Visualization of diesel fuel sprays in a high pressure, high temperature cell under engine-like conditions

R.J.H. Klein-Douwel, M. Douch, L.M.T. Somers, W.A. de Boer, and R.S.G. Baert
Section Combustion Technology/Internal Combustion Engines
Department of Mechanical Engineering
Eindhoven University of Technology, The Netherlands

Abstract
Spray formation from diesel fuel injection through a heavy duty multi-hole injector is studied in a newly developed high pressure, high temperature cell, using high speed shadowgraphy. The spray spatiotemporal evolution is found to reproduce well and is studied and geometrically analysed using a combination of methods found in literature. The geometrical analysis method is robust, spray penetration has been found to be proportional to \( t^b \) with \( b \approx 0.4 \), and the macroscopic spray angle \( \theta_{cone} \) varies with time during injection. The precombustion technique is used to obtain engine-like conditions.

Introduction
Meeting increasingly stringent exhaust emission regulations while maintaining or improving fuel efficiency is the main driver for modern diesel engine development. To this end new technologies are introduced to the diesel engine continuously. New, higher pressure, flexible, and electronically controlled fuel injection technology is prominent amongst them. Because of its innovative characteristics this technology enables new ways to influence the fuel-air mixing process and hence the combustion and the emissions formation. To make full and optimum use to the potential of this technology, a better and more fundamental understanding of the interaction between fuel injection and spray propagation is needed.

A lot of work has already been published on fuel spray propagation, with pressure and temperature values ranging from laboratory conditions to those found inside an engine. Most of this work was on sprays from light duty (passenger car type) fuel injection systems [1, 2, 3, 4] and heavy duty injectors [5, 6, 7, 8], often using special fuels and/or special single hole research nozzles. Only some studies were on high pressure heavy duty (haulage truck type) fuel injection systems [6, 8] and multi-hole injectors [7], but also there conditions where not always realistic, for instance because ambient gas pressure and temperature were not representative [6] or because single hole nozzles were used [8]. From literature it is known that the flow pattern inside a single hole injector deviates from that inside a multiple hole injector [9].

In addition, in most of these spray studies, data acquisition rate has been limited to one snapshot per fuel injection [1, 2, 3, 4, 5, 6, 7, 8, 10, 11, 12, 13]. Only a few studies have employed high speed photography [14].

Finally these studies also show many differences in the way the spray data are processed and analysed.

Specific Objectives
The goal of the research presented here is analysis of spray growth and dynamics. The emphasis of the first step in this work is on high speed shadowgraphy of fuel injections, enabling detailed spatial and temporal study of every single injection event, and on developing subsequently a robust geometrical spray analysis method. The latter is performed using a combination of methods found in literature, in an attempt to provide a consistent method describing spray propagation.

Most experiments have been performed with fuel injection into warm \( N_2 \) (200 °C), but some preliminary
results of fuel injection in a hot environment are also discussed.

Experimental setup

The Eindhoven high pressure, high temperature cell has a cubic inner volume of $108^3 \text{mm}^3$ and can withstand a maximum pressure of 10 MPa. The windows are made of 50 mm thick quartz and allow an unobstructed view of 80 mm diameter (windows 100 mm ø). For these experiments three windows are mounted in the cell: an entrance and exit window and a side window, all of equal size. All cell walls are electrically heated to 200°C, except the top surface, in which the injector is mounted. This is cooled to about 60°C to prevent premature fuel vaporisation.

The fuel used is regular, commercially available Diesel fuel, in order for the experiments to be as realistic as possible. The fuel pump is an air driven pump connected to a common rail system, capable of delivering a rail pressure of up to 200 MPa. The injector is an 8-hole Bosch heavy duty Diesel engine Common Rail satch-hole injector, with 0.184 mm ø orifices and a length/diameter ratio of $\approx 5$. In order to study a single fuel spray from this 8-hole injector, a thimble is constructed, which covers all but one orifice. The fuel delivered by the 7 covered orifices is led to the bottom of the cell by a drainpipe.

The setup for shadowgraphy is straightforward [15]. The signal is recorded by a high speed camera (Kodak Ektapro HS Motion Analyzer, model 4540). The camera is used at an image acquisition rate of 4500 Hz, the temporal resolution is therefore 222 µs. A spatial resolution of 0.4 mm/pixel is obtained, images have an 8-bit dynamic range and are 256 × 256 pixels. A typical example of a shadowgraph image is given in figure 1.

Experimental Results

Figure 2 shows an image sequence of a single fuel injection. Since the high speed camera already acquires a few frames before injection has started, these frames are used as a background signal and subtracted from successive frames. From the resulting images a region of interest is selected for further analysis. The opening time for the injector is 5 ms, which would cover 22.5 images, but the first part of the fuel injection is not observed in shadowgraphs because the light path is obstructed by the thimble.

The second to the tenth image in figure 2 (taking 2 ms in time) reveal that the base of the spray appears to exhibit almost straight edges, whereas at later times this part of the spray starts to become wrinkled, while the injector is still open. There are indications that this wrinkling may be caused by a temporary reduction in
rail pressure, which in turn would reduce the momentum input into the spray. Currently the common rail system is adjusted to minimise this effect.

**Geometrical analysis**

As found in literature, the edge of a spray is often determined by obtaining a contour at a certain fraction of the maximum signal intensity (from shadowgraphy or otherwise), where the threshold level used can vary from author to author. The cone angle can then be obtained by fitting a straight line through the base of this contour or rather taking the external tangent to the contour, but just over which distance this fit or tangent should be taken is not unambiguous [5, 6, 7, 8, 10, 12, 13, 2, 4].

The bisector of the cone angle can then be taken to be the spray axis [4], but other definitions are used as well. In some studies the tip of the spray is assumed to be at the intersection of the spray axis and the spray contour [1, 4], but in most studies the spray signal is projected onto the axis and a fixed fraction of the maximum projected signal intensity yields the position spray tip, the exact fraction used being again not unambiguously determined [5, 6, 7, 8, 10].

The method used in this work for geometrical analysis of the obtained image sequences is best illustrated by the example in figure 3. The begin and end points of an arbitrary axis are chosen such that it overlaps as good as possible with the real axis of the spray, which is not a priori well known. During analysis, an iterative method is used to optimise the axis coordinates. Figure 3a shows a region of interest with axis. Lateral profiles are obtained for every axial distance \( x \) (pixel row).

In such a lateral profile, an example of which is shown in figure 3b, the lateral distances \( y_1 \) and \( y_2 \) are determined at which the 90% level of intensities is reached. A threshold level of 90% is chosen so as to encompass most of the spray without being sensitive to possible noise in the (bright) background. Thus two contours \( y_1(x) \) and \( y_2(x) \) are obtained (see figure 3a).

Since the first part of the spray shadow is overlapped with the thimble shadow, the visible part of the spray will have a noticeable minimum width. This determines two offset values \( y_{1,\text{offset}} \) and \( y_{2,\text{offset}} \), where...
The averaged result of 5 nominally identical experiments is later part of spray development can be observed, where fitted to this relation (figure 5a, right graph), where the angles $\theta_1(x)$ are more or less constant for a significant part of the spray length. This indicates that a representative cone angle $\theta_{cone}$ can be determined for every image of a given time $t$. This is achieved by applying a median filter (in order to be insensitive to outliers) to $\theta_1(x)$, yielding $\bar{\theta}_1(x)$, and $\theta_{cone} = |\min(\bar{\theta}_1(x))| + \max(\bar{\theta}_2(x))$. The intersection of the two line pieces determining $\theta_{cone}$ corresponds reasonably well with the actual position of the injector orifice.

The length of the spray is determined by projecting the shadow onto the axis, id est lateral integration, see figure 4b. The start of the visible spray shadow is taken to be at the 10% level, but this value $x_{start}$ is only used as a limit before which calculations are physically meaningless. The end of the spray could be determined to be at a position where a (possibly different) final threshold level is met, preferably with the threshold as low as possible. While this may yield useful results in most cases, this method would fail in case there is a slowly decaying plateau which starts above the final (low) threshold. Therefore the derivative of the laterally integrated shadow profile is used to avoid this problem. Beyond the point where the shadow profile decreases to the final threshold (in figure 4b the 8% level is indicated) the axial position is determined where the absolute value of its derivative becomes smaller than a preset limit (in our case 0.015 is used). The above-mentioned values of 8% and 0.015 have proven to be good choices, as determined by testing multiple injection image sequences.

Simple geometrical calculations show that a projection error, due to possible non-perpendicularity of the spray axis to the light beam axis, is negligible.

Using the above described geometrical analysis method, image sequences obtained at rail pressures of 100 MPa and 150 MPa were processed to reveal temporal characteristics. The spray penetration $l$ versus time is shown in figure 5a on a log-log scale. Since high speed recording starts before the fuel injection begins, there is an offset $t_0 > 0$. Likewise, since the coordinate origin is arbitrarily chosen, there is an offset $\chi_0 \approx -17$ mm in determining the spray length, before which the spray shadow cannot be detected. The spray break-up length is computed to be smaller than $|\chi_0|$. Therefore only the other part of spray development can be observed, where a relation $l - \chi_0 = a(t - t_0)^b$ is expected [16]. The averaged result of 5 nominally identical experiments is fitted to this relation (figure 5a, right graph), where the offsets $t_0$ and $\chi_0$ have been varied to obtain the best fit to a straight line. During fitting, only the first one or two points prove to be very sensitive to $t_0$ and $\chi_0$. For $t - t_0 > 1$ ms hardly any influence of $t_0$ and $\chi_0$ on the fit is noticeable. Values of $t_0 = 0.55$ ms and $\chi_0 = -17$ mm are obtained. From the slope of the resulting fit, a time dependence of $b \approx 0.4$ is determined. Processing further injection data from more measurements (not shown), a value of $b \approx 0.40 \pm 0.05$ is estimated for our experiments.

The temporal behaviour of $\theta_{cone}$ is shown in figure 5b. For both rail pressures used in these experiments, it is clear that $\theta_{cone}(t)$ increases rapidly from small values to a more or less constant value of $25^\circ \pm 3^\circ$ for 100 MPa rail pressure and $24^\circ \pm 3^\circ$ for 150 MPa. This indicates that the rail pressure has only a small influence on the cone angle.

Figure 5: (a) Spray lengths versus time (rail pressure 150 MPa). Left: 5 individual injections and their average, right: fit of $l - \chi_0 = a(t - t_0)^b$ to the average (notice the log-log scale), a value of $b = 0.39$ is obtained. Note that after about 3 ms the edge of the window is reached; (b) cone angles for rail pressures of 100 MPa (left) and 150 MPa (right) for individual injections (values after end of injection are shown for reference only).

**Precombustion**

The results shown thus far have been obtained for injections into relatively cold $N_2$ (200 °C). In order to obtain
Figure 6: (a) Pressure trace (upper curve) recorded during the ignition of the indicated mixture of \text{C}_2\text{H}_4, \text{O}_2, \text{and N}_2 and the temperature derived from it (lower curve); (b) shadowgraph of fuel injected after precombustion at a temperature of \approx 900 \text{ K} and a gas pressure of \approx 1.2 \text{ MPa}. The fuel is already partially evaporated (the narrow white features are due to inhomogeneities in the expanding flame front).

Conditions similar to those inside an engine cylinder at the time of injection, the so-called precombustion technique is used: the cell is filled with an explosive mixture of (some or all of) \text{H}_2, \text{C}_2\text{H}_2, \text{C}_2\text{H}_4, \text{O}_2, \text{and N}_2 at relatively low pressure and this mixture is then ignited, which causes the pressure and temperature to rise (rapidly) above realistic engine conditions [8]. Figure 6a shows a pressure trace of the ignition of \text{C}_2\text{H}_4, \text{O}_2, \text{and N}_2. The temperature is calculated using the ideal gas law. After a short time, there is a window where pressure and temperature have reached engine-like conditions and fuel can be injected. Depending on any \text{O}_2 left and on dilution with \text{N}_2, the injected fuel will give a non-reacting or reacting spray. In figure 6b a shadowgraph of a non-reacting fuel spray is shown, injected after precombustion at a temperature of \approx 900 \text{ K} and a gas pressure of \approx 1.2 \text{ MPa}. The fuel is already partially evaporated, resulting in a much less dense shadow than in the experiments described above, which were performed at a temperature of only 473 \text{ K}. Note that the first part of the shadow (left) is darker than the later part. The expanding spherical flame front is already beyond the volume of space in which the fuel is injected, but since the signal of the shadowgraphy technique is integrated along the line of sight, small inhomogeneities in the flame front reveal themselves as narrow white features, visible in figure 6b as well.

**Discussion**

The method used to determine the spray contour at the 90\% level is similar to that used by Schneider [1]. The methods to determine the spray length and cone angle, however, are different in details.

Close to the spray tip, the shadow intensity is not much lower than the background luminosity, hence the lateral position \gamma_i of the contour is much more sensitive to possible noise in either shadow or background. It is observed in some images that the contour does not close properly at what is roughly determined by eye to be the tip of the spray. Therefore not the contour \gamma_i(x) is used to determine the spray length [1, 4], but the separate method described above, which turns out to be more accurate in these experiments.

In the work of Schneider [1], the tip of the injector is visible in the images and \theta_i(x) is determined in a way similar to the one presented here, but using the injector orifice as origin for calculations. Since in our experimental setup the injector tip is not visible and the spray already has a non-zero width when first visible, two offsets are established, which represent lines parallel to the spray axis, and \theta_i(x) is calculated with respect to these lines. A more detailed sensitivity analysis of the geometrical analysis method used in this work will be given in a forthcoming paper.

Many studies (see for instance references [16, 17, 18]) found a correlation \(l \propto t^{0.5} (\tan \theta_{ccone}/2)^{-0.5} \) after fuel spray break-up. Here \( b \approx 0.40 \pm 0.05, \) rather than \( b = 0.5, \) is found. A possible factor contributing to this difference may be due to the value of \( \theta_{cone}. \) In most of the aforementioned studies, the implicit assumption is that \( \theta_{cone} \) is constant with time, but this is clearly not the case in our experiments (figure 5b). The change in \( \theta_{cone} \) will result in an effectively different power \( b \) for the temporal behaviour of \( l. \) Recently, Sazhin and coworkers [19] have observed a power dependence of \( b < 0.5 \) as well.

**Conclusions**

A high pressure, high temperature cell with very good optical access has been constructed in which fuel injection from a heavy duty diesel engine injector is studied under engine-like conditions. The spray behaviour is found to be well reproducible. As a first step in detailed spray studies, high speed shadowgraphs of fuel injection have been obtained, which allow accurate analysis of spatial and temporal evolution of the spray (not just a single shot recording per injection). A general and consistent method for determining macroscopic spray geometry characteristics (spray length and cone angle) has been developed.

The spray length has been found to be proportional to \( l^b, \) where \( b \approx 0.4. \) At first instance this might be
found to disagree with the value of $b = 0.5$ as often derived from models, but the here observed time-dependence of the cone angle $\theta_{cone}(x, t)$ has to be included as well as second order effects found in recent modelling.

Finally, the precombustion technique has been used to create heavy duty engine-like conditions, but further research in this area is still needed in the current experimental setup.

Acknowledgments

Discussions with the DAF company are gratefully acknowledged, as well as STW for financial support and D. Bindraban for technical support.

References