18th Australasian Fluid Mechanics Conference
Launceston, Australia
3-7 December 2012

The Transient Behaviour of Hot Soot Base in an Optically-Accessible Automotive-Size Diesel Engine

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Abstract

In a diesel flame, high reaction temperature and locally rich air-fuel mixture cause soot particles formation that can be visualised without complex optical diagnostics setup. This strong signal of hot soot incandescence is useful to understand the overall structure and temporal evolution of sooting flame. For a free diesel-jet during a quasi-steady period of fuel injection, previous researchers performed a series of laser-based imaging diagnostics to obtain clear understanding of diesel combustion occurring in a heavy-duty, large-bore engine. However, in a small-bore automotive-size engine, the diesel flame would experience significant interaction with the surrounding piston wall quickly after the fuel injection resulting in much more complex and transient flame development. How this wall-interaction changes the current understanding of diesel combustion is one of the main focuses of our research group. As a first step to clarify the transient behaviour of wall-affected diesel flame, we performed high-speed imaging of hot soot luminosity in a light-duty optical diesel engine. Results show interesting behaviour indicating preference for the wall-affected jet to have shorter hot-soot base height than that of the free jet. Possible mechanism for the observed behaviour is the re-entrainment of hot combustion products whereby the wall-affected jet causes hotter ambient gas incorporation into the incoming jet.

Introduction

In diesel engine combustion research, the interaction between jet structures with surrounding in-cylinder chamber walls is of great interest as it heavily influences in-cylinder fuel-air mixing process and thereby pollutants formation. For instance, Bruneaux [4] observed that wall-impingement can limit the mixing rate in the central part of the jet prior to impact while enhancing it in the jet tip due to the formation of a jet-wall vortex, given that fuel injection pressure is sufficiently high. Abraham *et al.* [1] agreed that the wall contact with the jet may increase overall mixing rate despite the momentum loss during this wall impingement process. How the mixing rate is affected by wall impingement on diesel jets is also explored by Pickett and Lopez [12] as they investigated the relationship between wall position and the diesel flame base (lift-off) location in a constant-volume chamber. Findings show that free diesel jets could become non-sooting when impinged upon a wall due to greater mixing and cooling of the flame due to heat loss to the wall, whereby the benefit of increased mixing due to jet-wall vortex overcomes the decreased mixing at the central region as previously discussed by Bruneaux [4]. Wall interaction has also been found to increase pollutants formation such as particulate matter and unburned hydrocarbons [7,14]. Soot deposition on the wall [6,15] is also found to increase with wall impingement of the sooting diesel jet.

As such, numerous literatures are found on the jet-wall interaction and its effect on mixing and pollutants formation. However, the previous studies were conducted in either constant-volume combustion vessels or heavy-duty engine environments where the overall combustion is dominated by the mixing-controlled phase and a quasi-steady period of the combustion is easily found. The jet-wall interaction might impact the combustion more significantly in small-bore automotive-size diesel engines. This is because the reacting jet reaches the bowl-wall earlier after the start of fuel injection due to the smaller bowl diameter. More importantly, the smaller bowl diameter produces a rounder wall contour than engines of larger size and therefore creating a jet impingement on a more confined wall than plane

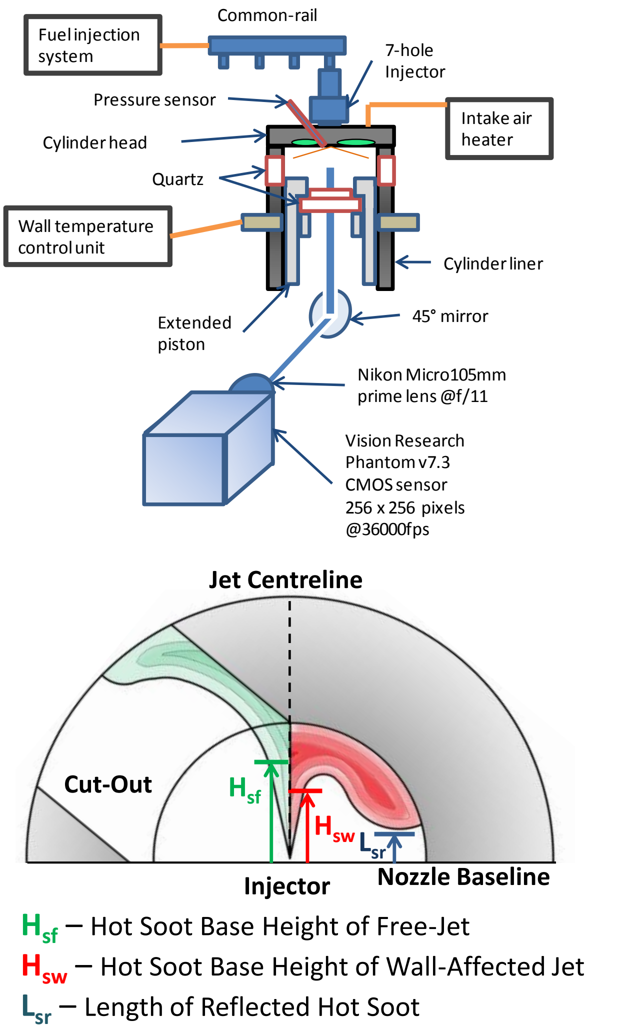

Figure 1. High-speed soot luminosity visualisation setup with a single-cylinder small-bore optical diesel engine (top). A 45° angled mirror located below the chamber provides optical access of the combustion chamber. A sectioned view of the bow-rim cut-out piston shows the separation of jet structures into a free-jet (green, bottom) and wall-affected jet (red, bottom).

wall. Also, the smaller displacement volume requires less fuel to obtain the same power of a larger engine and therefore the injection duration is shorter. As a result, the reacting jet development and the jet-wall interaction become more transient than quasi-steady as in a heavy-duty engine.

In this study, high-speed imaging of soot luminosity is performed to investigate overall structure of sooting diesel flame in an automotive-size diesel engine. The cycle-to-cycle fluctuations of high-speed movies and transient sooting flame behaviour under the influence of jet-wall interaction are discussed in great details.

Methodology

Optical Diesel Engine

The experimental setup using an optically-accessible diesel engine is represented in figure 1. Optical access of the combustion chamber is obtained by the use of a transparent quartz window as part of the piston top and a 45° angled mirror positioned in the void of the extended piston (see figure 1, top). The original piston top with simple cylinder-bowl geometry was modified through the removal of a section from the piston bowl-rim as represented in figure 1 (bottom). This bowl-rim cut-out allows a simultaneous investigation on the free-jet and wall-affected jet such that a half of the reacting jet penetrates further into the cut-out volume freely while the other half impinges on the bowl wall. For this study three variables are measured to characterise a temporal and spatial evolution of the sooting flames. These are annotated on figure 1 (bottom) as H_{sf}, H_{sw} and L_{sr} to represent the hot soot base height of the free-jet, the hot soot base height of the wall-affected jet, and the distance from nozzle baseline to the tip of the reflected jet, respectively.

Operating Conditions

The selected operating conditions with the engine specifications are listed in table 1. The engine is controlled by using an electric motor to reach a fixed constant speed of 1200 revolutions per minute (rpm). The wall temperature of the cylinder liner and firedeck was held constant at 363 K by delivering heated water. The intake air temperature was also fixed at 303 K. The swirl ratio of the used engine is 1.4.

Engine speed	**1200 rpm**
Displacement (single-cylinder)	**497.5 cc**
Bore	**83 mm**
Stroke	**92 mm**
Compression ratio	**15.2**
Swirl ratio	**1.4**
Wall (coolant)temperature	**363 K**
Intake air temperature	**303 K**
Injection Type	**Second-generation Bosch common-rail**
Number of holes	**1**
Nozzle type	**Hydro-ground, K1.5/86**
Nozzle diameter	**134 µm**
Hydraulic fuelling rate	**400 cc/30s @10 MPa**
Included angle	**150°**
Rail pressure	**70 MPa**
Injection duration	**1.4 ms**
Injection timing	**7.7 °CA bTDC**

Table 1. Engine specifications and selected operating conditions.

Details of the fuel injection parameters are also listed in table 1. A single-hole solenoid-type injector coupled with a common-rail system was used in this study. The fuel used was an ultra-low sulphur diesel (cetane number 46). The engine was skip-fired: the fuel injection occurs at an interval of ten engine cycles for a total of 300 engine cycles or a total of 30 fired cycles. This constraint was to ensure the window cleanliness by limiting residual combustion products such as soot deposition. This skip-firing also aimed to reduce residual gases for better repeatability and minimise cyclic stress on the optical parts.

Data Acquisition and High Speed Soot Luminosity Visualisation

In-cylinder pressure data is obtained using a pressure transducer (Kistler 6056A) with acquisition at every 0.072 crank angle degrees (°CA). High-speed visualisation of hot soot luminosity is obtained by using a high-speed CMOS camera (Vision Research Phantom v7.3) at 36000 frames per second with an image resolution of 256 by 256. At a fixed engine speed of 1200 rpm, this gives a 14-bit image at every 0.2 °CA interval. Natural hot soot luminosity is result of combustion that dominates the resulting emission spectra of a sooting flame [5].

All data is processed using an in-house-developed code using Matlab. The detection of the three variables identified on figure 1 (bottom) was performed using threshold-based boundary detection coupled with the most popular Otsu's method [11]. The movie is processed frame-by-frame to derive the heights of the hot soot as defined to be the lowest axial location of detected boundary. The detection of the variables annotated on figure 1 (bottom) was bounded by a range of 5 mm on the horizontal plane; H_{sf} is the lowest axial position of the flame boundary

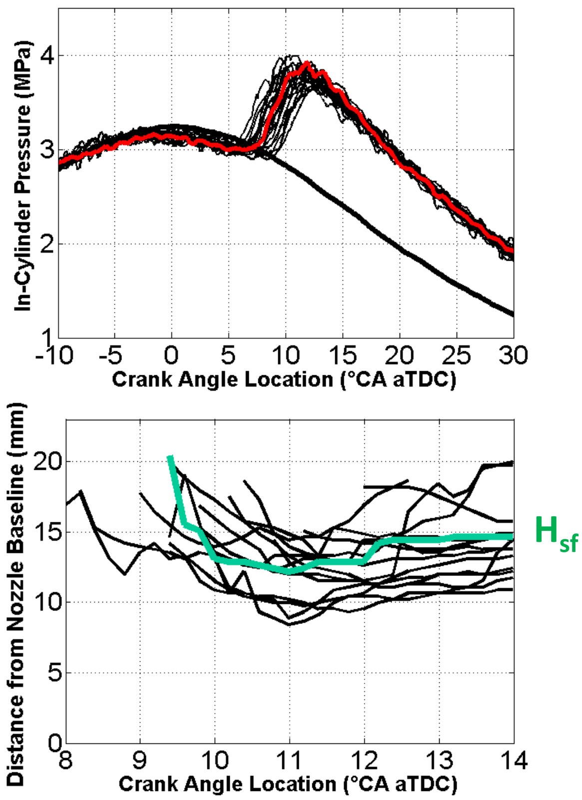

Figure 2. In-cylinder pressure trace of individual cycles (top, black lines) and chosen best representative cycle (top, red line) close to the mean of the variance. Corresponding hot soot base height of the free jet (H_{sf}) (bottom, green) is shown amongst the rest of the individual H_{sf} (bottom, black lines).

between the nozzle and 5 mm to the left of the nozzle tip, H_{sw} is bounded between the nozzle tip and 5 mm to the right of the nozzle tip, and L_{sr} is bounded between 10 and 15 mm to the right of the nozzle tip. The selection of these ranges was arbitrary but found to capture the trend in hot soot height variations consistently for all images taken in this study.

Cycle-to-Cycle Fluctuations

A total of 20 high-speed soot luminosity movies were captured at a fixed engine operating condition. From the results, the first noticeable finding was significant cycle-to-cycle fluctuations. Figure 2 illustrates the variance of in-cylinder pressure (top) and its corresponding hot soot base height of the free-jet (H_{sf}, bottom). Since the primary goal of this study is to clarify transient behaviour of sooting diesel flame, it was decided to retain the dynamics of an instantaneous cycle than to obtain ensemble (cycle) averaged soot luminosity image. Therefore a representative cycle was selected for further analysis. The basis for this selection is such that the cycle falls within the mean of the upper and lower limit of the variance and its corresponding high-speed movie has a stable and clear development of the hot soot base. The selected firing cycle is identified by a bold red-coloured line for in-cylinder pressure trace and a bold green line for H_{sf} in figure 2.

Results and Discussion

Figure 3 shows six selected frames with crank angle locations ranging between 8.2 to 13.4 °CA after top dead centre (aTDC) as annotated on the top left of each image. The corresponding soot heights and reflected hot soot length are plotted in figure 4. As annotated in figure 4, four notable events (A ~ D) can be derived from the trend of H_{sf}, H_{sw} and L_{sr}.

During event A which spans over the period of first detection of hot soot (8.2 °CA aTDC) to the end of injection (EOI, 10 °CA aTDC), it is clearly observed that hot soot first develops in the wall-affected jet. This behaviour is the first instance where jet-wall interaction accelerates soot formation. As a result, there exists a large gap between hot soot base heights for the two jets which continues to be present for all combustion phases.

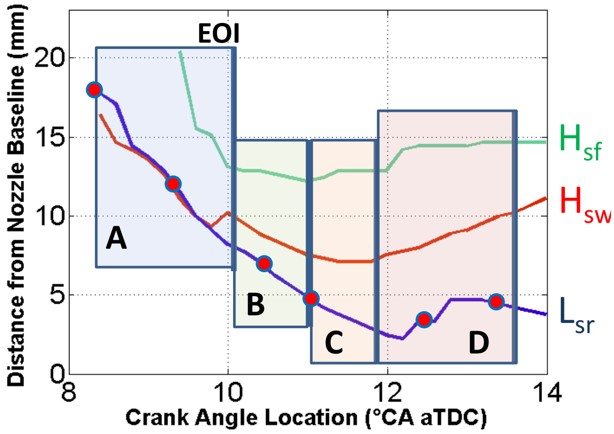

Figure 4. Hot soot base heights for free-jet (H_{sf}), wall-affected jet (H_{sw}) and length of the reflected hot soot (L_{sr}) over various crank angle degrees after the top dead centre (°CA aTDC). Four different events (A~D) are identified from the image analysis of soot luminosity. To illustrate, circle symbols are provided on the L_{sr} trace for each image time given in figure 3.

At the end of injection and during its transient, a sudden change of H_{sf} is observed, as a sharp upstream (towards the nozzle) movement decelerates and maintains a steady position at 13 mm away from the nozzle baseline. This is classified as event B. In comparison, the hot soot base height of the wall-affected jet H_{sw} continues its upstream movement suggesting that the same mechanism from event A still dominates despite termination of fuel injection. One potential cause for this upstream movement during the end-of-injection transient is the enhanced soot oxidation associated with the leaning out of fuel-air mixture near the injector region [9,10]. From previous studies, it is well known that the vortex-like shapes at the jet tips right after the end of injection result in increased mixing [2,3,8]. While identification of such shape cannot be confirmed within this study, it can be inferred that the radial dispersion shown in figure 3 can be associated with similar vortex mechanism.

However, neither the mixture leaning nor the vortex mechanism can explain the large gap between H_{sf} and H_{sw}. A study by Pickett and Lopez [12] using a combustion vessel and a confined wall suggests that jet-confinement coupled with wall-impingement may cause increased soot formation due to redirected combustion gases. In a more detailed study using a heavy-duty optical diesel

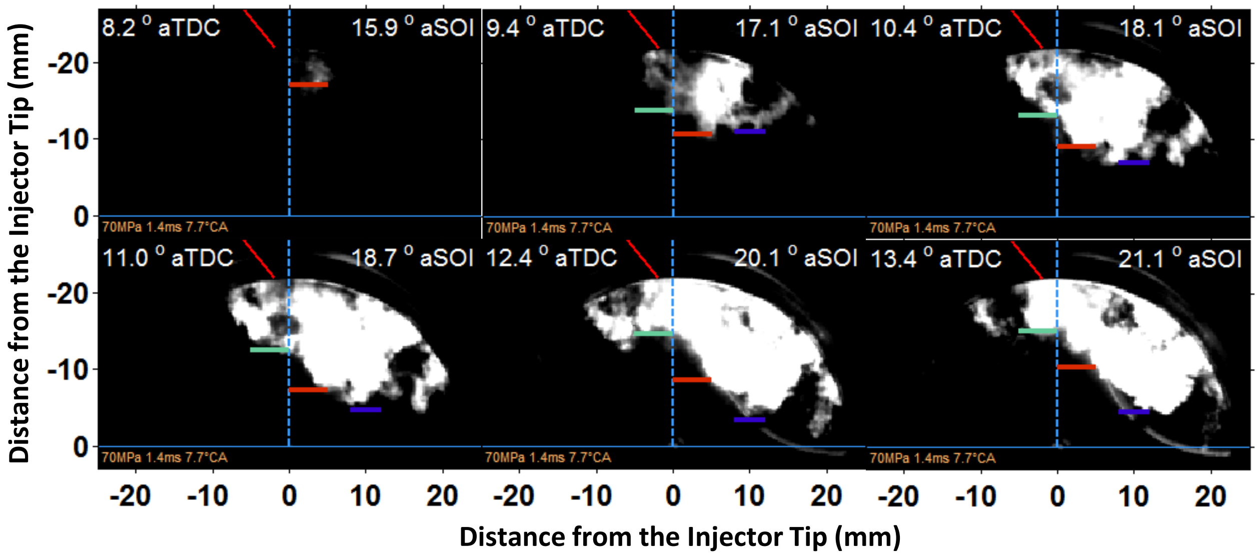

Figure 3. Temporal evolution of soot luminosity from 8.2 ~ 13.4 crank angle degrees after the top dead centre (° aTDC) that corresponds to 15.9~21.1 crank angle degrees after the start of injection (° aSOI). The end of injection occurs at 10° aTDC.

engine, Polonowski *et al.* [13] suggests "re-entrainment" to be the major cause of the observed behaviour. The theory suggests that hot combustion gases are reflected on the wall and incorporated back into the incoming diesel jet. While this finding was made on a heavy-duty engine, the current study in a small-bore diesel engine agrees with the finding on the basis of shorter H_{sw} compared to H_{sf}. This theory is further supported by the reflected soot base (L_{sr}) that also maintains its upstream movement. It is noticeable that H_{sw} decreases with decreasing L_{sr} suggesting that the upstream movement of wall-affected jet is driven by the increased re-entrainment of hot combustion products.

Between 11° to 12° CA in event C, H_{sf} begins to move downstream away from the nozzle as the injection momentum diminishes. By contrast, the wall-affected jet H_{sw} still shows strong tendency to move upstream despite the reduced injection momentum. This further supports the fact that H_{sw} is strongly affected by L_{sr} due to the re-entrainment of hot combustion products. It is only at the end of event C that it begins to move downstream alongside L_{sr}. The final event D shows no upstream movement signalling cooling down of the sooting flames.

Conclusions

The interaction between jet structures inside a concealed and tight environment with high temperature and pressure gradients have been successfully studied using an automotive-size single-cylinder engine with optical access. The piston was modified to allow for a simultaneous side-by-side comparison between a free-jet and a wall-affected jet. The high-speed movie shows details of a transient hot soot base behaviour of the wall-affected jet that can be explained by the re-entrainment of hot combustion products into the incoming jet. The major findings from this study can be summarised as follows:

- The free-jet shows a slower development of hot soot with less fluctuation in soot height than those of the wall-affected jet. This is expected due to the dispersion of most of its jet accumulating into an open cut-out volume of the piston bowl rim and thereby limited jet-wall interaction.

- Redirection of combustion gases explains the observed trend of hot soot in the wall-affected jet. The reflected sooting flame due to a sharp contour of the small piston increases the re-entrainment of hot combustion gases resulting in upstream movement of the hot soot base and thereby shorter hot soot height.

Acknowledgments

Experiments were conducted in the Engine Research Laboratory in the School of Mechanical and Manufacturing Engineering at the University of New South Wales. Support for this research was provided by the Australian Research Council under the grant number DP110103762.

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