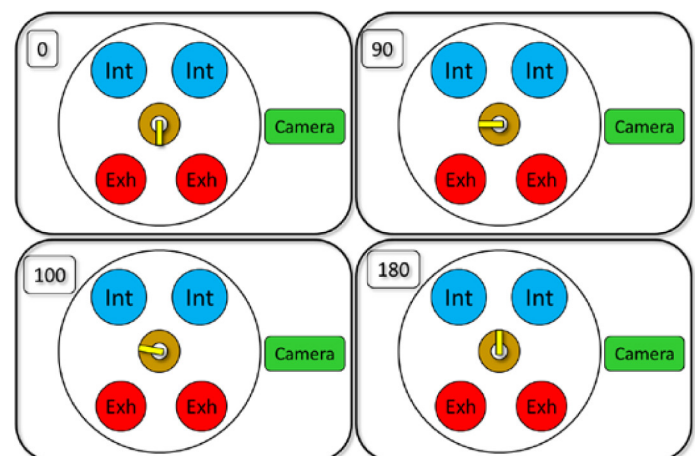


Figure 3. Definition of index angle in this study, viewing from top of the engine. "Int" and "Exh" stand for intake side and exhaust side respectively.

High-Speed Camera

The flame images were captured from 3°CA before the end of ignition coil dwell (the end of ignition coil dwell will be referred to as ignition timing in this paper) to 78°CA after ignition with Photron SA1.1 high-speed camera at 10,000fps frame rate. The camera is positioned on the front end of the engine, pointing to the tumble plane through the quartz liner. The image resolution is 768 × 512 pixels covering a 59mm × 40mm area on the tumble plane. The images presented in this paper are cropped to focus on the combustion area as

example of the camera view is shown in Figure 4, where on the left is the exhaust side and on the right is the intake side. This study focuses on the flame kernel propagation on the tumble plane.

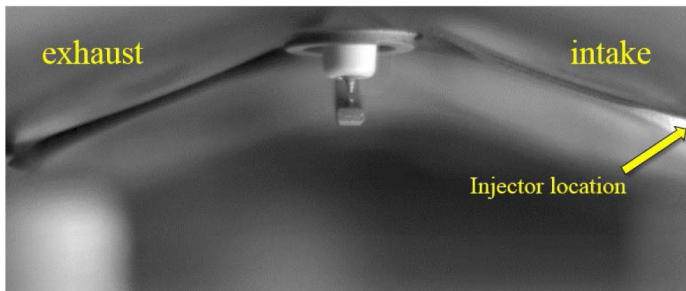


Figure 4. High-speed camera view (cropped); injector is located below the intake valves.

The operation parameters of the high-speed camera are tabulated in Table 3.

Table 3. High-speed camera configurations.

Camera Model	Photron SA 1.1
ISO	10,000
Frame Rate (fps)	10,000
Resolution	768x512
Lens	Nikon 85mm +12mm Extension
F/stop	1.4
Trigger	3°C A before ignition

Combustion Analysis

In-cylinder pressure was measured by a piezoelectric pressure transducer (PCB 115A04), which is installed through a port drilled between the intake valve and exhaust valve. The piston position was measured by an optical encoder with 0.5 degree resolution. The data was post-processed in Matlab to obtain the combustion related metrics using the 1D apparent heat release analysis with variable polytropics without heat transfer or crevice volume effects [16].

ENGINE OPERATION

The optical engine was skip-fired for 5 firing groups with each group composed of 15 motored and 10 fired cycles (Figure 5). The first five fired cycles of each firing groups were removed from statistical calculations and results, in consideration of the transitional state from the motored cycles to the fired cycles. The fuel was injected at 300 dB TDC to achieve a homogeneous mixing at the timing of the initial spark discharge, which occurs at 47 dB TDC.

The tests were conducted at 2.5 bar IMEP at 1000 rpm. Combustion phasing was controlled to an average of 8° ATDC, and the equivalence ratio was controlled near $\lambda = 1.38$, in order to introduce enough variations in combustion between cases. The test matrix is summarized in Table 4. Each test point was repeated and results of the two test runs were combined for statistical analysis; this results in 10 firing groups with 5 cycles in each for a total of 50 cycles at each

test point. In the first column of Table 4, DFW stands for double fine wire electrode design and oval-J stands for oval shape J plug electrode design. Notice for DFW, 0°, 90° and 180° orientation index were used and for oval-J electrode, 0°, 100° and 170° orientation index were used, due to lack of oval-J spark plugs of exact indexing at 90° and 180°. This difference is not expected to be significant based upon flow testing and discharge measurements in other studies [17].

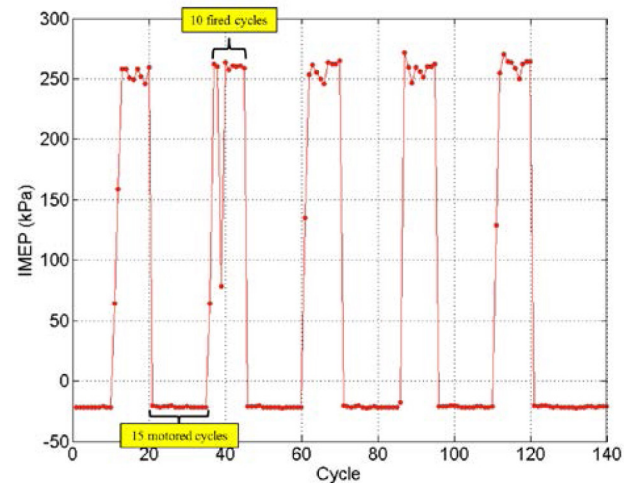


Figure 5. Skip-fire strategy: 5 groups of 15 motored cycles and 10 fired cycles.

Table 4. Test Matrix.

Spark Plug	Spark Plug Orientation (deg)	Target IMEP (bar)	Target Speed (RPM)	Target CA50 (dATDC)	Target Lambda (-)
DFW	0, 90, 180	2.5	1000	8	1.38
Oval-J	0, 100, 170				

DATA ANALYSIS METHODS

Mathematical Tools

The images of the cycle-by-cycle flame kernels were filtered by a 3×3 2D-median filter to remove noise and then processed by two equations for better understanding the statistical results. The equations are explained as follows.

2D Probability Distribution Function (2D-PDF)

The 2D-PDF shows the probability of the flame kernel reaching a certain point in the 2D space captured by the camera (equation (1)).

$$PDF_{2D,t} = \frac{\sum_{i=1}^n I_{t,i} \begin{cases} I_{t,i} = 1, I_{t,i} > \text{threshold} \\ I_{t,i} = 0, I_{t,i} < \text{threshold} \end{cases}}{n}$$

In equation (1) I denotes the image intensity matrix; t is the timing of the current processed image in the current cycle, either in milliseconds after ignition timing (msAIT) or crank angle degrees after ignition timing (dCA_AIT); i represents which cycle the current processed image is from, and n is the number of cycles.

The illustration of how 2D-PDF is calculated is shown in Figure 6 along with 1D-PDF which will be explained in the following section.

1D Probability Distribution Function (1D-PDF)

While 2D-PDF offers a visual image of probability distribution, it is difficult to do a case by case comparison. 1D-PDF serves as a good tool for this purpose. It describes the number of flame kernels along the vertical direction (column) as in Figure 6, and the number of flame kernels along the horizontal direction (row). In this study, focus is on 1D-PDF along the vertical direction equation (2).

$$PDF_{1D,t,c} = \frac{N_{Flame\ Kernel_{t,c}}}{n} \quad (2)$$

In equation (2) $N_{flame\ kernel}$ is the number of flame kernels, c indicates along the vertical direction.

A simple illustration of 1D-PDF and 2D-PDF is shown in Figure 6 using three images at 3msAIT from three random cycles of the 90° index double fine wire spark testing.

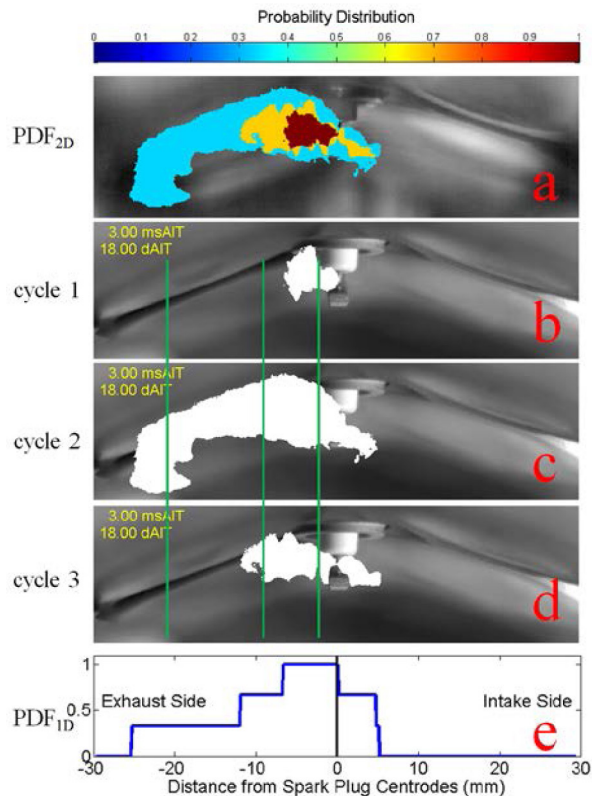


Figure 6. Illustration of 2D-PDF and 1D-PDF calculations. (a) 2D-PDF; (b) through (d) flames kernels at 3msAIT from three random cycles; (e) 1D-PDF

In Figure 6, the flame kernels in (b), (c), (d) are added onto each other and normalized over the number of cycles (3 in this illustration) and color-coded to get the 2D-PDF in (a). The 2D-PDF shows the spatial probability distribution of the flame kernels. To get the 1D-PDF shown in (e), the number of flame kernels are counted along the vertical lines across the three flame kernels in (b), (c) and (d). Three example vertical lines are shown in green. Along the first vertical line, one flame kernel is counted from (c); along the second vertical line, two flame kernels are counted from (c) and (d), and along the third vertical line, three flame kernels are counted in (b), (c) and (d). The results are then normalized over the number of cycles (3 in this illustration) to get the 1D-PDF in (e).

As can be seen in later sections, comparisons can be conveniently made by overlaying 1D-PDF of different cases.

Categorization of Initial Flame Kernel Convection Direction

The optical engine combustion chamber and intake system were designed to have counterclockwise flow viewing from the front of the engine with exhaust on the left and intake on the right. However, cycle by cycle variations in initial flame convection direction were observed. Therefore, the cycles are categorized based on the initial flame kernel convection direction, either to the exhaust side in concurrence to the designed tumble direction (denoted as group A), to the intake side counter to the designed tumble direction (denoted as group B). The grouping criteria is the flame kernel centroid location relative to the spark plug center at 3msAIT at shown in Figure 7. After the categorization, the data analysis methods discussed in the early part of this section are performed on the two groups.

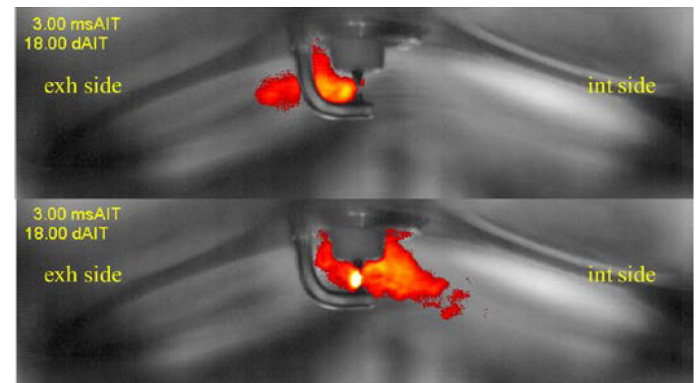


Figure 7. Sample initial flame kernel images at 3msAIT; upper: flame kernel convected to exhaust side in concurrence to the designed tumble direction (group A); lower: flame kernel convected to intake side counter to the designed tumble direction (group B).

The ratio of cycles of each group is summarized in Table 5. One interesting observation is that as the spark plug index orientation changes from 0° to 180°, the ratio of cycles in group B increases.