

Lift-Off Length in an Optical Heavy-Duty Diesel Engine

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ABSTRACT

High-speed OH chemiluminescence imaging is used to measure the lift-off length of diesel sprays in an optical heavy-duty diesel engine of 2 L displacement operated at 1200 rpm and 5 bar IMEP. Stereoscopic images are acquired at two different wavelengths (310 and 330 nm). Subtraction of pairwise images helps reducing the background coming from natural soot incandescence in the OH chemiluminescence images. Intake air temperature (343 to 403 K), motored top dead center density (18 to 22 kg/m³), fuel injection pressure (150 to 250 MPa), intake oxygen concentration (17 to 21 %vol) and nozzle diameter (0.1 and 0.14 mm) are varied and a nonlinear regression model is derived from the experimental results to describe stabilized lift-off length as function of the experimental factors. The lift-off length follows the general trends that are known from spray vessel investigations, but the strength of the dependence on certain variables deviates strongly from those studies. The experimental correlation obtained for the lift-off length in the aforementioned ambient conditions has the following form:

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

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INTRODUCTION

The lift-off length of a diesel jet is defined as the distance between the nozzle of the injector and the first downstream location of the diffusion flame [1]. This parameter is an important characteristic of diesel jets since ambient 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 dependent on 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 essential for predicting soot formation rates. Over the last decade extensive research has been carried out to get more fundamental knowledge on the lift-off length of diesel sprays. Influences of ambient air charge properties (temperature, density, and oxygen concentration), nozzle diameter, injection pressure and fuel properties have been characterized in constant volume combustion chambers [7,8,9,10,11,12,13,14]. The following empirical power law, describing the lift-off length H of a quasi-steady diesel jet as function of the ambient air charge properties and injection parameters, has been developed by Siebers and coworkers [14]:

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

Here, T_a is the ambient gas temperature, ρ_a the ambient gas density, d the nozzle diameter, U the injection velocity at the nozzle exit and Z_{st} the stoichiometric mixture fraction. C is a constant. 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 they are not changing significantly during combustion, due to the large volume of air in comparison to the fuel mass injected. Overall, [expression \(1\)](#) 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 high 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, creating 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 [14]. 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 of adjacent jets [16]. Jet-wall interactions also have an influence on the lift-off length of jets through recirculation of burned gas from the piston bowl periphery towards the center of the combustion chamber [17]. 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, the present study investigates the flame stabilization in an optical engine. The aim is to develop an expression similar to equation (1), although the magnitude of the exponents of each of the parameters composing equation (1) is expected to change due to the aforementioned deviations from a spray vessel. The parameters investigated here are the temperature and density of the charge, the nozzle diameter, the initial injection velocity and the stoichiometric mixture fraction. The specific effects of swirl and jet-jet interactions are planned to be presented in an upcoming publication.

EXPERIMENTAL SETUP

Design of Experiments

The core of the experimental matrix consists of a three-level central composite design with four 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 1.

Five experimental parameters are considered in this study: the intake air temperature T_{in} , the Top Dead Center (TDC) motored density ρ_{TDC} , the fuel injection pressure P_f , the intake oxygen concentration $[O_2]_{in}$ and the nozzle orifice diameter d . Two nozzle diameters are used and the matrix in Table 1 is reproduced for both of them. In total the matrix is composed of 66 individual runs which are replicated twice in random order.

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 [18]. The individual effects of the experimental factors are entirely decoupled and at the same time interaction effects are also detected. In addition, a central composite design contains several points to provide support for non-linear effects that create curvature in the response. Since all parameters are varied simultaneously, the data also provide support for cross-terms

(representing interaction effects). For these reasons, design of experiments generally result in more reliable regression models than more intuitive approaches do.

Table 1. Experimental matrix of operating conditions for one injector. Central composite design augmented with extra axial points.

T_{in} [K]	ρ_{TDC} [kg/m ³]	P_f [MPa]	$[O_2]_{in}$ [%vol]
343	20	200	19
358	20	200	19
373	20	200	19
388	20	200	19
403	20	200	19
373	18	200	19
373	19	200	19
373	21	200	19
373	22	200	19
373	20	150	19
373	20	175	19
373	20	225	19
373	20	250	19
373	20	200	17
373	20	200	18
373	20	200	20
373	20	200	21
343	18	150	17
343	18	150	21
343	18	250	17
343	18	250	21
343	22	150	17
343	22	150	21
343	22	250	17
343	22	250	21
403	18	150	17
403	18	150	21
403	18	250	17
403	18	250	21
403	22	150	17
403	22	150	21
403	22	250	17
403	22	250	21

Engine Setup

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 2. 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.

The combination of small nozzle hole size (0.1 and 0.14 mm), as compared to production type nozzles, together with long injection durations allow a quasi-steady diesel jet to develop even at low engine loads.

Table 2. 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 [-]	2.18
Fuel injection system	
Type	XPI common rail system
Number of holes	4
Orifice diameter [mm]	0.1 and 0.14
Inter-jet angles [°]	90
Included angle [°]	146

Gross Indicated Mean Effective Pressure (IMEPg) and combustion phasing (CA50) are kept constant at 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 injection pressures, nozzle diameters and dilution levels. The load is maintained constant by adjusting the injection duration in accordance with the different injection pressure levels and nozzle diameters. 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 and oxygen concentration). 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.

A diesel furnace operating at close to stoichiometric conditions is used as an external source of Exhaust Gas Recirculation (EGR). Dry EGR and fresh air are mixed and compressed to reach targeted intake oxygen concentrations. The intake air charge is heated before the intake manifold. Intake air temperature variations from 343 K to 403 K (cf. Table 1) correspond to estimated TDC motored 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 [19].

Optical Diagnostics

Two separate optical setups are used for recording time-resolved hydroxyl radical (OH) chemiluminescence images and for measuring the emission spectra of one of the diesel jet flames.

OH Chemiluminescence

OH radicals are present in reaction zones where high temperature heat release occurs [20]. 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]. However, the OH chemiluminescence signal can suffer from high background levels of soot radiation. This is especially true in optical engine applications, where soot clouds are recirculated toward the center of the combustion chamber after piston bowl-wall impingement. Operating conditions are also expected to affect the level of soot radiation and/or the intensity of the OH chemiluminescence signal collected. For this reason, an attempt is made in this study to reduce the background from natural soot incandescence on the images. Stereoscopic imaging is used to simultaneously acquire two images of the sprays at different wavelengths. One image, called the “online” image, is taken at the wavelength of the OH emission peak. The second image is taken outside of the OH emission peak and is called the “offline” image. The online image contains both the OH chemiluminescence signal and some soot background. Ideally the offline image should only include soot background and subtraction of the two images should therefore reduce the soot background.

The optical setup for the OH chemiluminescence imaging is composed of a high speed Photron Fastcam SA-X CMOS camera combined with a Lambert HS IRO 2-stage image intensifier, a UV lens (B. Halle lens, $f=100$ mm, $f\#2$) and a stereoscope. An interference filter centered at 310 nm (10 nm FWHM) is used for the online image, and another interference filter centered at 330 nm (10 nm FWHM) for the offline image. A schematic view of the experimental setup for the chemiluminescence imaging is shown in Figure 1.

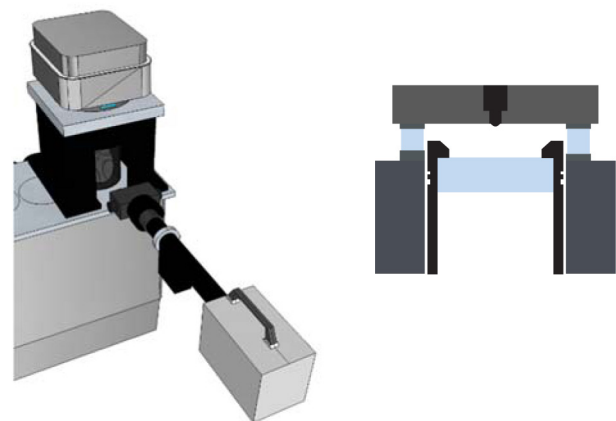


Figure 1. On the left-hand side a view of the experimental setup for the high-speed OH chemiluminescence imaging. On the right-hand side a cross-section view of the piston elongation assembly.

Camera and image intensifier settings were selected to get a satisfactory compromise between spatial and temporal resolution of the diesel jets. The jets are imaged from beneath through the quartz piston. In order to avoid overlapping of the stereo images, however, only three out of four sprays can be visualized. Images are recorded at a rate of 12,500 frames per second, which is the maximum frame speed possible when using the full camera chip. It corresponds to one image per 0.58 CAD at 1200 rpm. The image resolution is 1024*1024 pixels corresponding to an image ratio of 0.102 mm/pixel. The camera exposure time is set to 78 μ s, the maximum time possible for the selected frame speed. The image intensifier gain is set between 700 and 800 depending on the operating conditions. This gain is the voltage across the micro-channel plate of the image intensifier, which can be adjusted between 400 and 940 V. 80 frames are recorded per cycle and 30 fired cycles are recorded for each operating condition.

Flame Spectroscopy

Flame emission spectra of one of the diesel jets are recorded in order to confirm the predominance of OH radicals at the lift-off region. Measurements are based on 10 accumulated spectra corresponding to 10 skip fired engine cycles.

The experimental setup for the flame spectroscopy measurements consists of an Acton SpectraPro 2300i spectrometer coupled with a Princeton Instruments PI-MAX 3 ICCD camera and the B. Halle UV lens mentioned above. The spectrometer grating was set to 300 lines per mm and it had a dispersion of 0.08 nm/pixel. A schematic of the optical setup is shown in [Figure 2](#).

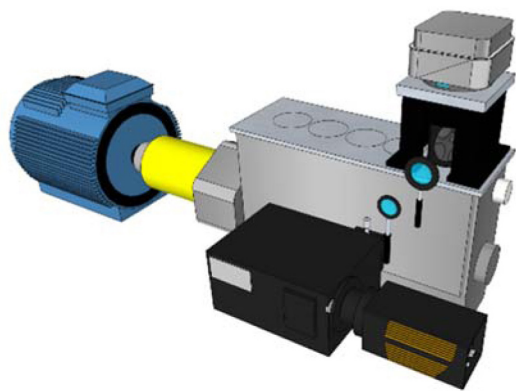


Figure 2. View of the engine rig with the optically accessible cylinder and the optical setup for the flame spectroscopy measurements.

Flame Spectra

The flame spectra are composed of a background due to natural soot luminosity and of a distinct peak centered near 310 nm corresponding to OH* emission. The background is broadband following the Planck radiation law with intensity increasing for longer wavelengths. The background intensity is lower than the OH chemiluminescence peak in the selected wavelength range.

The measured flame emission spectra correspond to the conditions described in [Table 1](#). Both injectors were tested under a variation of intake oxygen concentration and at different CAD positions. Pixel

intensities on the images corresponding to the lift-off region of the spray are averaged to build up an intensity signal as function of the collected wavelength. The signal intensity on the images is normalized for each injector. Therefore intensity levels cannot be compared between injectors. The wavelength range displayed spans between 250 and 370 nm.

The effect of intake oxygen concentration on the flame emission spectra of sprays for both injectors is visible in [Figures 3](#) and [4](#). The peak intensity of OH chemiluminescence is decreasing with reduced oxygen concentration due to lower combustion temperatures. These spectral measurements confirm that the OH chemiluminescence can be distinguished from the soot radiation background down to the lowest oxygen concentration (17 [%vol]) used in the test matrix in [Table 1](#).

The soot background intensity is higher for the 0.14 mm injector, which is expected since the reduced air-entrainment into the jet increases soot formation. The interference filter for the offline image is centered at 330 nm, outside of the OH chemiluminescence peak. It can also be observed in both [Figures 3](#) and [4](#) that soot background intensity levels at 310 nm and 330 nm can be considered to be relatively similar for each nozzle. This is the justifying reason for using the offline image for background subtraction from the online image.

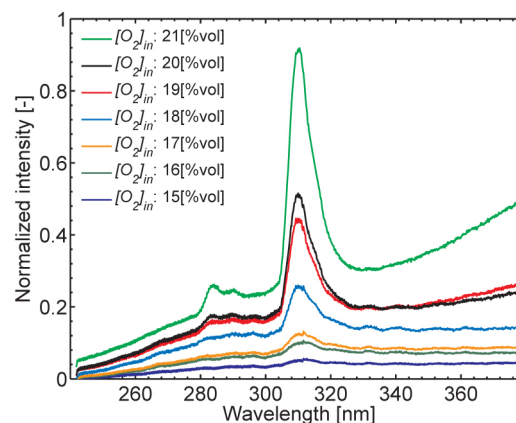


Figure 3. Flame emission spectra near the lift-off region of one of the sprays of the 0.1 mm injector. Intake oxygen concentration is varied from 15 to 21 [% vol] and emission spectra are acquired at CA50 timing.

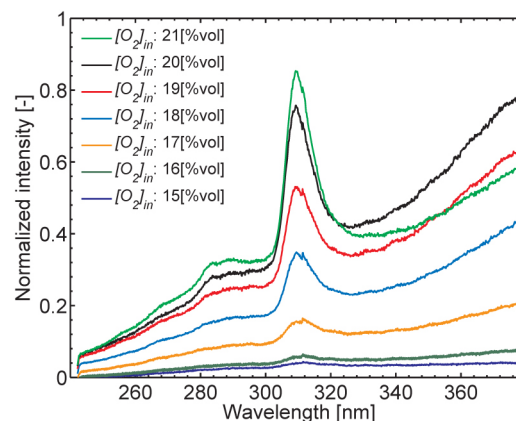


Figure 4. Flame emission spectra near the lift-off region of one of the sprays of the 0.14 mm injector. Intake oxygen concentration is varied from 15 to 21 [% vol] and emission spectra are acquired at CA50 timing.