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Effects of Injection Timing and Spark Timing on Flame Propagation in an Optically Accessible Spark-Ignition Direct-Injection (SIDI) Engine

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Abstract

This study aims to provide a preliminary insight into the effect of injection timing and spark timing on flame propagation in a wall-guided spark-ignition direct-injection (SIDI) optical engine. High-speed imaging of natural combustion luminosity was performed for various injection timings and spark timings while other operating conditions were fixed. Injection timings have been selected based off our previous study using the same engine which compared the mixture formation properties of flash-boiling sprays to non-flash boiling sprays. Spark timings were also varied to investigate its influence on the ignition kernel development and flame propagation. Results have shown that later injections tend to create a richer region surrounding the spark plug, which leads to more rapid initial kernel development. The data also suggests that varying the spark timing has an effect on flame propagation speed such that earlier spark timing leads to earlier and faster flame propagation. This is likely due to the associated changes in piston speed and in-cylinder pressure.

Introduction

SIDI engines are becoming commonplace amongst gasoline fuelled cars on the market today. When compared to port fuel injection (PFI) engines, SIDI engines are able to offer many advantages in fuel economy, tailpipe emissions and performance [1,2,3,8]. These advantages are mainly due to the charge cooling effect which increases volumetric efficiency and also allows for the use of higher compression ratios. Another benefit of SIDI engines is the ability to use a lean stratified charge at low and part load, thereby reducing throttling losses.

Advancements in SIDI technology are still required to address issues such as misfiring of lean mixtures , unstable combustion of stratified charges due to cycle-to-cycle variation and soot emissions due to wall-wetting and locally rich regions [2]. To achieve these advancements, a fundamental knowledge base of SIDI engine combustion must be compiled. This study focusses on the flame propagation properties of an SIDI engine when injection timing and spark timing are altered. Particular attention has been placed on comparing the combustion of flash boiling sprays to non-flash boiling sprays.

Experiments

Measurements are obtained through the post processing of high speed images, which provides crank-angle resolved information on mean flame radius and flame speed. Unless otherwise noted, top dead centre (TDC) refers to the expansion stroke, and increments are measured in crank angle degrees (CAD).

Optical Engine

The experiments were carried out in an optically accessible single-cylinder SIDI engine using a wall guided injection system, as shown in figure 1. Optical access is provided by a quartz piston crown via a 45 degree mirror placed in the void of the extended piston (swirl view) and a quartz cylinder liner which replaces the top 30 mm of the cylinder wall (tumble view) - note that for the purposes of this study only the swirl view was utilised. A high-speed CMOS camera (VisionResearch Phantom v7.3) fitted with a 105-mm focal length f/2 lens (Nikon Nikkor) was used to image natural combustion luminosity. The framing rate was fixed at 10,000 Hz which corresponds to 0.72 CAD per image in the present study.

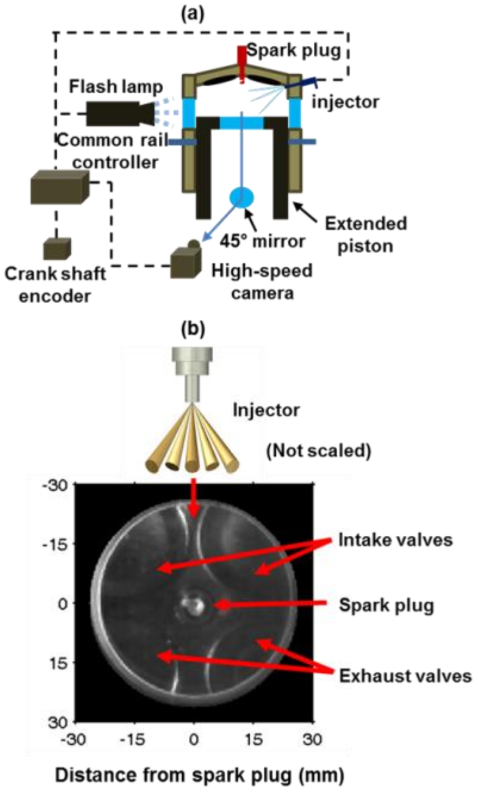

Figure 1: (a) Schematic diagram of optical engine and (b) field of view through the piston crown, with injector orientation shown above.

The engine has a single-cylinder displacement of 500 cm^3 with a square bore and stroke of 86 mm × 86 mm and a geometrical compression ratio of 10.5. A double over-head camshaft valve-train provides two intake valves and two exhaust valves. More detailed engine specifications are listed in table 1.

Operating Conditions and Control Parameters

The engine was motored at 1200 rpm using a 37 kW AC motor. Coolant was heated to 363 K to simulate a warmed-up engine condition. The intake temperature, while not controlled, was measured to be 320 K throughout the experiments. No throttling or boost was supplied to the intake manifold, representing a full-load condition for a naturally aspirated engine. Control parameters such as injection timing and spark timing were provided by a universal engine controller (Zenobalti ZB-9013B) using reference signals from a rotary encoder (Autonics E40S8) mounted on the crank shaft. This setup allowed the engine to be skip fired on a 1 in 10 cycle - i.e. fuel and spark are only supplied on every 10th engine cycle to allow residual exhaust gasses to be expelled and to ensure that the quartz windows would not overheat and burst. The engine operating conditions are summarised in table 2.

Engine specifications

Displacement (cm^3)	500
Bore/stroke (mm)	86/86
Compression ratio	10.5
Valve system	DOHC
Intake valve open (CAD aTDC)	7
Intake valve close (CAD aTDC)	247
Exhaust valve open (CAD aTDC)	496
Exhaust valve close (CAD aTDC)	720

Table 1: Optical engine specifications. Note that valve timings are specified in relation to intake TDC.

Operating conditions

Engine speed (rpm)	1200
Coolant temperature (K)	363
Temperature in intake manifold (K)	320
Intake pressure (MPa, abs)	0.1
Skip firing	1 in 10

Table 2: Engine operating conditions and control parameters.

Fuel and ignition system specifications

Fuel injector	Continental DI XL2
Number of nozzle holes	6
Injection pressure (MPa)	15
Injection timings (CAD bTDC)	270, 180, 60
Injection duration (ms)	2.6
Air/fuel equivalence ratio (ϕ)	1
Spark timings (CAD bTDC)	15, 10, 5

Table 3: Fuel supply system specifications and control parameters.

Fuel Supply and Ignition System

Fuel was supplied to the injector via a tank, high pressure pneumatic pump and a custom-made one-cylinder fuel rail. The injector used for the study was a Continental DI XL2 – a 6-hole SIDI injector. The nozzle-hole arrangement is asymmetrical as shown in figure 1(b). An injection pressure of 15 MPa was chosen as this is the maximum pressure specified for the fuel rail. To achieve a stoichiometric air/fuel mixture, the injection duration was set to 2.6 ms. This injection duration was determined by measuring the fuel mass per injection using a Bosch tube-type injection rate meter. Spark details here. Full details are shown in table 3.

Selection of Injection Timing

Flash-Boiling Sprays

Flash-boiling occurs when fuel is injected into an environment where the ambient pressure is lower than that of the saturation pressure of the fuel. Many studies including one which was carried out on the same engine [3] have shown that the flash-boiling phenomenon is capable of increasing air/fuel mixing capabilities [5,7].

A pressure trace for a motored cycle of the engine from our previous study on the flash-boiling sprays [3] is shown in figure 2. It can be seen that when fuel is injected at 270 CAD before expansion TDC (90 CAD after intake TDC), the in-cylinder pressure is a low 100 kPa, which is lower than the saturation pressure for gasoline at the fuel rail temperature. Note that in regular engine operation, this pressure would be significantly higher due to residual exhaust gases, however skip firing allows for these gases to be expelled from the engine. At 60 CAD bTDC (300 CAD after intake TDC) the in cylinder pressure is 400 kPa, which is higher than the saturation pressure of the fuel.

The effect of flash boiling can be clearly seen in figure 3. The top image (flash-boiling) shows a cloud-like structure with a narrow spray angle, whereas the bottom image (non flash-boiling) shows individual spray plumes for each hole of the injector. In the present study, the same 270 and 60 CAD bTDC as well as 180 CAD bTDC injection timings have been selected to investigate the correspondence between flash-boiling/non-flash-boiling sprays and flame propagation properties.

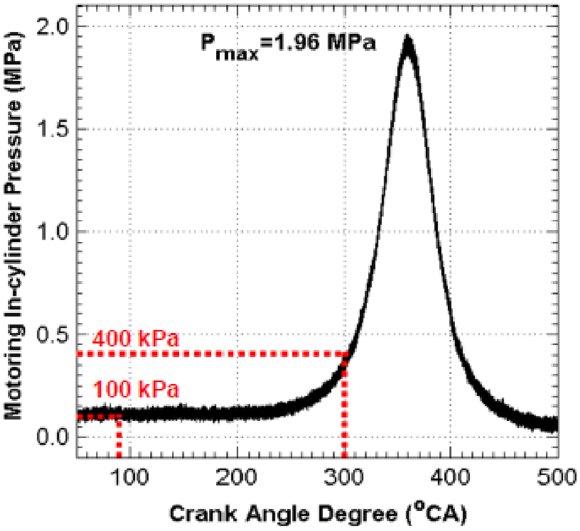

Figure 2: In-cylinder pressure versus crank angle. The 100 kPa line corresponds to 270 CAD bTDC and the 400 kPa line corresponds to 60 CAD bTDC [3].

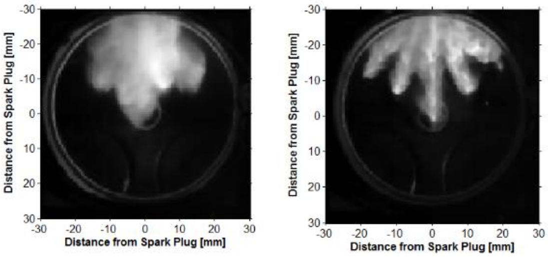

Figure 3:Non-flash boiling spray - injection timing 60 CAD bTDC (left); and flash boiling spray - injection timing 270 CAD bTDC (right). Both images taken at 3.6 CAD aSOI [3].

Post-Processing of Flame Propagation Images

An in-housed-developed Matlab code was used to post-process images obtained using a high-speed camera. Otsu's boundary detection method [4] based on a user definable threshold level was employed to calculate the flame area for each greyscale image. With the image-scale and the frame-rate of the camera being known (10 kHz) it was then possible to calculate the mean radius and mean flame propagation speed for each image. To ensure validity, no more data points are collected once a portion of the flame-front reaches the edge of the field of view. Figure 4 below shows three consecutive images for one case with the boundary detection line overlayed.

Results and Discussion

Influence of Injection Timing

Injection timing plays a significant role in the mixture formation of the air/fuel charge. As mentioned previously in-cylinder pressure increases greatly during the compression stroke of an engine and this has a great effect on the structure of the fuel spray, particularly in the flash-boiling case. Another consideration which must be taken into account is the mixture formation time – late injections are likely to be more stratified in nature when compared to an early injection which has more time to form a homogenous charge.

Figure 5 shows the mean radius of the flame for various crank angle locations. The results are plotted for different fuel injection timings at fixed spark timing of 15 CAD bTDC. From the figure it is seen that a later injection appears to lead to earlier initial kernel development. In the case of the flash-boiling spray (270 CAD bTDC) [3] the initial kernel development is noticeably slower, suggesting that the increased mixing results in a significantly leaner region in the vicinity of the spark plug when compared to the more stratified charges.

The mean radius data in figure 5 was used to estimate the flame propagation speed as shown in figure 6. The mean flame propagation speed appears to be similar between all three cases once the kernel has developed, suggesting that mean flame speed is more dependent on overall mixture properties (i.e. air/fuel ratio) than local mixture properties. More data will be required in future studies to analyse this trend in more detail.

Influence of Spark Timing

Altering spark timing has the effect of shifting the phasing of the combustion event in relation to the crank position. In an attempt to minimise the cycle-to-cycle variation involved with stratified charges [2] and allow ample mixture formation time, the injection timing was kept constant at 270 CAD bTDC for this part of the study.

Figure 7 shows the mean radius of the flame for various crank angle locations and for three different spark timings. As expected, retarding the spark timing has the effect of delaying the initial kernel development by the same amount. The figure shows that the ignition delay period is roughly 5 CAD for each case.

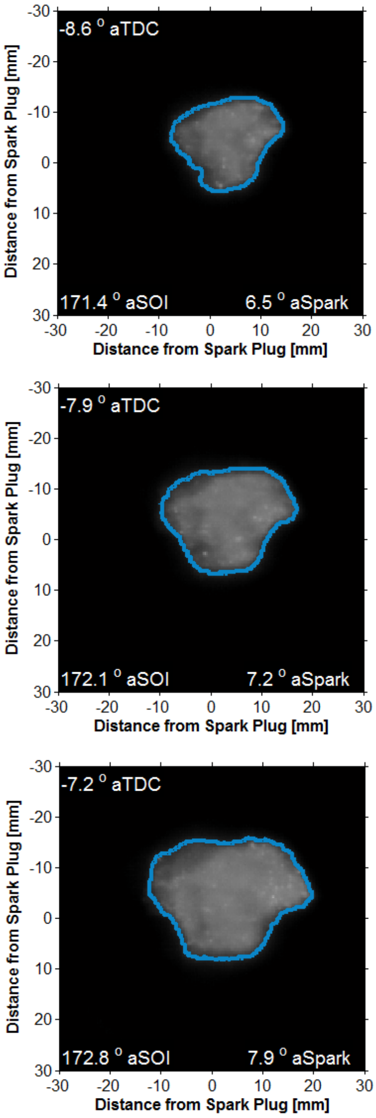

Figure 4: Three consecutive flame propagation images with the boundary detection overlayed; injection timing 180 CAD bTDC, spark timing 15 CAD bTDC.

More interesting trends can be seen by analysing the flame propagation speed for each case as seen in figure 8. It can be seen that the flame speed is higher for the 15 CAD bTDC case, suggesting that phasing the combustion event away from TDC may reduce burn time. There are two phenomena which support this theory – a higher piston speed increases the turbulent kinetic energy and lower in-cylinder pressure has been shown to increase flame speed [6]. Again, more data along with in-cylinder pressure traces is due to be collected in a future study to analyse this trend more thoroughly.

Conclusions

High speed image analysis has been carried out in an optically accessible SIDI engine to investigate the effect of injection timing and spark timing on flame propagation. Flame area, radius and propagation speed were calculated using the in-house-developed Matlab code for boundary detection. The major findings from this study are as follows:

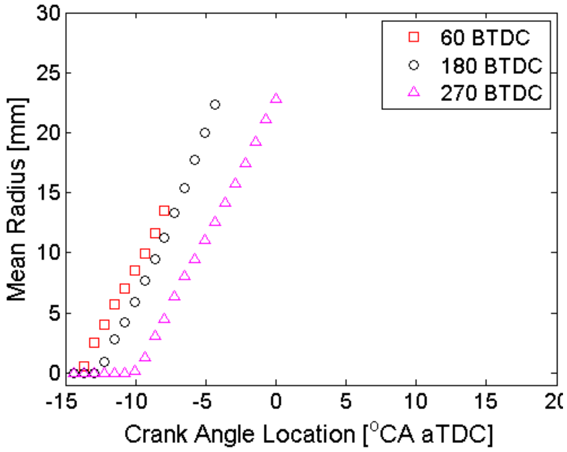

Figure 5: Mean radius vs crank angle location for various injection timings. Spark timing 15 CAD bTDC

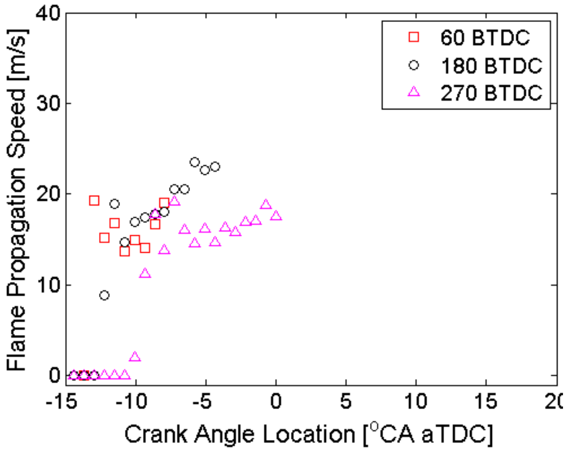

Figure 6: Flame propagation speed vs crank angle location for various injection timings. Spark timing 15 CAD bTDC.

- Injection timing plays a large role in the initial flame kernel development. This is due to early injection timing leading to increased mixing, resulting in a leaner region in the vicinity of the spark plug when compared to the more stratified charges.
- Mean flame propagation speed is more dependent on overall mixture properties than local mixture properties.
- Spark timing affects flame propagation speed. This observation is supported by two known phenomena – a higher piston speed increases the turbulent kinetic energy and lower in-cylinder pressure has been shown to increase flame speed.

Acknowledgments

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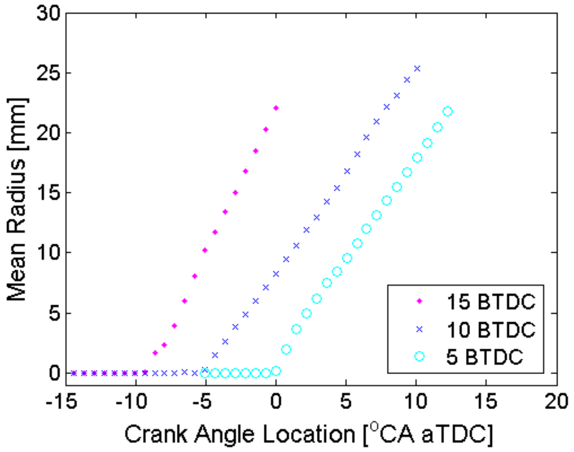

Figure 7: Mean radius vs crank angle location for various spark timings. Injection timing 270 CAD bTDC.

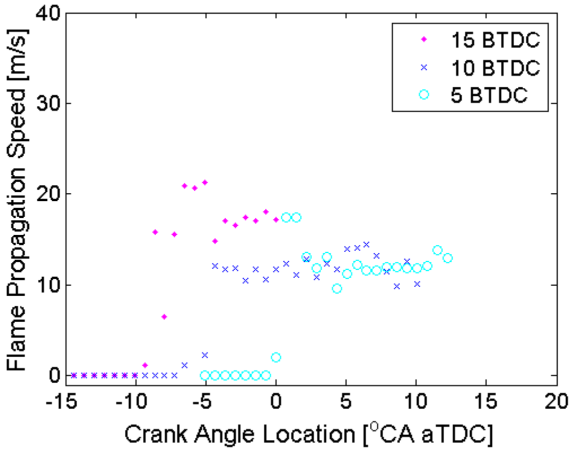

Figure 8: Flame propagation speed vs crank angle location for various spark timings. Injection timing 270 CAD bTDC.

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