THE INFLUENCE OF ORIFICE DIAMETER ON FLAME LIFT-OFF LENGTH

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Abstract

This paper reports on the experimental investigation of the flame lift-off length for five different orifice diameters (∅0.100, ∅0.130, ∅0.160, ∅0.190, and ∅0.227 mm) of a diesel injector nozzle. The flame lift-off was determined from the measurement of 308 nm OH chemiluminescence for different fuel injection pressures using commercial diesel fuel and a Common Rail fuel injection equipment of passenger car size. The fuel injection pressures were 450, 900, and 1350 bar. The experiments were conducted at air pressures of 30, 50, 70, and 90 bar and at an air temperature of 750 K in a constant pressure spray chamber. It was observed that the flame lift-off length increases with increased injection pressure and increased orifice diameter.

Introduction

The emission legislation of the future will be very stringent and demand much lower emissions of nitrogen oxides and soot for diesel engines. The emission formation in a diesel engine is mainly governed by the fuel spray and mixing processes that are caused by the fuel injection. Many parameters influence the spray formation, e.g. orifice diameter, injection pressure, multi-injection events, gas density, combustion chamber shape, gas motion etc. Besides the spray formation and ignition, the combustion of the spray is also important. A certain time after start of combustion the diffusion (or mixing controlled) flame will stabilize at a constant distance from the fuel injector nozzle. This distance, from the nozzle orifice to the start of the flame, is called the "flame lift-off length". Within this distance, a substantial amount of air is entrained into the spray. Since more entrained air provides locally leaner conditions within the spray, less fuel-rich zones that can form soot are created. Hence, the larger the distance, the leaner the spray and less soot formed. A larger flame lift-off length should thus be beneficial.

The flame lift-off length has been investigated in the case of gas jets by several researchers described in [1, 2]. The results show that, with increased gas injection velocity, the flame lift-off length increases approximately linearly with the injection velocity and, with sufficiently high gas injection velocity, the flame could be extinguished. Quenching the flame may also occur in the opposite case with a too low gas injection velocity. With respect to diesel injection, one of the first flame lift-off length investigations was made in a numerical study in 1994 [3]. The results implied in this case as well that an increase in injection velocity led to a larger flame lift-off length. Some later experimental investigations [4] have used a constant volume chamber in which a pre-mixed gas is combusted in order to generate a hot diesel-like environment into which the diesel fuel is injected and ignited. This paper reports on an experimental study of the flame lift-off length using a constant pressure chamber where the air is preheated before reaching the chamber in which the diesel fuel is injected and burned.

Experimental set-up

Flame lift-off lengths were determined using OH chemiluminescence emissions around 308 nm. In the kinetic description of OH chemiluminescence it is assumed that excited OH radicals, OH^*, are created through the reaction $CH+O_2 \leftrightarrow CO+OH^*$ [5]. The light emitted from a flame at 308 nm has a strong OH chemiluminescence component, and this is a good marker of high temperature, stoichiometric combustion, which is the case for spray combustion [4, 6]. The excited OH^* molecules can lose their excitation energy either by collisional relaxation, $OH^*+M \leftrightarrow OH+M^*$, where M is another molecule absorbing energy from OH^*, or by emission of a photon, $OH^* \rightarrow OH+h\nu$, the latter being the OH chemiluminescence used in this work. Comparison of measured and numerically predicted chemiluminescence is discussed in [7].

The experimental set-up can be rather simple owing to the chemiluminescence method. The set-up consisted of a constant pressure chamber, a fuel injection system, a fuel injection control box, a 308 nm filter, an intensified CCD camera and a computer to synchronize the camera with the injector.

In the spray chamber of constant pressure, gas (air) flows continuously through the chamber. The velocity of the gas that passes through is relatively low (around 0.1 m/s) as compared to the velocity of the injected spray. The spray chamber receives pressurized air from a compressor. The air temperature can also be regulated up to 900 K.

The spray chamber has four quartz windows perpendicularly placed to allow optical access. The air is introduced at the top and fuel is also injected in the top by a fuel injector placed in the center of the air stream. The fuel injection equipment consisted of a Common Rail fuel injection equipment of a passenger car size with a capability of a maximum of 1600 bar rail pressure. The Common Rail pump was driven by an electric motor.

A control box from Genotec controlled the fuel injection event in the Common Rail injector. The capability of the control box is three injection events in a row with a possibility of individual settings for spacing, rising, full lift and falling times. The fuel injection event in this investigation was set to have one injection with a rise time of 0.5 ms up to full lift. The injection at full lift was then withheld for 2.5 ms before closing with a falling time of 0.5 ms.

The image grabbing was done by a LaVision DynaMight 2000 CCD camera. This intensified CCD camera had a 94-mm f/4.1 quartz photo lens (SODERN Cerco UV) and a CCD array of 512 by 512 pixels in size. The dynamic range was 16 bits. The light emitted by the OH chemiluminescence falls in a region around 308 nm. A bandpass interference filter centered at 308 nm with a 15 nm FWHM (Full Width Half Maximum) was thus placed in front of the camera. A schematic overview of the system is given in Fig. 1.

Five diesel injector nozzles with one orifice placed in the axial direction were tested. The nozzle orifice diameter differed between the nozzles and ranged from a diameter of 0.100 mm up to a diameter of 0.227 mm. All nozzles had 13.5% HE ground. The nozzles were tested at a 100 bar differential pressure without a needle and in a transient test with different injection durations and different rail pressures to obtain the fuel flow. Table 1 shows the nozzle specifications.

Orifice Diameter [mm], D	0.100	0.130	0.160	0.190	0.227
Orifice Length/Diameter, L/D	10	7.70	6.25	5.26	4.41
Fuel flow @ 100 bar differential test [liter/min]	0.03	0.08	0.13	0.19	0.31
Discharge Coefficient, Cd	0.404	0.630	0.697	0.715	0.826

Table 1. Nozzle specification.

The experimental matrix for the five nozzles consisted of three fuel injection pressures, $P_{\text{Injection}}$, of 450, 900 and 1350 bar, and four gas pressures (back pressures), P_{Chamber}, in which the spray was injected. The gas pressures were varied in steps of 20 bar ranging from 30 bar up to 90 bar, at a constant gas temperature of 750 K. The fuel injection velocity can be calculated by Eq. 1.

$$U = C_D * \sqrt{2 * \frac{(P_{Injection} - P_{Chamber})}{\rho_F}} \tag{1}$$

The discharge coefficient, C_D, decreases with decreased orifice diameter, D. The orifice length to diameter, L/D, is at the same time increased leading to relatively greater influence from the orifice walls. This larger friction loss and a larger relative influence from “vena contracta” reduce the fuel flow. It has been shown for nanojets with orifice diameters ranging from 2 to 6 nm that the injection pressure needed to overcome the friction had to be 5000 bar [8]. The C_D drop for smaller orifices results in a lower injection velocity, U.

Commericial diesel fuel was used in this investigation. The diesel fuel had a sulphur level of 110 ppm-wt, a lower heating value of 42.91 MJ/kg and a density, ρ_F of 0.8368 kg/litre at 15 °C. The cetane number was 51.8, the stochiometric air-to-fuel ratio 14.58 and the viscosity was 2.58 mm^2/s at 40 °C. The boiling temperature ranged from 192 °C to 364 °C.

Fifty images were taken at all different test points in the test matrix and then averaged. The timing of each of the 50 images was such that the exposure took place during 0.8 ms, starting at 2 ms after the start of injection. An average image of the OH chemiluminiscence for the orifice diameter of 0.130 mm at 50 bar gas pressure (back pressure) and a fuel injection pressure of 900 bar is shown in Fig. 2. The corresponding intensity profile as a function of distance from the injector is shown in Fig. 3. This profile contains the integrated intensity of the full flame.

The flame lift-off was determined by first subtracting the background from the images. The flame lift-off length was then determined as the distance from the nozzle tip along the profile to the point at which the OH chemiluminescence intensity had reached 5 % of the peak intensity of the profile.

Results

When the gas pressure (density) into which the fuel is injected is increased, the injection velocity is reduced because of the decrease in the pressure drop across the nozzle orifice, see Eq. 1. This reduction in injection velocity is not large since the injection pressure is much higher than the gas pressure. The increase in gas pressure leads to a higher density where the molecules are more closely spaced leading to higher drag forces. The increased gas pressure leads also to an increase in secondary break-up. The liquid fuel penetration is reduced by these effects [9]. The shorter fuel penetration makes the burning of the fuel occur closer to the orifice and, for this reason, the lift-off is affected by higher gas pressure, see Figs. 4 and 5. Another effect of increased gas density (pressure) is that the ratio between gas density and fuel density increases. This leads to a wider spray angle that gives the fuel greater exposure towards the surrounding gas (air) [9] and increases the mixing rate between gas and fuel [10]. It also increases the entrainment of gas into the fuel rich spray [11, 12], which leads to shorter ignition delay and which would also result in a shorter flame lift-off length.

The injection velocity has a great influence on the flame lift-off length. Increasing the fuel injection pressure leads to increased injection velocity (kinetic energy). The injected fuel will penetrate longer in the chamber for a certain time [11] during which the fuel evaporates, mixes with the surrounding hot gas and ignites. The diffusion flame will thereby be located further away from the nozzle tip, resulting in a longer flame lift-off length than would be the case with a low injection velocity (Figs. 4 and 5). Figure 5 shows the simulated result of flame lift-off length, normalized with the orifice diameter, from Karlsson *et al.* [3] for the case of 50 bar and 800 K. The linear slope shows the same trend for the experimental data in this study when the curves are extrapolated. The curves will then go through origo for this 50 bar gas pressure case. This is not the case for the other gas pressures tested, however (see Figure 4). Logically, the flame life-off length here would go through origo, but this indicates that the flame life-off length is probably not linear to the injection velocity for lower injection velocities than were tested.

Figure 5 shows the dependence of the flame lift-off length on the orifice diameter. A larger orifice diameter leads to a larger flame lift-off length. With an increase in diameter, the area increases with the square to the diameter and the discharge coefficient, C_D, will also increase, as discussed earlier. This leads to a rapid increase in the fuel mass flow, $\dot{m}$, which can be calculated by Eq. 2.

$$\dot{m} = C_D * A_N * \sqrt{2 * \rho_F * (p_{Injection} - p_{Chamber})} \qquad (2)$$

The higher fuel mass flow has a higher total kinetic energy that leads to a larger liquid fuel phase penetration. Owing to a larger fuel core, the entrainment of surrounding hot gas will be relatively lower than for a smaller orifice diameter and the evaporation cooling lost to the surrounding gas will be higher because of the increase in injection rate. The mixing rate of the fuel and surrounding gas will also decrease [10]. This results in a longer ignition delay [13, 14] and a longer flame lift-off length. Normalizing the flame lift-off length with the orifice diameter leads to a relatively larger flame lift-off length by a decrease in the orifice diameter, see Fig. 5. Since at the same time the fuel mass flow decreases, this would lead to a relatively leaner fuel spray, as reported by [4, 12]. The resulting effect of the leaner conditions in the spray leads to less engine-out soot from a diesel engine [15]. All of the orifice diameters investigated show a higher value of flame lift-off length than the simulated results, at 50 bar gas pressure, of Karlsson *et al.* [3]. Karlsson used n-heptane instead of diesel fuel, which has a similar cetane number but a lower latent heat value and a temperature of the surrounding gas that was 50 K higher than in this study.

The results obtained in this study show a generally longer flame lift-off length as compared with the results of Siebers [4], who used a higher fuel temperature of 436K and higher gas temperature ranging from 800K to 1300K. The higher temperature of the surrounding gas leads to an increased enthalpy transport to evaporate and ignite the fuel and results in shorter flame lift-off lengths. Examinations of flame lift-off lengths for a gas jet in an industrial furnace have also shown the impact of gas temperature [16]. The ignitability properties of the diesel fuel can also contribute to a difference in absolute numbers for the flame lift-off length.

Conclusion

The flame lift-off length was determined by the use of OH chemiluminescence from a burning diesel flame. The OH chemiluminescence was obtained by filtering the wavelength band around 308 nm. Five different orifice sizes were examined. The following conclusions could be drawn as the injection pressure and gas pressure were varied.

- The flame lift-off length decreases with increasing gas pressure (back pressure) because of a lower injection velocity and less penetration of the liquid part of the fuel. The flame location and lift-off will thus be closer to the nozzle.
- Increasing the injection pressure (injection velocity) increases the flame lift-off length. The higher injection pressure leads to a higher kinetic energy that sends the fuel farther from the nozzle during the time required for the injected fuel to be evaporated and ignited.
- The flame lift-off length increases with an increase in the diameter of the orifice. Increasing the orifice diameter will increase the fuel mass flow (the flow area increases as the square to diameter, along with the increase in C_D) which leads to a relative lower entrainment of air into the fuel spray. With an increase in the size of the orifice the kinetic energy of the spray increases, leading to longer fuel penetration and flame lift-off. The cooling losses are higher for a larger fuel mass flow and the specific turbulent kinetic energy is lower for a larger orifice, which leads to a lower mixing rate and thereby to a longer ignition delay and larger flame lift-off length.
- Normalizing the flame lift-off length with orifice diameter indicates the relatively larger lift-off length with a smaller orifice diameter, which would be beneficial from an air entrainment standpoint. The normalization shows a higher value for all orifice sizes than the flame lift-off length simulated by Karlsson *et al.* [3]. Extrapolation of the curves shows a linear relation between the flame lift-off length and injection velocity.
- The rapidly decreasing discharge coefficient with decreased orifice diameter puts a limit on the useable orifice size.

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Nomenclature

A_N	$[m^2]$	Nozzle orifice area
C_D		Discharge coefficient
D	[m]	Orifice diameter
L	[m]	Orifice length
$P_{Chamber}$	[Pa]	Chamber pressure (gas pressure)
$P_{Injection}$	[Pa]	Fuel injection pressure
$\dot{m}$	[kg/s]	Fuel mass flow
U	[m/s]	Injection velocity
ρ_F	$[kg/m^3]$	Density of fuel

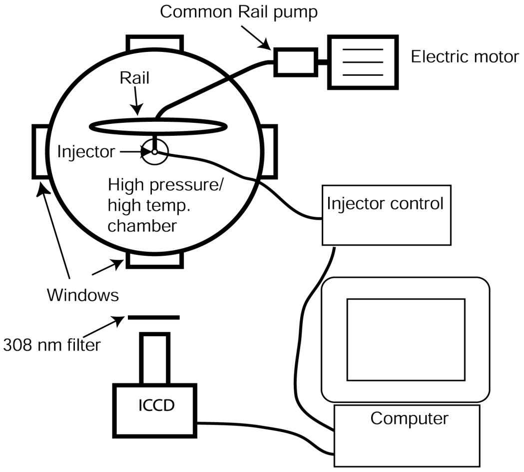

Figure 1. Experimental set-up.

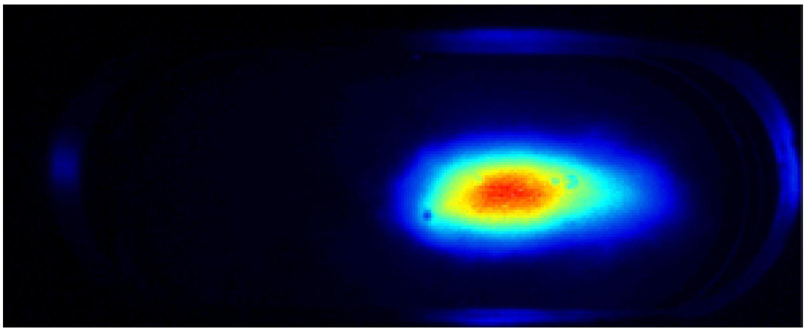

Figure 2. Image of OH chemiluminiscence for the orifice diameter of 0.130 mm at 50 bar gas pressure and 900 bar fuel injection pressure. The injector nozzle tip is located at the left side of the image.

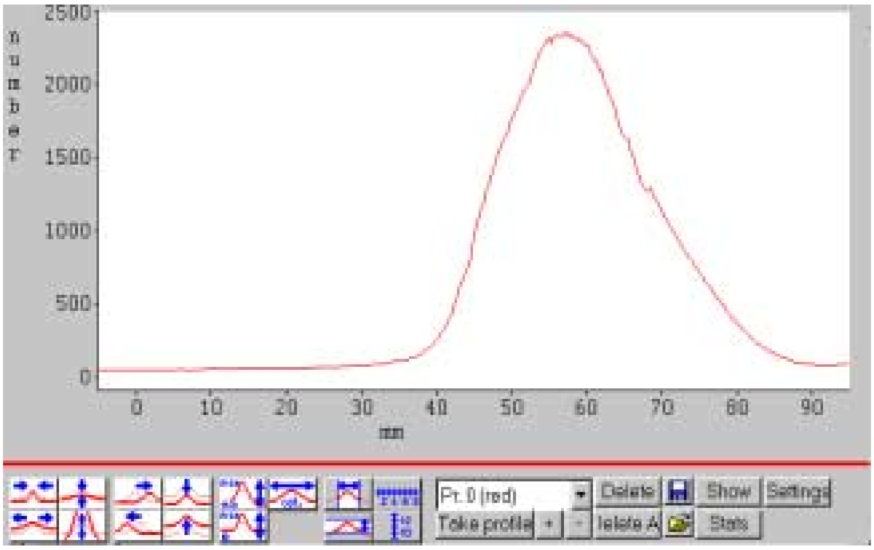

Figure 3. Intensity profile of the image in figure 2. The flame lift-off length in the actual image was determined to be 38.25 mm, where the relative intensity increase has reached 5 % of the peak intensity.

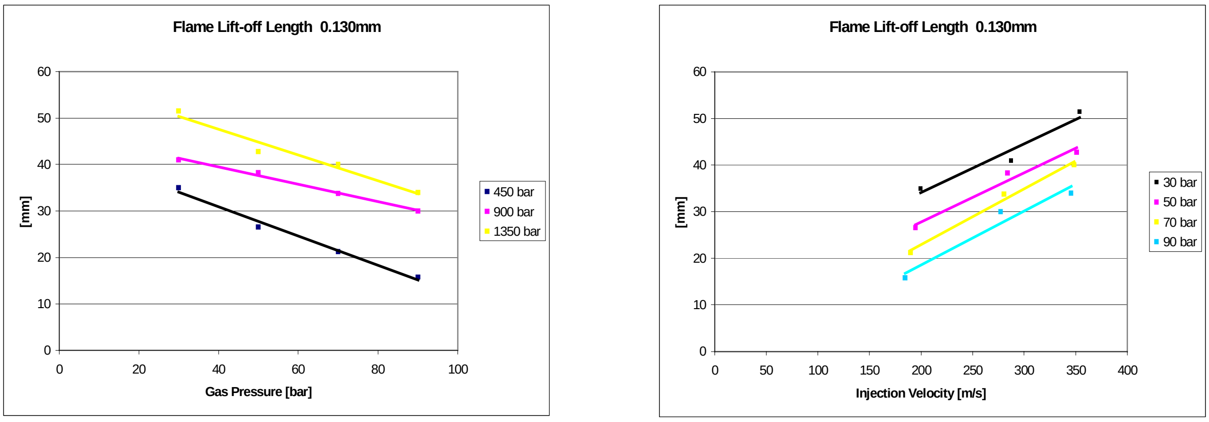

Figure 4. Flame lift-off length for the orifice diameter of 0.130 mm. To the left, the flame lift-off length as a function of the gas pressure for the three different injection pressures is shown. To the right is the flame lift-off length as a function of injection velocity for the four different gas pressures.

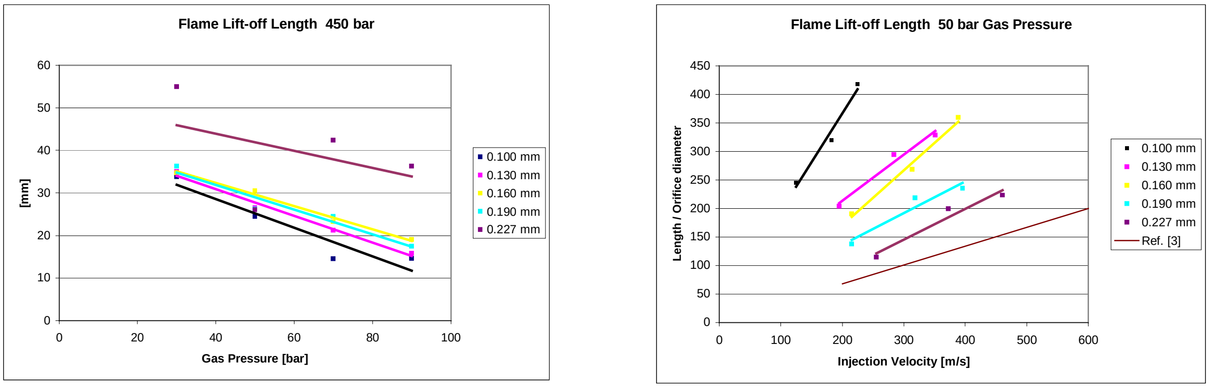

Figure 5. Flame lift-off length for all orifice diameters. On the left, the flame lift-off length at the injection pressure of 450 bar for all orifice diameters is shown. To the right, the flame lift-off length normalized by orifice diameter for all diameters at 50 bar gas pressure is shown together with the simulated result from ref. [3].