

Effect of Injection Pressure on Transient Behaviour of Wall-Interacting Jet Flame Base in an Automotive-Size Diesel Engine

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ABSTRACT

Influence of the injection pressure on the temporal evolution of lifted jet flame base upon the bowl wall impingement has been studied in a small-bore optical diesel engine. Previous studies suggest that the jet-wall interaction causes re-entrainment of combustion products into the incoming jet, which shortens the lift-off length during the injection and thereby increasing downstream soot. After the end of injection, the flame base slowly moves downstream as the diminishing jet momentum results in reduced re-entrainment. How the injection pressure impacts this transient behaviour of the flame base is a main focus of the present study. Common-rail pressure was varied from 70 to 160 MPa at a fixed injection mass (10 mg per hole) and timing (7°CA bTDC). Ensemble-averaged hydroxyl (OH*) chemiluminescence images of 30 firing cycles at various times after the start of injection show that indeed the flame base moves towards the nozzle in accordance with increasing penetration of wall-reflected jet during the injection, supporting the re-entrainment theory. When the injection pressure is increased, the higher jet momentum allows higher penetration rate of the wall-reflected jet possibly enhancing the re-entrainment. However, the faster shortening of lift-off length at higher injection pressure conditions is not observed because the injection ends earlier and therefore the diesel flame develops mostly after the end of injection when the re-entrainment is unlikely. As a result, the shortening of the lift-off length before the end of injection shows no correspondence with injection pressure for tested injection conditions of this study. By contrast, the injection pressure affects the increasing trend of lift-off length after the end of injection. The 70 MPa case shows a very slow recession of the flame base towards the bowl wall due to low jet momentum. The 130 and 160 MPa injection cases also show a slow recession despite very high jet momentum because the original location of the flame base is observed near the wall and develops along the wall curvature. Therefore, the 100 MPa condition with high jet momentum as well as near-nozzle location of the original flame base shows the highest increase of lift-off length after the end of injection.

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INTRODUCTION

Fuel injection pressure undoubtedly plays an important role in air-fuel mixing, flame development and soot formation in direct-injection diesel engines. For instance, increased injection pressure causes enhanced air entrainment [1,2] and increased distance between the nozzle and lifted flame base (*i.e.* lift-off length) [3, 4, 5], which can be used to reduce soot formation in conjunction with small nozzle-hole diameter [4,6]. Soot formation is suppressed because increased injection pressure leads to decreased equivalence ratio at the flame base for equivalent mass of injected fuel [5,7] as well as reduced soot residence time [5], both of which are a direct result of high injection velocity. It is understood that increased injection pressure causes increased

pre-combustion air-fuel mixing [3] and hence enhanced premixed burn phase of diesel combustion [7,8], which also reduces soot emissions [4].

Jet-wall interaction is another important factor influencing air-fuel mixing, diesel flame development and soot formation [9, 10, 11, 12, 13, 14]. In realistic diesel engine environments, reacting jet reflects off the bowl (or cylinder liner) wall as the injection continues and as a result hot combustion products are redirected back towards the nozzle (to the centre of the combustion chamber) [7,9,12, 13, 14]. Some of these hot gases are entrained into the incoming jet, namely "re-entrainment" [7,9,13]. The result is decreased lift-off length due to the re-entrainment of high-temperature gases. It is well known that short lift-off length means increased mixture equivalence ratio at the flame base and

hence increased downstream soot formation [7]. Therefore, the re-entrainment caused by jet-wall interaction should be minimised to suppress soot formation.

The jet-wall interaction is strongly influenced by injection pressure because the jet impingement on the wall becomes stronger as the jet momentum increases [15]. Previous studies [12,16] suggested that stronger jet impingement on the wall can lead to decreased soot formation and increased soot oxidation as the high sooting region near the impingement point can be avoided. On the other hand, increased jet momentum would cause higher penetration of the wall-reflected jet head, which might increase the re-entrainment and thereby increasing soot formation. However, it was found that the re-entrainment would not cause increased soot at realistic engine conditions [7]. This was because the results of higher injection pressure are not only the increased jet momentum but also shorter injection duration for a delivery of fixed amount of fuel. That is, the re-entrainment would be reduced because the duration of hot combustion products recirculation would be shortened.

This study aims to provide further details of the injection pressure effects on the re-entrainment phenomenon and subsequent diesel flame base behaviour. The experiments were performed in an automotive-size diesel engine that has higher jet-wall interaction and re-entrainment due to shorter distance between the nozzle and bowl (or liner) wall than that of heavy-duty diesel engines in which most of previous jet-wall interaction and re-entrainment studies were conducted. Previously in a small-bore optical diesel engine, we obtained visual evidence of lift-off length shortening that occurred only during the injection event when the jet momentum was high enough to cause the re-entrainment [17]. This study is an extension of our previous work using similar experimental approaches but with an emphasis on injection pressure variations. Hydroxyl (OH^*) chemiluminescence imaging was performed for a range of common-rail pressures (70~160 MPa) at a fixed injected fuel mass (10 mg per hole) using a single-hole injector with orifice diameter of 134 μm . The OH^* chemiluminescence images were post-processed to determine lift-off length for various times after the start of injection including before and after the end of injection period.

EXPERIMENTS

Engine Setup and Operating Conditions

Optical diesel engine

A single-cylinder automotive-size diesel engine has been modified to provide optical access to the combustion chamber as depicted in Figure 1 (top). In this study, bottom-view images of the chamber were obtained via a quartz piston and a 45 degree angled mirror at the void of the extended piston assembly. The piston does not retain a re-entrant-type bowl shape of the base engine but has simplified cylindrical bowl geometry. The design of this engine allows physical access to

the chamber provided by a drop-down liner using hydraulic ram so that cleaning of the quartz windows is conducted in-between runs to minimise signal attenuation associated with soot deposition. The fuel used was a conventional ultra-low sulphur diesel (ULSD) with cetane number of 51.

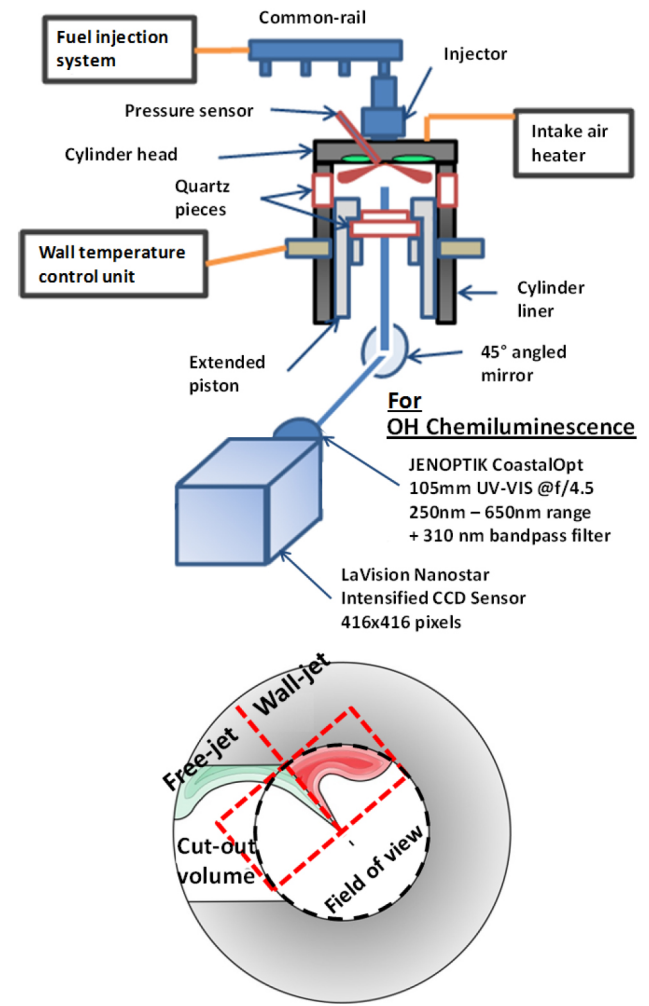


Figure 1. Schematic diagram of the small-bore optical diesel engine used in this study and OH^* imaging setup (top). Shown at the bottom is a jet trajectory of single-hole injection with respect to the bowl-rim cut-out.

As seen on the bottom of Figure 1, additional modification was made to the piston to allow a bisection of the single-jet. It was included to allow half of the jet to penetrate further distance along its trajectory without impingement on the bowl wall ("free-jet") while the other half of the jet has greater and earlier interaction with the bowl wall ("wall-jet"). This was made possible by removing a portion of the piston bowl rim such that the jet intersects in its centreline as shown in the schematic. The dashed-line circle denotes the field of view that was limited by the piston quartz window. The dashed red box annotates the area selected for

image analysis and discussion of the single-jet flame development.

Operating conditions

Table 1. Engine specifications and selected operating conditions.

Engine speed	1200 rpm			
Displacement (single-cylinder)	497.5 cm ³			
Bore	83 mm			
Stroke	92 mm			
Compression ratio	15.2			
Swirl ratio	1.4			
Wall (coolant) temperature	363 K			
Intake air temperature	303 K			
Injector type	Second-generation Bosch common-rail			
Number of holes	1			
Nozzle type	Hydro-grounded, K1.5/0.86			
Nozzle diameter	134 µm			
Included angle	150°			
Injected fuel mass	10 mg			
Rail pressure (MPa)	70	100	130	160
Injection duration (ms)	2.36	2.08	1.66	1.53
Injection timing	7°CA bTDC			

Engine specifications and selected operating conditions are listed in Table 1. The engine was operated with an electric motor at a constant speed of 1200 rpm. The single-cylinder engine was naturally-aspirated and had displacement volume of 497.5 cm³. The light-duty engine had a geometric compression ratio of 15.2 taking into account of the piston bow-rim cut-out. The base engine equips with an intake port throttle that controls the swirl ratio. In this study, however, the throttle was not used and a swirl ratio was fixed at 1.4 throughout the experiments. Heated coolant water of 363 K with a feedback control of temperature was fed into the engine head, engine block and cylinder liner of the optical engine to simulate warmed-up conditions. The air temperature measured right upstream of the intake port was 303 K. A second generation Bosch common-rail system was connected to a single-hole injector of 134 µm (nominal) nozzle-hole diameter and 150° included angle. We used laser-welding technique to modify a conventional injector with 7 nozzle holes such that only one hole was left open while the rest 6 holes were blocked. The single-hole injection was selected to allow long injection duration that can prolong the jet-wall interaction for investigation of the re-entrainment without breaching the operational limits of the optical parts in the engine. It was noted that 10 mg of injected fuel mass per hole corresponded to upper-mid to high load conditions in small-bore engines. A range of injection pressure was tested while holding the injected mass constant. Therefore, the injection duration (actual) was reduced from 2.36 to 1.53 ms

as the injection pressure was increased from 70 to 160 MPa. The start of injection (SOI) was fixed at 7 crank angle degrees before top dead centre (°CA bTDC) so that the injection event occurs at the same ambient air conditions.

Control system

Fuel injection system was controlled using a timing control unit and pressure control valve (Zenobalti 5100). The crank angle position was recorded using an encoder (Autonics E40S) connected to the crankshaft, which was used to generate injection signals at a selected crank angle degree. The single-cylinder optical engine was skip-fired at every 10th cycle to minimise cyclic loadings on quartz windows and reduce residual gases from the preceding fired cycle.

Measurement Techniques

In-cylinder pressure

In-cylinder pressure was measured using a piezoelectric pressure transducer (Kistler 6056A). To minimise effects of the inherent cycle-to-cycle variations and signal noise, the data was ensemble-averaged for a total of 30 fired cycles. The averaged in-cylinder pressure trace was then used to calculate a trace of apparent heat release rate using a simple one-dimensional energy equation [18].

OH* chemiluminescence

The exothermic reactions of hydrocarbons occurring at high-temperature and stoichiometric conditions (e.g. CH + O₂ → CO + OH*) allow hydroxyl (OH) radicals to be formed and chemically excited (i.e. OH*) [19]. Since OH* radicals are good indicators of near-stoichiometric regions and high heat release rate, they are widely used to define flame lift-off length [20,21]. In this study, OH* chemiluminescence imaging was performed to investigate wall-interacting diesel jet development and flame base behaviour. An intensified charge-coupled device (ICCD, Lavision Nanostar) camera was used in conjunction with a 310 nm band-pass-filter (10 nm full width at half maximum) to capture the emission of excited OH* radicals as they return back to their ground state [21]. The intensifier gain was fixed at 45% throughout the experiments. The camera was coupled with a 105 mm ultraviolet lens with f/4.5 that has a transmission of 85% or higher at 250 ~ 650 nm range. One might be concerned with interferences from CH emissions and luminosity of soot that present at a range of 306 ~ 310 nm but OH* signal is known to be dominant at 310 nm [19,21]. Obtained OH* chemiluminescence images were linearly averaged using a total of 30 images from 30 individual firing cycles for various crank angle locations. This averaging process was to address issues of inherent cycle-to-cycle variations. Samples were taken at every 0.5°CA from the first detectable instance of OH* signal to the end of main heat release to understand temporal evolution of diesel flame.

Definition of Parameters

Wall-jet and free-jet

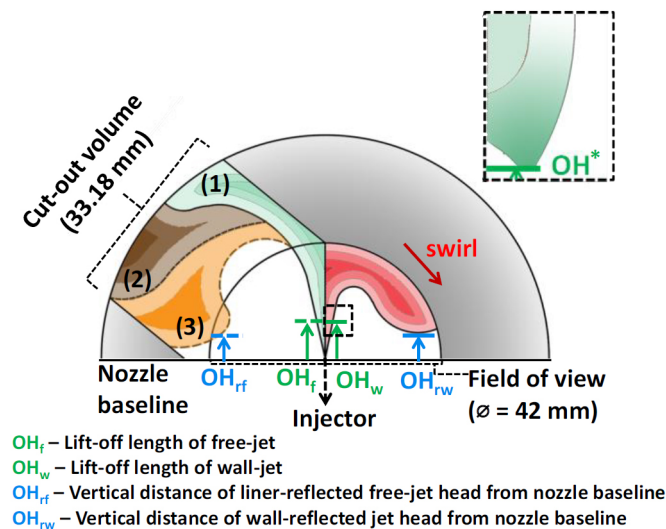


Figure 2. Schematic diagram of one-hole diesel injection in a modified piston with bowl-rim cut-out. The jet penetration stages within the cut-out volume are illustrated for (1) liner-wall/jet interaction, (2) further jet penetration upon the wall impingement, and (3) reappearance of the reflected jet head in the field of view.

A schematic diagram of the bisected single-jet trajectory is shown in Figure 2 to provide definitions of variables used in the present study. The right-hand side of the jet with jet/bowl-wall interaction is defined as the “wall-jet” while the left-hand side is identified as the “free-jet”. Since the injection timing (7°CA bTDC) was selected near the top dead centre, the spray targeting suggested that this side of the jet would impinge on the bowl wall. Two variables with the notation “w” are used for the wall-jet including OH_w for the lift-off length and OH_{rw} for distance between the wall-reflected jet head and nozzle baseline. The notation “r” therefore stands for wall-reflection of the jet. The sketch depicts a bowl-rim cut-out on the left-hand side of the piston where a half of the jet penetrates further with lack of jet/bowl-wall interaction. The notation “f” is selected since this side of the jet is free from the bowl wall impingement (*i.e.* “free-jet”) although the jet eventually impinges on the cylinder-liner wall and therefore should be distinguished from jets without wall interaction. The OH_f and OH_{rf} are defined for the free-jet lift-off length and distance between the cylinder-liner-wall-reflected jet head and nozzle baseline, respectively. In Figure 2, OH* regions are filled with different colours, with red for the wall-jet and green for the free-jet. As shown in Figure 1 (bottom), the field of view of the used quartz piston did not allow visualisation of the flame development within the cut-out volume. However, for illustration purposes, penetration stages of the “free-jet” are portrayed by (1) green, (2) dark brown and (3) orange colour-

filled areas. It was believed that the free-jet impinged on the cylinder liner wall at stage (1), continued to penetrate along the cylinder-liner wall at stage (2), and eventually redirected back into the field of view at stage (3) enabling the detection of OH_{rf}. Compared to a symmetric jet with both sides of the jet impinging on the bowl-wall, this approach made it possible to directly compare lift-off lengths of the jets with different degrees of jet-wall interaction.

Flame base and lift-off length

In OH* chemiluminescence images, the lifted flame base was defined as the point vertically nearest to the nozzle baseline within a horizontal band of 0 to 5 mm, where 0 mm is the position of the injector. The lift-off lengths (OH_w and OH_f) were then estimated using distance between the flame base and nozzle baseline. While the 5-mm bar was chosen from simple visual inspection, it was based on a well-known diesel jet structure [4]. That is, the flame base is detected as a point where the rich premixed flame and diffusion flame meet as shown in the magnified view of the flame base in Figure 2. A similar definition was used in Ref. [7] but a narrower range of 2 mm was selected. A wider band of 5 mm of this study is justified since the spray angle is wider due to larger hole diameter (134 μm over 110 μm) as well as lower injection pressure (70 ~ 160 MPa over 140 ~ 240 MPa). The vertical distance from the nozzle baseline to the head of the wall-reflected combustion gases (OH_{rw} and OH_{rf}) was similarly measured using a horizontal bar in a range of 15 ~ 20 mm from the jet axis.

Post-Processing of Images and Cycle-to-Cycle Variations

Cyclic variations are caused by irregularities in mixture distribution, charge motion and local ambient-gas conditions [7,22]. Such variations are unavoidable in realistic engine environments. To ensure that the acquired results are statistically significant, OH* images were linearly averaged for 30 individual cycles and error margins were calculated. Examples of these individual cycles are shown on the leftmost column of Figure 3 for 70 MPa injection case taken at 9°CA after TDC (aTDC). Shown as a white dot is the position of the injector and as a circle is the outline of piston bowl. The white clouds are signals of high temperature reaction zones where chemically excited OH* radicals emit chemiluminescence. Two different cycles (#10 and #21) indeed show measurable cycle-to-cycle variations. The 30-cycle-averaged image is shown next to these individual images. It is notable that OH* signals are very weak near the bowl-wall region, which might be attributed to the flame quenching [13, 23-24]. Another potential cause was signal attenuation due to soot deposition; however, thorough window cleaning between engine runs ensured no such deterioration to impact the OH* signals.

The boundaries of OH* chemiluminescence images were obtained using an in-house developed MATLAB code. The