

Lift-Off Length in an Optical Heavy-Duty Diesel Engine: Effects of Swirl and Jet-Jet Interactions

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ABSTRACT

The influence of jet-flow and jet-jet interactions on the lift-off length of diesel jets are investigated in an optically accessible heavy-duty diesel engine. High-speed OH chemiluminescence imaging technique is employed to capture the transient evolution of the lift-off length up to its stabilization. The engine is operated at 1200 rpm and at a constant load of 5 bar IMEP. Decreasing the inter-jet spacing shortens the lift-off length of the jet. A strong interaction is also observed between the bulk in-cylinder gas temperature and the inter-jet spacing. The in-cylinder swirl level only has a limited influence on the final lift-off length position. Increasing the inter-jet spacing is found to reduce the magnitude of the cycle-to-cycle variations of the lift-off length. The measured lift-off lengths, at their stabilized positions, are combined with a previous database composed of variations of intake air temperature, motored top dead center density, fuel injection pressure, intake oxygen concentration and nozzle diameter. A non-linear regression model based on the power law form proposed by Siebers *et al.* is developed for describing the stabilized lift-off length of diesel jets as function of the ambient in-cylinder conditions, jet-flow and jet-jet interactions. The model has good accuracy. Although it is only validated for this particular engine environment it identifies the parameters that have the dominating effect on the lift-off length.

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INTRODUCTION

In classical diesel combustion the fuel-air mixture auto-ignites after a short ignition delay and a lifted diffusion flame establishes at a certain distance from the injector. The distance between the nozzle of the injector and the first downstream location of the diffusion flame is defined as the lift-off length of a diesel jet [1]. The lift-off length is an important characteristic since air-entrainment into the central, soot-forming region of the jet is only feasible up to the lift-off position. For a given fuel, the soot formation rate is therefore largely determined by the temperature and the equivalence ratio of the fuel-air mixture at the lift-off position [2, 3, 4, 5, 6]. The understanding of the physical processes governing the lift-off length and its stabilization during the quasi-steady phase of combustion is therefore essential for predicting soot formation rates.

The fundamental relationship linking the lift-off length to the ambient conditions, the nozzle hole geometry, the injection pressure and fuel properties have been established in constant volume combustion chambers [7, 8, 9, 10, 11, 12, 13, 14]. Siebers and coworkers proposed an empirical power law [14] describing the lift-off length H [mm] of a quasi-steady diesel jet as function of the ambient gas temperature T_a [K], the ambient gas density ρ_a [kg/m³], the nozzle diameter d [mm], the injection velocity at the nozzle exit U [m/s] and the stoichiometric mixture fraction Z_{st} :

$$H = C T_a^{-3.74} \rho_a^{-0.85} d^{0.34} U^1 Z_{st}^{-1}$$

(1)

C is a constant equal to $7.04 \cdot 10^8$. This model is based on an extensive experimental database covering a wide range of conditions relevant for modern diesel engines. Ambient conditions prior to the injection event can be accurately determined in combustion vessels and, due to the large volume of air in comparison to the fuel mass injected, they are not changing significantly during combustion. Overall, [equation \(1\)](#) accurately predicts stabilized lift-off lengths of free jets measured in combustion vessel environments with quiescent ambient conditions [15].

However, prediction of lift-off lengths with [equation \(1\)](#) is complicated in engine applications and some deviations have been identified [16]. The main source of errors lies in the estimation of temperature and density of the ambient gas entrained into the jets. These are varying in time and space during the injection event. They are affected by the piston motion, compression by the burned gases, as well as convective and radiative heat transfer to the cylinder walls. Measurements from in-cylinder pressure transducers cannot give a precise approximation of these parameters due to the inhomogeneity of the gas state in the cylinder. Another difference is that combustion chambers in diesel engines have features that are not present in combustion vessels. Nozzles with multiple holes are used in engines, resulting in interactions between the jets. There are also interactions between the in-cylinder flow field (swirl, squish and tumble) and the jets. The proximity of the piston bowl surfaces also generate jet-wall interactions. Reservoirs of hot combustion products are accumulated around the diffusion flame of diesel jets and they are most likely affecting the lift-off length of diesel jets through local recirculation at

the lift-off region [17]. For this reason, jet-jet interactions modify the ambient temperature between the jets and Chartier *et al.* [16] showed that they affect the lift-off length. It was shown that a closer spacing between the jets reduces the lift-off length. They also reasoned that jet-wall interactions should have an influence on the lift-off length through recirculation of burned gas from the piston bowl periphery towards the center of the combustion chamber [16, 18]. For these reasons, an unknown proportion of hot burned gas is re-entrained at the lift-off region of the jets in an engine combustion chamber.

In short, spray vessels provide stable, repeatable conditions but do not reproduce important features of internal combustion engines. To shed light on how those features can be expected to affect the lift-off length in engines, a former study investigated the flame stabilization in an optical heavy-duty engine [19]. The parameters in [equation \(1\)](#) were varied and the following non-linear regression model was derived from the experimental database:

$$H = A T_{bulk}^{-1.43} \rho_{bulk}^{-0.83} d^{0.41} U^{0.48} Z_{st}^{-0.75} \quad (2)$$

A is a constant equal to $3.34 \cdot 10^3$. The bulk gas temperature T_{bulk} and density ρ_{bulk} replace the ambient temperature T_a and density ρ_a used in [equation \(1\)](#), since they have been shown to be better predictors of the entrained-gas temperature in an engine environment [16]. The variables in [equation \(2\)](#) are expressed in the same units than in [equation \(1\)](#).

The present study is supplementary to the previous lift-off length investigation in the same facility [19]. The aim of the present work is to integrate in [equation \(2\)](#) the effects of jet-jet and jet-flow interactions through two variables; the inter-jet angle and the in-cylinder swirl level. For practical reasons the number of experimental variables has been limited to five in total. The two dominant variables from [equation \(2\)](#) are selected plus the nozzle hole diameter which is an interesting parameter for engine designers. Despite its high weight in [equation \(2\)](#), the charge dilution has been chosen not to be considered here. This choice is further motivated from a diagnostics point of view where a stronger chemiluminescence signal is obtained without dilution. The experimental factors chosen for this study are therefore the spacing between the jets, the swirl level, the nozzle diameter, the temperature and density of the air charge.

EXPERIMENTAL SETUP

Engine Configuration

Experiments are conducted on a Scania D12 heavy-duty diesel engine converted for optical access on one of the cylinders. A general description of the engine geometry and its fuel injection system is given in [Table 1](#). N-heptane mixed with a lubricant (Chevron Synfluid) at a concentration of 0.5% by volume is used as a surrogate for diesel fuel. N-heptane is practical for optical measurements since it has a cetane number comparable to regular diesel fuel while being less sooting. As the present research is focused on the general trends of the lift-off length, fuel property effects fall outside the scope. Finally using n-heptane gives the possibility to compare these results with our previous lift-off length database produced with this fuel.

Gross Indicated Mean Effective Pressure (IMEP_g) and combustion phasing (CA50) are kept constant close to 500 kPa and 9 Crank Angle Degrees After Top Dead Center (CAD ATDC), respectively. The CA50 is held constant by adapting the start of injection timings to the different nozzle diameters. The load is maintained constant by adjusting the injection duration in accordance with the different nozzle diameters. The fuel injection pressure is kept constant at 2000 bar. No dilution of the intake air charge with Exhaust Gas Recirculation (EGR) is used in this experiment. The intake oxygen concentration remains at 21% for all the cases. In order to minimize systematic measurement errors, a standardized operating procedure is used to ensure stable thermodynamic conditions of the engine and stable intake air flow conditions (pressure, temperature). The engine coolant temperature is kept constant around 353 K. The engine is operated at 1200 rpm in skip-fire mode at a rate of one fired cycle for 10 motored cycles.

Table 1. Engine and injector specifications.

Engine base type	Scania D12
Number of cylinders	1
Number of valves	4
Bore [mm]	127
Stroke [mm]	154
Displacement [L]	1.95
Geometric compression ratio	15.6:1
Swirl number [-]	0.2 - 1.2 - 2.2
Fuel injection system	XPI common rail system
Number of holes	4
Orifice diameter [mm]	0.1 - 0.12 - 0.14
Inter-jet angles [°]	45 - 90 - 135
Included angle [°]	146

The intake air charge is heated before the intake manifold. Intake air temperature variations from 343 K to 403 K (see [Table 3](#)) correspond to estimated motored TDC temperatures ranging from 809 K to 977 K. These estimations are obtained applying the ideal-gas law with a corrected engine compression ratio. In-cylinder volume traces are corrected for variations in squish height due to deformation of the optical piston assembly during engine operation. A detailed study of dynamic mechanical deformations of piston assemblies in optical engines and possible corrections for volume traces is available in [20].

The combination of small nozzle hole sizes (as compared to production type nozzles) and long injection durations allow a quasi-steady diesel jet to develop even at low engine loads. Injectors with symmetric and asymmetric nozzle cups are used to vary the inter-jet angle and therefore the degree of jet-jet interactions. The schematics in [Figure 1](#) show the two types of nozzle cups used. The symmetric nozzle has four sprays equally spaced at 90°. For the asymmetric injector, the sprays of interest are the isolated one at 135° (hole 1 in [Figure 1](#)) and the confined spray at 45° (hole 3 in [Figure 1](#)). In total a set of six injectors is used to combine variations of nozzle hole sizes and inter-jet angles.

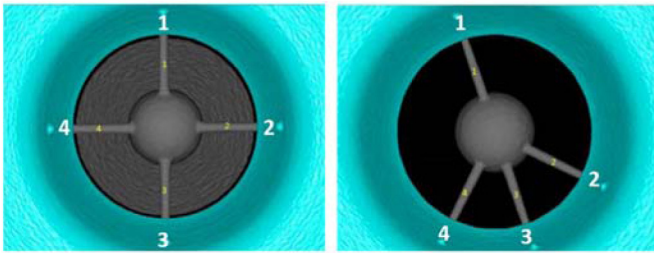


Figure 1. On the left hand side a symmetric nozzle cup with 0.12 mm holes. On the right hand side an asymmetric nozzle cup with 0.1 mm holes. The holes are numbered from one to four.

An example of the hole-to-hole diameter discrepancy is given in Table 2 containing the outer diameters d of the holes as measured by X-ray imaging. The deviation of the diameter from hole to hole is low, 0.7% for the symmetric injector and 1.3% for the asymmetric injector in Table 2, and the holes sizes are close to their nominal values.

Table 2. X-ray measurements of the nozzle hole size of the asymmetric and symmetric nozzles from Figure 1.

Symmetric	Hole 1	Hole 2	Hole 3	Hole 4	Mean
$d[\text{mm}]$	122.3	121.6	120.8	122.7	121.9
Asymmetric	Hole 1	Hole 2	Hole 3	Hole 4	Mean
$d[\text{mm}]$	94.7	94.2	96.8	96.2	95.5

The in-cylinder swirl level is changed by varying the degree of obstruction of the inlet ports in the cylinder head. Different mask plates are used to block the intake airflow. These plates were previously calibrated on a swirl test bench with the same cylinder head and inlet manifold as the one used for this experiment. The swirl level can be reduced from its nominal value of 2.2 down to 0.2. The intake air boost pressure level is adjusted for each combination of mask plates in order to compensate for the air mass flow losses induced by the partial blocking of the inlet ports. The swirl number also commonly referred as the swirl ratio is defined as the ratio of the angular velocity of the solid-body rotating flow to the engine speed.

For all the experiments, a piston bowl of 80 mm is used. In a second separate experiment, a piston crown with identical geometric shape and a 70 mm bowl diameter is used in order to investigate the influence of this geometric parameter on the lift-off length, at a limited number of operating conditions. Due to the higher geometric compression ratio with the smaller bowl diameter, the intake boost levels were reduced and adjusted to reach similar motored TDC densities and temperatures as with the larger piston.

Design of Experiments

The core of the experimental matrix consists of a three-level central composite design with five factors to which additional axial points are added to facilitate the visualization of the experimental parameters. The complete list of experimental conditions is shown in Table 4 in the Appendix. Five experimental parameters are considered in this study: the swirl level R_s , the inter-jet angle θ , the nozzle orifice

diameter d , the intake air temperature T_{in} and the motored TDC density ρ_{TDC} . In total the experimental matrix is composed of 39 individual runs which are replicated once.

Central composite designs have the advantage of capturing most of the relevant information in a minimal number of experiments for a given set of experimental factors [21]. The individual effects of the experimental factors are entirely decoupled. Since all parameters are varied simultaneously, the data also provide support for cross-terms (representing interaction effects). Central composite designs further contain several points to provide support for non-linear effects that create curvature in the response. For these reasons, design of experiments generally result in more reliable regression models than more intuitive approaches do.

Optical Diagnostics

Hydroxyl radicals (OH) are present in reaction zones where high-temperature heat release occurs [22]. It has been demonstrated that chemiluminescence emission from excited OH radicals is a suitable marker of the high-temperature reaction zone of diesel jets and can therefore be used for determining the lift-off length [7].

The optical setup for the OH chemiluminescence imaging is composed of a high speed Photron Fastcam SA-X2 CMOS camera combined with a Hamamatsu high-speed gated image intensifier, a UV lens (B. Halle, $f=100$ mm, $f\#2$) and an interference filter centered at 307.1 nm (25 nm FWHM). An overall schematic view of the experimental setup for the high-speed chemiluminescence imaging is shown in Figure 2a. A cross-section view of the combustion chamber with the optical access is depicted in Figure 2b. The piston bowl has a flat bottom made of quartz and vertical walls made of metal. The bowl rim has a chamfer in the upper half.

Camera and image intensifier settings were selected to get a satisfactory compromise between spatial and temporal resolution of the diesel jets. The selected settings allow capturing of the transient evolution of the lift-off position for all of the four sprays. However, the field of view of the camera does not include the entire combustion chamber out to the piston bowl walls. As a consequence, for most of the operating conditions, the very early downstream position of the lifted flames just after the auto-ignition event are beyond the portion of the bowl imaged and therefore they are not captured. The jets are imaged from beneath through the quartz piston. Images are recorded at a rate of 50,000 frames per second which approximately corresponds to one image per 0.14 CAD at an engine speed of 1200 rpm. The image resolution is 512*456 pixels corresponding to an image ratio of 0.1209 mm/pixel. The camera exposure time is set to 19 μs , the maximum time possible for the selected frame speed. The image intensifier gain is set to its minimum value which is 600. The gain is the voltage across the micro-channel plate of the image intensifier, which can be adjusted between 600 and 900 V for this model. 250 frames are recorded per cycle and 30 fired cycles are recorded for each operating condition. The camera is triggered 3 CAD After Start Of Injection (ASOI) command.

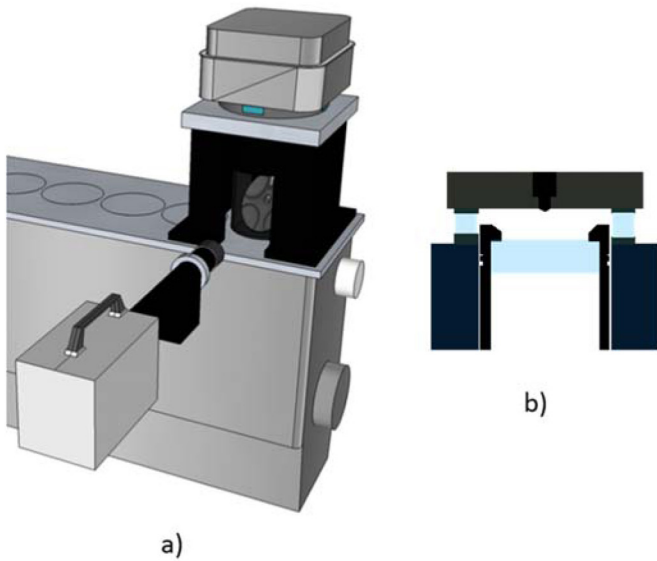


Figure 2. a) Sketch of the optically accessible cylinder and the imaging setup b) Cross-section view of the combustion chamber with the quartz piston and windows.

Image Analysis

An example of instantaneous OH chemiluminescence images is shown in Figure 3. The left-hand side shows the isolated spray with 135° inter-jet angle θ and the confined spray with 45° inter-jet angle θ . On the right-hand side image, all four spray are equally spaced at 90° . Since the image color scales differ, pixel intensities cannot be directly compared between images. However, the physical scales are the same.

As can be seen in Figure 3, the piston bowl which has a diameter of 80 mm is not fully imaged.

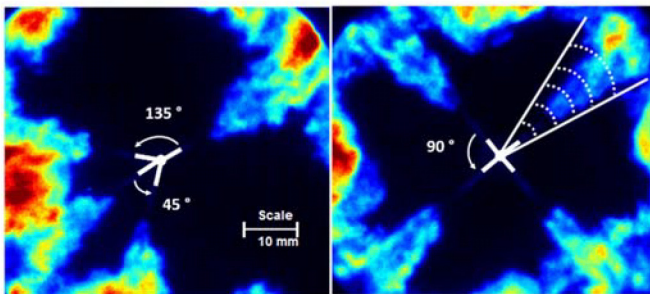


Figure 3. OH chemiluminescence images recorded at 8 CAD ATDC. On the left-hand side the 0.1 mm asymmetric injector (experiment number 1, cf. Table 3). On the right-hand side the 0.12 mm symmetric injector (experiment number 23, cf. Table 3). The position of the injector is marked by a white dot. The physical scale is identical for both images. An illustration of the arc of circles used in the image processing are marked with dashed points on the right-hand side of the figure.

A preliminary background subtraction is performed on the image under analysis. The first two images after the camera trigger are discarded and the following eight frames are averaged and used as a background image. The first appearance of OH chemiluminescence signal occurs after the time frame chosen for creating the background image. For the symmetric injectors, the lift-off length of each of the four sprays is evaluated and an average is calculated. On the other

hand, for the asymmetric injectors, only the confined ($\theta = 45^\circ$) and the isolated spray ($\theta = 135^\circ$) are of interest, so only their lift-off lengths are evaluated. In previous works, a nozzle tracking algorithm was used in order to find on each frame the precise location of the injector and then remove the potential positioning error due to vibrations of the engine test bench during operation [23]. This technique relies on the scattered light from the droplets in the liquid phase of the jet for identifying the location of the sprays and subsequently the center position of the injector. In most of the cases here, due to the relatively short camera exposure times, the liquid scattered signal is too weak in comparison to the camera background noise level. The nozzle tracking algorithm is therefore not used here. Instead the nozzle position for each injector is determined from accumulated images over a complete cycle. From cases where the liquid jet is partially visible, the error of position has been investigated and is well below 10 pixels, corresponding to less than a millimeter at most.

Concentric arcs of circles are drawn across the spray, forming a pie-shaped evaluation sector (see. Figure 3). The signal function from the spray is obtained by summing up radially the pixel intensities of each arc of circle along the spray axis. This signal represents the distribution of the OH chemiluminescence intensity along the spray axis. The mean value of the signal function over the first couple of circles is subtracted from the signal function. A threshold corresponding to 15% of the signal function maximum is taken to determine the lift-off length. This threshold level ensures that no remaining noise pixels are detected upstream of the lift-off region, which could lead to miscalculations. A sensitivity check revealed that a threshold value of 15% does not underestimate the lift-off lengths. This is due to the existence of a relatively steep gradient between the background pixel intensity in the vicinity of the injector and the intensity of the pixels in the lift-off region of the jets. Finally the lift-off length is corrected for the included angle and the nozzle cup half diameter.

The lift-off length has been previously observed to be asymmetric in presence of swirl which displaces hot gases from the up-swirl side (or windward) towards the down-swirl (or leeward) side of the jet [16, 24]. The down-swirl side has a shorter lift-off length than the up-swirl side. The detection algorithm presented above finds the first downstream appearance of OH signal above the threshold value. Therefore, only the down-swirl lift-off length is calculated here. A later section is specifically dedicated to the effect of the swirl level on the lift-off asymmetry. It has been verified with the database [19] that there is no influence on the final regression model whether a mean value between up and down-swirl lift-off length is taken or not. Therefore, in favor of the algorithm robustness, the up-swirl side of the lift-off length is disregarded.

RESULTS AND DISCUSSIONS

Inter-Jet Spacing

An example of time-resolved lift-off length evolution is presented in Figure 4. The time base is in crank angle degrees ASOI command. The mean lift-off length over 30 engine cycles is plotted and the standard