Macroscopic diesel fuel spray shadowgraphy using high speed digital imaging in a high pressure cell

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Abstract

Spray formation from diesel fuel injection through a realistic heavy-duty multi-hole common rail injector is studied in a newly developed high pressure, high temperature cell, using digital high speed shadowgraphy at 4500 frames per second. Care is taken to establish accurate synchronisation between camera and injection system and because of the relatively large exposure time, an effective camera image time is calculated for every frame. Further emphasis is given to determining the actual start of fuel mass injection by comparing (for each injection) a predetermined, rail pressure dependent needle relaxation distance to the actual needle lift signal. The spatiotemporal evolution of the spray is found to reproduce well in general, but often sprays suffer from short-lived, small, laterally moving anomalies, which influence axial motion and the spray cone angle. High speed shadowgraphy allows this to be observed and taken into account. After an overview of methods found in the literature, an algorithm for geometrical analysis is presented, which is based on an extension of a combination of those methods. In this algorithm, a local spray angle $\theta_i(x)$ is determined from lateral cross-sections at 80% of the shadow level in order to encompass most of the spray without being too sensitive to background noise. The macroscopic cone angle $\theta_{\text{cone}}$ is derived from the approximate constancy of $\theta_i(x)$ over a relatively long axial distance. Spray penetration is obtained by lateral integration of the spray shadow. A procedure for accurate correlation of spray growth with time shows that the growth is proportional to $t^b$ with $b = 0.57 \pm 0.02$ for a common rail pressure of 150 MPa and a gas density $33 \text{ kg/m}^3$ ($\text{N}_2$ at room temperature). The exact value of $b$ is very sensitive to uncertainties in synchronisation and the start of injection determination. The spray cone angle $\theta_{\text{cone}}$ is not constant, but varies with time during an injection, mainly as a result of spray shape changes.

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1. Introduction

Meeting increasingly stringent exhaust emission regulations while maintaining or improving fuel efficiency is the main drive 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 combustion and emissions formation. In order to make full and optimum use of the potential of this technology, a better and more fundamental understanding of the interaction between fuel injection and spray propagation is needed.

For the diesel engine development engineer knowledge of spray shape evolution is very important: when deciding on the fuel injection equipment to match a given combustion concept her (his) objectives are optimum fuel distribution within the combustion chamber together with high fuel air mixing rate. Similarly, fuel spray growth analysis is used increasingly in assessing the quality of new fuelling equipment [1,2].
In recent years, new, electronically controlled fuel injection technology is being introduced that combines increasing flexibility and ever higher maximum injection pressures (up to 250 MPa has recently been reported [3]). The possibility of more sophisticated fuel injection strategies (e.g. multiple short injections [4]) under conditions different from those in conventional engines (for instance late in the exhaust stroke for exhaust temperature increase or early in the compression stroke aimed at homogenous charge compression ignition) has resulted in a burst of new research activities aimed at answering new unresolved questions. The analysis and characterization of the effect of charge compression ignition has resulted in a burst of early in the compression stroke aimed at homogenous the exhaust stroke for exhaust temperature increase or from those in conventional engines (for instance late in. Although this emphasizes the need to carefully determine the timing of the different images, little information on this subject can be found in the literature. In fact, in some studies a fictitious start of injection is determined from a priori assumptions on the initial spray penetration rate [12,21].

Typically the spray length (penetration) and spray angle (also called macroscopic or cone angle) are used for characterising a (mature) spray. In the literature several definitions of these parameters can be found and several algorithms for obtaining them have been suggested, but often no consensus is found, hampering comparison of the results.

Finally, several studies have tried to correlate spray penetration rate with time. Given the differences in the above-mentioned imaging techniques, definitions and processing algorithms, it is no surprise that they show important differences in the observed increase of spray penetration and cone angle with time.

This paper reports on the use of a typical high speed video system for the analysis of the evolution with time of the shape of sprays produced by a modern, heavy-duty common rail injector. Emphasis is (amongst others) on the method used to carefully synchronise the spray images with time, on dynamic phenomena and on relating spray growth to time. Furthermore, starting from an overview and assessment of different definitions and methodology mentioned in the literature for spray shape analysis, a robust methodology for spray analysis is presented. This paper also presents the result of applying this methodology to a limited number of injection experiments and compares these results with data from the literature.

2. Experimental setup

Spray research has been performed in a number of test rigs: special research engines, rapid compression machines, flow rigs and constant volume, high pressure, high temperature cells (also known as bombs). The constant volume test cell is considered a best compromise for fundamental heavy-duty diesel spray research as it combines good optical access, large observation area and good control (reproducibility) of fresh charge conditions before injection. For reaching a representative pressure and temperature level in such a device, different solutions have been proposed. Some bomb rigs use direct heating of the walls of the test cell, see...
for instance Refs. [22–24]. Because of material strength limitations this tends to put a limit on the maximum temperature and pressure that can be reached (a maximum of 905 K at 7 MPa – prior to combustion – was demonstrated in Ref. [24]). Other bomb test rigs have used a constant, small flow of fresh gas to provide a clean environment for each injection [25,26]. This approach results in similar limitations on pressure and temperature. Furthermore, both approaches result in significant radiative heat transfer from the hot test cell walls to the injected fuel. Other designs use a pre-injection of fuel which ignites before the main injection takes place [8–10]. This, however, entails the possible risk of charge stratification. A rather clean environment can be obtained by the so-called precombustion technique, in which the cell is filled with a combustible gas mixture which is ignited just before injection [12,21,27]. This is also the approach taken in the experimental setup used in the work presented here.

2.1. High pressure cell and fuel injection

The Eindhoven high pressure, high temperature cell is designed to create realistic heavy-duty engine-like conditions. It has a cubic inner volume of $10^7 \, \text{mm}^3$ and can withstand a maximum pressure of 35 MPa, depending on window material. Currently quartz windows are employed, of 100 mm $\times$ 50 mm thickness, limiting the maximum pressure to 10 MPa. The large windows enable following the spray development for a relatively long time. For the experiments presented here three windows are mounted in the cell: an entrance and exit window and a side window, all of equal size. Although all cell walls can be electrically heated to 200 °C, current experiments are performed at room temperature, which also allows a higher, more engine-like gas density for the same cell pressure. If the cell walls are heated, the injector holder is cooled to about 80 °C to prevent premature fuel vaporisation.

Fig. 1a shows a schematic of the fuel injection equipment. The fuel used is regular, commercially available Diesel fuel, in order for the experiments to be as realistic as possible. Fuel specifications are given in Table 1. 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 common rail sack-hole injector, with 0.184 mm orifices and a length/diameter ratio of $\approx 5$. In these experiments the injection duration is typically 5 ms. In order to study a single fuel spray from this 8-hole injector, a kind of thimble is constructed, which covers all but one orifice. The fuel delivered by the seven covered orifices is led to the bottom of the cell by a drainpipe.

Fig. 1b gives a typical recording of the needle lift and the rail pressure during injection. Due to the characteristics of the fuel supply system, the actual rail pressure immediately before injection varies slightly from one injection to another and the maximum needle lift reached varies accordingly, in a linear fashion. The reproducibility of the shape, however, of both the needle lift and the rail pressure curves, is very good. When performing 15 nominally identical injections, uncertainties are $\leq 0.5\%$ for the rail pressure during entire injection (growing up to 4% after
end of injection) and $\leq 0.3\%$ for the needle lift during the fully opened phase ($\leq 4\%$ during needle rise). Only when the needle is already closing the injector again, a somewhat larger uncertainty of $\leq 11\%$ is observed in the shape of the needle lift signal. But since that is at the very end of fuel injection, it is not of importance for the work presented here.

All experiments presented in this work have been performed with fuel injection into $N_2$ at room temperature using a common rail pressure of 150 MPa, at a static gas pressure of 2.9 MPa, corresponding to a density of 33 kg/m$^3$. The precombustion technique is not used in the study presented here; its results will be given in a forthcoming paper.

2.2. Shadowgraphy

The setup for shadowgraphy is straightforward [28]: a Xe arc lamp is used as a continuous light source and its light is focused onto a pinhole and then collimated by an $f = 1000 \text{ mm}$ lens to a beam slightly larger than the visible window diameter, indicated in Fig. 1a. After exiting the light is focused by an identical lens onto the camera lens system. 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 $\mu$s and the exposure time (due to camera hardware equal to the reciprocal of the acquisition frequency) is slightly less than 222 $\mu$s (due to signal read-out). The images acquired have an 8-bit dynamic range and a size of $256 \times 256$ pixels. In order to study spray growth for the maximum possible time, including the spray reaching maturity, the entire window is imaged onto the camera. This results in a spatial scale of the images of 0.4 mm/pixel. The resolving power of the optical system is estimated to be a little worse than 1 pixel. In the illumination correction process, described below, division of images is required, which is sensitive to noise in the raw images. Considering the optical resolving power, raw images are therefore smoothed over $2 \times 2$ pixels before further processing.

Ideally the back window illumination would be uniform and of such intensity so as to just avoid overexposure of the camera system. Any overexposure, even if only localized, might result in the weak outer edges of the spray shadow not being detected, which in turn would lead to incorrect image interpretation and apparently smaller/narrower sprays than in the case of no overexposure. Therefore care is taken not to overexpose the camera system. It turns out that in this case also the illumination of the back window is not uniform, but exhibits some spatial variation. Furthermore, since cleaning the cell windows between subsequent injections is relatively cumbersome and therefore not always carried out, minor window fouling may be present as background signal as well. Fig. 2a shows an example of a spray shadow image obtained during injection.

The illumination nonuniformity and weak window fouling are therefore corrected as outlined in the following. In an ideal case, the illumination as observed by the camera would be $I_0 = 1$. The spray shadow has its own transmission $\tau_{s,xy}$ with $0 \leq \tau_{s,xy} \leq 1$, where $\tau_{s,xy}$ depends on the location $(x,y)$ in the image. Thus the ideal spray shadow image $J_0$ would be $J_0 = I_0 \tau_{s,xy}$. In reality, however, the illumination is $I_1$ which is given by $I_1 = \eta_{xy} I_0$, where $\eta_{xy}$ is the illumination efficiency factor ($0 \leq \eta_{xy} \leq 1$). It incorporates the light beam nonuniformity as well as weak window fouling on both the front and back windows, and its spatial variation is assumed to be constant during the short acquisition time for an image sequence of a single injection (typically 10 ms). The obtained spray shadow image $J_1$ is therefore determined by $J_1 = I_1 \tau_{s,xy} = \eta_{xy} I_0 \tau_{s,xy} = \eta_{xy} J_0$. Hence the corrected spray image is given by $J_0 = J_1 \eta_{xy}^{-1}$.

Fig. 2. (a) Unprocessed spray shadow image; injector nozzle position and nozzle hole centre line are indicated. Shadows of the thimble and drainpipe are clearly visible. (b) Illumination corrected image of (a).
The illumination efficiency \( \eta_{\text{xy}} \) is calculated by normalizing the intensities in an early image of the image sequence, where no spray shadow is yet detected. The illumination corrected result of Fig. 2a is given in Fig. 2b: the illumination nonuniformity and the weak window fouling are completely removed. The remaining small noise is due to a slow, large scale circulatory gas motion inside the cell (often observed), which is yet fast enough to cause a noticeable difference between the time of recording the background image and the time of the actual spray image. This noise is small, however, as will be shown later, and it is more pronounced when the time difference mentioned becomes larger, i.e. when the spray shadow reaches the opposite edge of the window. The emphasis of this work, however, is on the relatively early phase of fuel injection. The above mentioned correction procedure breaks down if window fouling becomes too strong, but that condition is avoided by cleaning the windows after 5–10 fuel injections.

2.3. Injector nozzle position and axis

When correlating spray growth evolution with time, it is important to accurately know the spray origin. In our high pressure cell the injector tip is obscured by the thimble. But from the construction blue-prints it is determined where the opening of the injector nozzle (of the one hole used in the experiments) is located relative to the shadows of the thimble and the drainpipe as recorded by the camera. The angle between drainpipe and nozzle axis is also known (see Fig. 2a). Hence the direction of the nozzle axis and the position where the spray exits the nozzle are established, the latter with an accuracy of ±0.25 mm.

Care is taken to ensure that the nozzle axis is perpendicular to the light beam. Simple geometrical calculations show, however, that a projection error due to possible non-perpendicularity is negligible, even for a deviation as large as 5° (much larger than is reached in the setup).

2.4. Start of fuel mass injection

As will be discussed later, it is of utmost importance to know exactly when fuel mass injection starts relative to the synchronisation of the camera image sequence. Therefore the needle lift and common rail pressure transient curves are recorded simultaneously with the image sequence, for each injection separately. This is done at a 1 MHz sample rate by an in-house developed data acquisition system (TUeDACs).

Since the functional form describing spray growth is one of the subjects of interest of the current study, no assumptions on its early phase are made with respect to start of injection (unlike Refs. [12,21]). Baert and Vermeulen [17] define the start of injection when the needle lift has reached 5% of its maximum. In contrast to these methods, separate characterization measurements of the injector used here have been performed. The results are published elsewhere [29]. The main conclusion, as far as the current work is concerned, is that the injector needle, after start of needle lift, first has to relax over a short distance, before the actual injection of fuel mass begins. This relaxation distance, corresponding to the elastic deformation of the injector needle, depends linearly on the common rail pressure before injection and can thus be corrected for.

2.5. Synchronisation

Although image storage by the camera system (identical to the one used in Refs. [13,15]) could be started by an external trigger pulse (as is done in Ref. [13]), it turns out that the image acquisition frequency is regulated by an internal clock (not externally triggerable), which is not synchronised to the external storage pulse. This would result in a timing uncertainty for the images of one interframe time. Since the interframe time, which is the reciprocal of the acquisition frequency, is 0.22 ms in this work, this timing uncertainty would be too large. Therefore a single trigger pulse is derived from the camera’s internal clock, as shown in Fig. 3. This single pulse, which has a fixed delay (±1 µs) with respect to the camera clock, is used to trigger both the fuel injection system and image storage on the camera. The needle lift is recorded simultaneously and the relaxation distance of the injector needle [29] is then used to determine the actual start of mass injection relative to the camera image time. The resulting accuracy is ±0.05 ms.

2.6. Effective image time

Due to camera hardware, the exposure time of the camera system is equal to the interframe time (i.e. 0.22 ms)

![Fig. 3. Internal camera clock signal (—) and the fixed delay, single pulse derived from it (—), which triggers both image storage (\( \checkmark \)) and fuel injection. Actual fuel injection starts at 3.88 ms (—), as derived from the needle lift (—, from Fig. 1b). Image numbers are indicated, time relative to start of experiment.](image-url)
minus a negligible read-out time. During this relatively long exposure, motion blurring may occur (spray velocity order of magnitude is $10^2$ m/s), resulting in spray tip position uncertainty. In order to minimise this effect, an effective time is assigned to each image, based on the assumption of a relatively sharp spray edge and on a piece-wise linear approximation for spray motion during an exposure.

From Figs. 2b and 4 (to be discussed later) it is clear that the sides of the major upstream part of the spray, where transverse velocities are low, have a relatively sharp edge, i.e. a steep transition from black to white in the image. Only at the front of the spray, where the highest velocities are expected, there is a larger region with intermediate (grey) values. This unsharp frontal region is expected to be predominantly caused by motion blurring of a sharp spray edge during the relatively long exposure time. Sharp edges have been observed before in fuel spray shadowgraphy (see e.g. Refs. [8,15,17,21,30], using ambient densities often comparable to that used here), for exposure times ranging from 25 ns [15] to 28 µs [21].

Furthermore, in order to check the sharp front edge hypothesis, a few experiments have been performed in the current setup under similar conditions with a much faster camera (Phantom V7.1) running at 47,400 images per second at an exposure time of only 2 µs. These results [31] clearly show that also the tip of the spray has a sharp edge under the conditions used here. Averaging 11 subsequent of these short exposure images (corresponding to 0.21 ms) yields a result very similar to the images obtained at 0.22 ms exposure with the slower Kodak camera.

Therefore an intermediate grey value, as observed at the spray tip in the images presented here, can be converted to an effective time instant at which the sharp edge of the spray tip has passed the observation area. For the calculation of this effective image time a constant velocity is assumed between start and end of a single exposure. This is not completely correct, but as soon as spray growth has slowed down enough (typically after about 0.5 ms after injection start), this piece-wise linear approximation is valid, as will be seen below. Only for the first phase of spray growth, $t \leq 0.5$ ms, does the linear approximation

![Fig. 4. Shadowgraph subsequence of a single fuel injection (from 0.06 to 3.17 ms after start of injection). Note the appearance and disappearance of the bulge indicated by arrows (between 1.1 and 2.0 ms). Eventually the opposite window edge is reached.](image-url)
not hold well. Uncertainty in this early phase, however, does not affect the results of the later phase \((t \geq 0.5 \text{ ms})\), which is the main subject of this study. Since in our analysis the spray contour is established at 80% intensity (\textit{vide infra}), the effective time assigned to an image (used for later analysis) lies at 80% of its exposure time. Changing the threshold intensity to for instance 90%, would result in a shift of the time basis by 10% of the interframe time, or 0.02 ms, which is almost negligible (as discussed later).

3. Shadowgraphy results and geometrical analysis

3.1. High speed sequences

An example of a spray shadow image sequence is shown in Fig. 4. In this case the common rail pressure just before injection is 149.4 MPa. In Fig. 4 a small anomaly is indicated between 1.1 and 2.0 ms after start of injection. It might be thought that this irregularity could be caused by a deviation in needle lift and/or common rail pressure during injection (recordings shown in Fig. 1b), but comparison of all recorded needle lift and pressure traces for nominally identical conditions reveals good reproducibility (as discussed above) and no deviations in the case of the injection presented in Fig. 4 can be found. In fact, all needle lift and rail pressure traces of the injector used in this work correspond very well to simulations [29]. The exact cause for small, short-lived anomalies like this remains to be investigated, but similar effects may have been captured by Baert and Vermeulen [17] in some of their still photographs. In general, however, it is clear that especially the upstream part of the spray shadow exhibits relatively straight edges.

3.2. Geometrical analysis

3.2.1. Spray contour

In literature several methods are presented to obtain a spray contour. Often a somehow binarized image is used, see for instance Refs. [8,12,13,21]. In order to obtain a binarization threshold, Naber and Siebers [21] use the intensity histogram of a spray image, which contains a peak at high intensities due to the background and one at low intensities due to the spray shadow. The threshold is then chosen midway between the two maxima. However, during spray growth in an image sequence as we present here, the relative contribution of the shadow to the intensity histogram will increase and may cause a shift in location and height of the histogram maximum associated with it. This will possibly affect the binarization threshold and thus leading to a systematic shift in the computed spray contour as function of time. Others like Verhoeven and co-workers [12] and Morgan et al. [13] use a somewhat subjective threshold, chosen to obtain optimum results. In Refs. [14–17] it is not specified how a spray contour is determined, although it is used in one way or another in those publications.

The method used in this work for geometrical analysis of the obtained image sequences is best illustrated by the example in Fig. 5a, which shows a region of interest. Lateral cross-sections are obtained for every axial distance \(x\) (pixel row); an example is presented in Fig. 5b. The spray contour is defined as the collection of locations \((y_f(x) < 0\) and \(y_f(x) > 0\)) where the intensity \(I\) obeys

\[
I - I_{\text{min}} = f_t(I_{\text{bg}} - I_{\text{min}}),
\]

where \(I_{\text{min}}\) is the minimum intensity observed in the spray shadow, \(f_t\) is a threshold level \((0 \leq f_t \leq 1)\) and \(I_{\text{bg}}\) is the average background intensity outside the spray. Subpixel interpolation is used to enhance the spatial resolution of the contour \(y_f(x)\). The value for \(f_t\) must be established such, that most of the spray is included in the contour, \textit{i.e. maximising} \(f_t\), while minimising the sensitivity to noise in the bright background. In Fig. 5b the locations \(y_f\) are indicated for \(f_t = 0.8\). Due to the steep gradients, varying \(f_t\) by \(\pm 0.1\) (indicated as well) results in a contour shift of only \(|\Delta y_f| \approx 0.5\ \text{pixel}, which is almost negligible (cf. Refs. [9,10]). At the spray tip the shift \(|\Delta y_f|\) will be somewhat larger, but that part of the contour is not used in further calculations. Considering the effect of \(f_t\) on the macroscopic cone angle \(\hat{\theta}_{\text{cone}}\) as well, discussed in the next section, leads to a choice of \(f_t = 0.8\).

3.2.2. Local spray angle and macroscopic cone angle

In literature no consensus is found on what is called a spray (cone) angle, equivalent spray angle or standard angle.\(^1\) Sometimes the acute angle of an equivalent isosceles triangle is used, where the triangle has the same area and height as the entire spray [33] or only the upstream half of it [13,21], or an isosceles triangle is combined with a semicircular top [34]. In another method the spray width at a certain axial position yields a local angle and the standard spray angle equals the local angle at for instance 50% of the spray length [33] or at 60 nozzle diameters from the injector [9,10,35]. Often, however, a straight line is fit through (an upstream) part of the spray contour [3,12,15,36] or a tangent (external or otherwise) to the contour is taken, but over which distance a linear fit or a tangent is to be taken appears to be ambiguous or arbitrary [12,15,17,21,23,36–42].

Information on the spray angle which is obtained from only the upstream half of the spray [13,16,21] or at a so-called standard distance [9,10,35] is often used for correlating spray penetration with models (see for instance Refs. [21,32]). But it may be argued that considering an angle somehow derived from the entire spray may be more meaningful when such correlations are made. Therefore a more general approach for deriving a macroscopic cone angle based on the contours \(y_f(x)\) is used in this work.

\(^1\) Sometimes it is even not clear at first within a paper [16,21] or from one paper [32] quoting another [4] whether the full angle (side-to-side) or only half of it (axis-to-side) is meant.
Fig. 5. (a) Region of interest of a spray image: the spray contour and the lines calculated for $\theta_{cone}$ are indicated. (b) Cross-section through the spray, (+) signs indicate pixel positions. The values of $y_i$ where the threshold level of 80% ($\circ$) is met are indicated (vertical — lines), 70% ($\triangledown$) and 90% ($\triangle$) threshold levels are indicated as well. (c) Local angles $\theta_i(x)$, median filtered $\theta_i(x)$ and the method of determining $\theta_{cone}$. (d) Variation of $\theta_{cone}$ versus threshold level $f_t$. (e) Normalized laterally integrated shadow $I_s$ and its derivative. Spray tip position is indicated by the vertical — line near $x = 149$. 

$\theta_{cone}$, $\theta_1$, $\theta_2$, $\theta_1$ (median), $\theta_2$ (median)
From the contours $y_i(x)$ a local angle $\vartheta_i(x)$ can be calculated with
\[
\tan \vartheta_i(x) = (y_i(x) - y_{i,\text{offset}})/\Delta x \quad (i = 1, 2).
\] (2)

The offset value $y_{i,\text{offset}}$ is used to account for the blockage of the early spray position by the thimble (as opposed to Ref. [9]). From the results in Fig. 5c it is clear that $\vartheta_i(x)$ is more or less constant over a relatively large part of the spray. Due to the nature of Eq. (2), for small $x$ any change in $y_i(x)$ will be amplified in $\vartheta_i(x)$. This effect is mitigated by the subpixel interpolation of $y_i(x)$, but still some overshoot can be seen around the start of the spray. Note that due to the nature of Eq. (2), $\vartheta_i(x)$ is relatively insensitive to the exact $f_i$ value used.

The approximate constancy of $\vartheta_i(x)$ for a significant part of the spray indicates that a representative cone angle $\vartheta_{\text{cone}}$ can be determined for every image of a given time $t$. This is achieved by applying a median filter to $\vartheta_i(x)$, yielding $\vartheta(x)$. In this filtering method, performed to be insensitive to outliers, the central value in a sliding window of 1/3 of the spray length is replaced with the median of all values within the window. The cone angle is then defined as
\[
\vartheta_{\text{cone}}(x) = \left| \min(\vartheta_1(x)) \right| + \max(\vartheta_2(x)),
\] as presented in Fig. 5c as well. The two lines indicating $\min(\vartheta(x))$ and $\max(\vartheta(x))$, i.e. together forming $\vartheta_{\text{cone}}$, are shown overlaid in Fig. 5a. As can be seen in this figure, the actual spray contour closely follows these two lines for about 2/3 of the entire spray. The intersection of the two lines corresponds reasonably well to the actual position of the injector nozzle.

Although the contour $y_i(x)$ and the local spray angle $\vartheta_i(x)$ are rather insensitive to variations in the threshold level $f_i$ (vide supra), the dependence of $\vartheta_{\text{cone}}$ on $f_i$ may not be a priori clear. Therefore $f_i$ has been varied from 0.1 to 0.95 in a $\vartheta_{\text{cone}}$ calculation. The result is presented in Fig. 5d, from which it is clear that $\vartheta_{\text{cone}}$ varies by less than about $\pm0.25^\circ$ (or less than $\pm1\%$) for $0.3 \leq f_i \leq 0.85$. Therefore $f_i = 0.8$ is used throughout this work.

3.2.3. Spray length

In some studies the spray tip is defined to be at the intersection of the spray contour and its axis [9,33,36], where the latter may be the bisection of the cone angle [36], a line from the nozzle through the centroid [21,33] or the centre line of the nozzle hole [9,17]. In other work the location (axially) farthest from the nozzle [13,17,42] or the length of the projection of the spray onto its axis is used [23,38,39]. A method where 50% of the pixels on an arc of $\vartheta/2$ (centred on the axis) is dark [13,21] will by definition miss the very tip of the spray, even if it is assumed to be semicircular [34]. Sometimes even slightly subjective measures need to be taken [12].

The methods described above work less well if the spray tip is not axisymmetric or if the tip is not at the axis. Significant lateral deviations are for instance been observed before in Ref. [17] in the current work and in other (yet unpublished) data (see for instance Ref. [31]). In order to take the entire spray shape into account, a more general method is developed in the current work. Using the centre line of the nozzle hole as spray axis, the shadow intensity is laterally integrated over the width of the region of interest (Fig. 5a). The result is a normalized shadow $I_c$, as shown in Fig. 5e. Edge detection is then applied: the spray tip is located at the position where $|dI_c/dx|$ becomes $<0.015$ in the region where $I_c \leq 0.10$ (these values yield consistent results in most injection experiments). As can be deduced by comparing Figs. 5a and 5e, the spray tip position determined in this way corresponds well to the closure of the contour at the tip. The sensitivity to the size of the integration area is found to be low (typical width 140 pixels; variation by $\pm50\%$ yields a tip position shift of less than 0.2 pixels).

4. Time evolution of fuel injection: results and discussion

4.1. Spray cone angle

Using the above described geometrical analysis method, image sequences obtained at a nominal common rail pressure of 150 MPa (average of 10 experiments: $150.7 \pm 1.3$ MPa) were processed to reveal temporal characteristics. The behaviour of $\vartheta_{\text{cone}}$ is shown in Fig. 6a for four individual injections. For the first data points (around 0.05 ms after start of injection) the visible part of the spray is still very short and its shape still rather capricious, as can be seen for instance in the first image in Fig. 4. This may lead to a very large (injection #13) or relatively small (#12, 14, and 15) value for $\vartheta_{\text{cone}}$. For the next few data points, up to about 1 ms, injections #13–15 exhibit a clear maximum, much larger than later values and that of injection #12. These short-lived maxima in $\vartheta_{\text{cone}}$ are caused by the early, most upstream part of the spray not yet having reached its fully developed shape. An example is shown in the inset of Fig. 6a. Injection #12 also suffers somewhat from this effect, but $\vartheta_{\text{cone}}$ stays rather large up to 2 ms after start of injection, because of the presence of the lateral anomaly already described (cf. Fig. 4). Indeed, once this anomaly has disappeared, $\vartheta_{\text{cone}}$ reverts to values observed for the other injections. Temporal variation of $\vartheta_{\text{cone}}$ during an injection (almost) entirely due to variation in spray shape (which might be imagined as deviation from a perfectly triangular upstream part). Image noise, due to the large scale, slow circulatory gas motion (vide supra), becomes only important towards the end of injection #15, slightly increasing $\vartheta_{\text{cone}}$. After the end of injection (around 5 ms) the (upstream part of the) spray shadow stops appearing like a triangle, whence $\vartheta_{\text{cone}}$ becomes less meaningful. But during the main part of the injection, $\vartheta_{\text{cone}}$ lies between $25^\circ$ and $30^\circ$.

In the literature different values for the spray cone angle of diesel sprays are found. Differences are a result of differences in fuel specifications, nozzle geometry and ambient
gas density and temperature. Actual values vary in a broad range between 8° and 22°. At first glance this is smaller than the values found in this study. However, for strongly cavitating (cylindrical) nozzles, Payri et al. [30] observed spray cone angles between 25° and 30°. And Schneider [9] and Boulouchos and co-workers [10] have also found angles between 25° and 30°. In a different set of experiments [29], the hydraulic behaviour of the nozzle used in the present study is characterized. From these experiments it is clear that – for the conditions in this study – the fuel flow exiting the nozzle would be indeed strongly cavitating, supporting the observed values of \( \vartheta_{\text{cone}} \). It should also be borne in mind that the angle measured depends as well on the experimental technique used. Mie (back-)scattering is often used (see for instance Refs. [3,33]), but this method only records light (in a small solid angle) scattered by the liquid phase (typically observed at 90° or 180°), whereas shadowgraphy records the combined effects of scattering in all directions (except around 0°) and absorption. This may lead to Mie scattering results yielding a smaller apparent angle. So although our values may appear to be somewhat larger than some other published values, they are considered to be acceptable.

4.2. Spray length and growth

The spray tip propagation of the same injections as in Fig. 6a is presented in Fig. 6b, together with their average. It can easily be seen that the spray tip of injection #12 is slowed down, relative to the other injections, between 1.1 and 2.0 ms. This slowing down of the tip movement coincides exactly with the presence of the anomaly indicated in Fig. 4 and with the larger than average value for \( \vartheta_{\text{cone}} \) between 1.1 and 2.0 ms after start of injection, as noticed before (cf. Fig. 6a). This effect of spray tip velocity decrease during the presence of a laterally growing irregularity has been observed to occur in more fuel injections (not shown here), irrespective of exact injection conditions. It may be explained by loss of axial momentum, which is turned into lateral momentum. As mentioned before, these small, short-lived anomalies are not expected to be related to needle lift or common rail pressure deviations, since the latter are very well reproducible (Fig. 1b).

The effect of momentum transfer would also be expected to show up when correlating the spray length to \( 1/\sqrt{\tan \vartheta_{\text{cone}}/2} \), a term which is (apart from the direct time dependence) also found in most models (for instance in Refs. [21,32]): a lateral deviation would widen the spray and slow it down, as discussed before. Plotting spray length versus \( 1/\sqrt{\tan \vartheta_{\text{cone}}/2} \) (not shown) does indeed reveal a weak correlation, but the effects of spray shape variation (influencing \( \vartheta_{\text{cone}} \), see Fig. 6a) are large enough to prevent a clear relation from being observed.

Since most fuel injections may exhibit a minor deviation at one time or another, and since these are relatively short-lived and small, it is allowed to average the spray tip propagation data of (nominally) identical injections, in order to compare the results to relations found in the literature.

In general (see for instance Refs. [3,21]) the tip velocity will increase rapidly from zero to its maximum value, during a period so short that it cannot be observed in the present study. In this period the tip velocity will be determined by the fuel injection velocity, as the momentum exchange between fuel parcels (produced by atomization) and ambient gas is not yet significant. As spray growth proceeds, the effect of ambient gas density will become noticeable and fuel velocity will drop. At this time the spray tip velocity will be the result of the two competing processes. The transition between these two processes is often described as spray break-up (see for instance Ref. [7]). After this transition, slowing down of the tip by the ambient gas is
dominant and the spray tip position may be described by [7]
\[ l - l_0 = a(t - t_0)^b, \]  
(4)
where \( l_0 \) and \( t_0 \) are often referred to as the spray break-up length and time, respectively. In general \( b = 0.5 \) has been observed or postulated, see for instance Refs. [3,5,7,11,17,21,30,33,39,43,40].

It is sometimes assumed [7] that for \( t < t_0 \) spray penetration is at constant velocity. Considering the data in Fig. 6b, it is observed that linear interpolation between the origin and the first averaged data point yields an apparent velocity of 156 m/s and interpolation between the first and second averaged data points yields a velocity of 70 m/s. This indicates that the spray tip velocity already decreases, so a period of constant velocity is not observed and spray break-up is thought to have already occurred before the first spray shadow signal is detected. Thus the first (averaged) data point in Fig. 6b poses upper limits to the spray break-up length and time: \( l_0 \leq 9.3 \) mm and \( t_0 \leq 0.06 \) ms for the current experimental setup. From Fig. 6b it is furthermore clear that after \( t \approx 0.5 \) ms the tip velocity changes only slowly, confirming the validity of the piece-wise linear approximation used in calculating the effective image time (vide supra).

Fig. 7 presents the fuel injection velocity (i.e. exit velocity at the nozzle), calculated from separate fuel mass injection rate measurements of the injector used in this work [29,44]. As can be seen, the injection velocity reaches 400 m/s already about 0.3 ms after start of fuel injection for the conditions presented here. These velocities are much higher than the observed velocities, corroborating the fact that the earliest phase of spray propagation is not visible in the current setup.

When considering the later stages of spray growth \( (t \gg t_0) \), trying to establish a relation like Eq. (4) is facilitated by plotting the average spray tip position on a log-log scale, as shown in Fig. 8 (symbols), where a straight line indicates a constant power \( b \). This applies to the last part of the observed spray growth (just before the opposite window edge is reached), which is fitted to the relation
\[ y = at^b. \]  
(5)
This fit (which neglects \( l_0 \) and \( t_0 \) holds well after about 1 ms (see Fig. 8), resulting in a slope \( b = 0.57 \pm 0.01 \) and a prefactor \( a = 52.3 \pm 0.2 \) mm ms\(^{-1} \) (with the error derived from the fitting procedure [45]). The fit does not hold well for times before \( \approx 1 \) ms. There may therefore be an intermediate regime in which the competition between fuel injection and ambient gas resistance results in a larger slope \( b \) (Fig. 8, Eq. (5)), decreasing with time until it is constant after \( \approx 1 \) ms. A next series of nominally identical injections yields \( b = 0.56 \pm 0.01 \) and \( a = 52.3 \pm 0.4 \) mm ms\(^{-1} \). This is indicative of the experimental uncertainty. Another indication for this can be obtained by changing the intensity threshold from 80% to for instance 90%. This results in a shift of effective image time of 0.02 ms (vide supra), which in turn yields the values \( b = 0.58 \pm 0.01 \) and \( b = 0.55 \pm 0.01 \), respectively, for the two nominally identical injection series. The difference in \( b \) is only \( \pm 0.01 \), which is negligible. Therefore a combined value of \( b = 0.57 \pm 0.02 \) is considered in the rest of the discussion.

This value is clearly larger than 0.5, the value often postulated [5,7,43] when correlating fuel spray penetration with time. The value of 0.5 is based on a presumed analogy between a (liquid) fuel jet and a gas jet [5,43]. But values of \( b \) clearly differing from 0.5 have been observed as well when fitting experimental data to Eq. (5): 0.38 has been observed.

![Fig. 7. Fuel injection velocity \( v \) (---) (divided by 10 for ease of comparison), injected momentum rate \( dI/dt \) (---) and its equivalent top hat profile (---) obtained from the current injector at a rail pressure of 141.6 MPa in separate experiments [29,44]. The equivalent top hat profile starts at 0.29 ms.](image1)

![Fig. 8. Average spray tip position (from Fig. 6b, symbols with error bar) on log-log scale. Data points between 0.9 and 2.4 ms (circles) are used for fitting to Eq. (5), the --- line is an extrapolation of this fit. Fits (of the same data points) to Eq. (6) (---) and (7) (---) are shown as well for comparison.](image2)
in Ref. [23]; 0.45–0.53 in Ref. [12]; 0.55 in Ref. [38]; 0.55–0.59 in Ref. [9]; 0.57 in Ref. [11] and 0.64 in Ref. [19]. Delacourt et al. [3] compare their experimental data with a \( \sqrt{t} \) propagation, but allowing the power of time to be adjustable and fitting to Eq. (5) might have yielded a different value for \( b \). So not only has the \( \sqrt{t} \) time dependence not always been observed experimentally, it also attracts detailed attention from a theoretical point of view. Sazhin et al. [32], for instance, have introduced a second time-dependent term in their model, apart from the \( \sqrt{t} \) factor, which may effectively yield a power of time different from 0.5. The latter may also result if the time dependence of \( \vartheta_{\text{cone}} \) is taken into account, instead of the often used implicit assumption that it is constant.

For the purpose of comparison, a functional form

\[
y = a\sqrt{t - t_i},
\]

has also been fitted to the same data, as is shown in Fig. 8 as well. This results in a slightly worse fit, but above all it intersects \( y = 0 \) at a time \( t_i = 0.19 \) ms, a time when fuel injection is already going on for some time. And fitting a function \( y = a\sqrt{t} \) (i.e. setting \( t_i = 0 \) in Eq. (6); not shown) to the data points in Fig. 8 (similar to Ref. [3], described above), would have resulted in a “good” fit, but it would have captured less effects of spray tip penetration behaviour.

The sensitivity of the fit and especially of the slope \( b \) to the exact time since start of mass injection is demonstrated well by another comparison. Naber and Siebers [21] use an injection system that exhibits a top hat profile (“square pulse”) for the fuel mass injection rate and the injector of Verhoeven et al. [12] exhibits a very fast rise in injected volume rate. In Fig. 7 the injected momentum rate is shown for the injector used in the current work. The data are calculated from separate measurements (not shown here) at a rail pressure of 141.6 MPa [29,44], which is close to that of the experiments shown here. Also plotted is an equivalent top hat profile, which has the same total area. It is clear that the injected momentum rate rises and falls more gradually than the equivalent top hat profile. Since the equal total area condition is not enough to determine start and end of the top hat profile, the time integral of the injected momentum rate is calculated as well. A linear fit is made to the slope of this integral between 20% and 80% of its maximum. The slope of this fit defines the top hat height, whereas the intersections of this linear fit with the 0% and 100% levels of the integral define the top hat start and end. In this way the equivalent top hat profile is found to start at a time of \( t_e = 0.29 \) ms after actual start of mass injection, even later than when the fit of Eq. (6) intersects the zero spray length line. Adapting Eq. (5) for the start of the equivalent top hat profile gives

\[
y = a(t - t_e)^b.
\]

Fitting this relation to the same data points as used before yields \( b_s = 0.46 \pm 0.01 \) (given \( t_e = 0.29 \) ms). This is shown in Fig. 8.

From the discussion above it may become clear that it is rather difficult to say anything significant about the value of \( b \) (the power of time with which the mature spray grows) if the timing information of the images is not carefully calibrated with respect to the actual start of mass injection. As might already be glimpsed from Eq. (4), the value of \( b \) depends only very little on the exact value of \( l_0 \), so based on this data a better measure than its upper limit cannot be given for \( l_0 \). And although the dependence of \( b \) on \( l_0 \) is much larger, a more accurate estimate of \( t_0 \) (below its upper limit) can also not be determined, based on current data. It might be suggested that a nonlinear, least-square curve fitting routine solve for all four parameters \( l_0 \), \( t_0 \), \( a \) and \( b \) of Eq. (4) simultaneously. But a test using such a routine revealed (and the closeness of the three fits for the time period of interest, described above, already hints at it) that the obtained parameter values, especially \( b \), critically depend on the initial (guessed) values, the tolerances and convergence criteria imposed and on the number of iterative steps allowed. The resulting parameter values varied much more widely with changing input parameters than when a judicious choice of the coordinate system was made, as is used in the rest of the work presented here.

5. 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 can be studied under engine-like conditions. As a first step in detailed spray studies, high speed shadowgraphs of diesel fuel injection have been obtained at room temperature at 150 MPa common rail pressure and 2.9 MPa gas pressure (density 33 kg/m\(^3\)). Great care has been taken to determine the actual start of fuel mass injection and to assign an effective image time to the images, which have a relatively long exposure time due to the camera used here. The effective image time is based on motion deblurring of a sharp spray edge and on a piece-wise linear approximation which holds well for \( t \geq 0.5 \) ms after actual start of fuel injection. Hence an accurate time base, commencing with fuel injection start, has been established. This turns out to be critical for later analysis.

Spray behaviour is found to be well reproducible in general, but high speed imaging, as opposed to acquiring just a single image per injection, also easily reveals that not all fuel sprays behave identically, all conditions being equal. Small, short-lived anomalies, moving laterally, are sometimes observed during spray propagation, which are directly related to a simultaneous reduction in axial spray tip velocity and which also may increase the spray cone angle \( \vartheta_{\text{cone}} \). Therefore care has to be taken when combining data from several injections. If just a single image per injection were available, a plethora of injections would be necessary to obtain enough data points for fitting the spray propagation to an expected functional behaviour, whereas high speed shadowgraphy can make do with much less
injections. In addition, the above mentioned anomalies might easily be missed or perhaps rejected as an outlier, when using single shot images.

A general and consistent method for determining macroscopic spray geometry characteristics (spray length and cone angle) has been developed. In this method, lateral cross-sections of the spray shadow are used to obtain the spray’s width at a preset threshold level of 80% and hence a spray contour. From these the local, axially varying angle \( \theta_i(x) \) is calculated. A macroscopic cone angle \( \theta_{cone} \) is defined by the extrema of the median filtered \( \theta_i(x) \). The spray tip position is found by lateral integration of the shadow intensities and applying edge detection to the thus obtained curve. All this is done as a function of time, which may be useful in improving models, like the ones presented in Refs. [7,21,32]. The spray contour and the penetration are determined to subpixel accuracy. The spray contour, the local angle \( \theta_i(x) \) and the cone angle \( \theta_{cone} \) are relatively independent of the actual preset threshold level.

Using this spray analysis algorithm, a number of series of diesel fuel injections has been studied, each employing nominally identical conditions. The determined average velocity in the earliest detectable phase (up to 156 m/s) is already more than twice as low as the (maximum) fuel injection velocity determined from separate measurements in a Zeuch vessel [29]. It is suggested that spray propagation in this earliest visible phase, which lasts about 1 ms for the current conditions, is governed by the competition of fuel injection delivering momentum to the spray tip and ambient gas resistance already slowing down the spray tip, i.e. momentum exchange between liquid and gas phase. After this early phase, the spray tip propagation can be described by Eq. (5), with a resulting value of \( b = 0.57 \pm 0.02 \) for the conditions employed here. This deviates from the often used \( \sqrt{b} \) behaviour, which is sometimes prescribed when fitting experimental data. Fitting to Eq. (5) will, however, yield more insight. The value of \( b \) is rather sensitive to any uncertainty in the time elapsed since actual start of fuel mass injection. Therefore the injector used here has been characterized in separate experiments [29] in order to accurately establish the actual start of injection. Determining the start of injection from back-extrapolation of spray propagation data, as is sometimes found in the literature [12,21], may introduce errors. Differences in the value of \( b \), as encountered in the literature, might therefore also be partially due to timing uncertainties and to differences in injected momentum.

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