

Effects of Nozzle Geometry on the Characteristics of an Evaporating Diesel Spray

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ABSTRACT

The effects of nozzle geometry on diesel spray characteristics were studied in a spray chamber under evaporating conditions using three single-hole nozzles, one cylindrical and two convergent, designated N1 (outlet diameter 140 μm , k-factor 0), N2 (outlet diameter 140 μm , k-factor 2) and N3 (outlet diameter 136 μm , k-factor 2). Spray experiments were performed with each nozzle at two constant gas densities (15 and 30 kg/m^3) and an ambient temperature (673 K) at which evaporation occurs, with injection pressures ranging from 800 to 1600 bar. A light absorption and scattering method using visible and UV light was implemented, and shadow images of liquid and vapor phase fuel were recorded with high-speed video cameras. The cylindrical nozzle N1 yielded larger local vapor cone angles than the convergent nozzles N2 and N3 at both gas densities, and the difference became larger as the injection pressure increased. The vapor phase penetration values for nozzle N1 and N3 were quite similar and always lower than those for N2. This is consistent with the impingement measurements, which showed that the momentum flux of nozzle N1 was only slightly greater than that of nozzle N3, while that of nozzle N2 was substantially greater. The vapor volume fractions measured along the spray's center line were well explained by the one-dimensional transient diesel jet model, indicating that diesel spray vaporization is controlled by turbulent fuel-air mixing.

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INTRODUCTION

It is known that spray development influences combustion-related variables in diesel engines such as the combustion efficiency and engine-out emissions, and spray development is strongly affected by atomization and rates of air entrainment into the spray. Air entrainment into the spray can be increased and engine-out soot emissions reduced by using high injection pressures while suppressing cavitation inside the nozzle, according to experiments performed with injection pressures of up to 3200 bar and injector nozzles with a k-factor of 2 and 25% hydro-grinding [1]. Several studies have also shown that using injectors whose orifices are more convergent (i.e. which have higher k-factor) or have more hydro-grinded nozzle orifices can reduce diesel engines' soot emissions by increasing air entrainment [2, 3, 4]. However, other investigations have suggested that these combustion variables are independent of the nozzles' internal flow properties and depend only on spray momentum and air entrainment resulting from the fuel jet's momentum. This conclusion was drawn on the basis of experiments conducted using two nozzles with the same momentum (one with 0% hydro-grinding and another with 20% hydro-grinding) [5]. It was also stated by Siebers [6] that vaporization in a diesel spray is controlled by air entrainment into the spray (i.e. by turbulent mixing) based on extensive experimental spray data.

However, there are uncertainties about the effects of nozzle geometries on spray properties, partly because cavitation inside the nozzle can enhance the primary break-up and subsequent atomization

of the liquid jet [7, 8]. It was also reported that under cavitation conditions a cylindrical nozzle produces a better air-fuel mixture than a convergent nozzle because it generates a greater spreading angle and outlet velocity [9]. Furthermore, a non-hydro-grinding nozzle reportedly generated stronger cavitation and thus smaller ligaments in a liquid jet than a hydro-grinding nozzle [10]. Finally, a CFD study of various nozzle configurations indicated that a cylindrical nozzle enhanced primary break up and therefore produced smaller droplets (and thus a less fuel-rich reaction zone and lower soot emissions) than a convergent nozzle [11].

As summarized above, there is no clear consensus concerning the effects of nozzle conicity and the associated cavitation on spray properties. This work aims to clarify these issues by presenting new data on the relationship between nozzle conicity and the characteristics of the evaporating spray.

Many different nozzle types can be used in spray experiments. Nozzle conicity can be varied by varying the inlet diameter while maintaining a constant outlet diameter, or vice versa [11, 12, 13]. In the experiments reported here, since the injection rate and spray properties are affected by the nozzle outlet diameter and k-factor, three different nozzles were used: one with a k-factor of 0 and 140 μm outlet diameter, and two with a k-factor of 2 but different outlet diameters (140 μm and 136 μm). The latter of which has the same nominal flow rate as the cylindrical nozzle. High speed cameras were used to capture images showing the development of liquid and vapor sprays formed by these three nozzles.

The experiments presented herein were conducted under evaporating conditions because in the operating range of a real heavy-duty diesel engine, the injected liquid fuel is vaporized within a few hundred microseconds. Payri et al. [13] recently investigated the liquid length resulting from different nozzle geometries under evaporating conditions, while the effect of nozzle geometry on the liquid/vapor length and vapor spreading angle have been studied by Zhang et al. [12]. However, it is not possible to determine the effects of nozzle geometry on the distribution of fuel between the liquid and vapor phases by considering only the liquid/vapor length and the spray's spreading angle. Therefore, we conducted qualitative measurements of the vapor volume fraction by using a light absorption and scattering (LAS) approach that resembles the laser absorption and scattering technique used by Nishida and co-workers [14, 15, 16]. In addition, we measured the liquid and vapor phase local cone angle and length.

PRINCIPLES OF THE OPTICAL MEASUREMENTS

The LAS technique is a line-of-sight extinction technique that generally has several advantages such as a high signal-to-noise ratio, low ambient temperature dependence and no fluorescence quenching. It commonly uses two wavelengths, one wavelength (typically in the visible, i.e. 400-700 nm) that is scattered by liquid droplets but not absorbed and another (usually in the ultraviolet, or UV, range) that is used to detect the absorbance of the vaporized fuel. To quantitatively measure vaporized spray concentrations, LAS experiments [14, 15] have been performed using model fuels such as 1,3-dimethylnaphthalene [14] or a mixture of 97.5% n-tridecane and 2.5% 1-methylnaphthalene (α -MN) [16]. Mixtures of n-dodecane with 2% and 10% α -MN were recently tested as LAS tracer fuels under evaporating conditions in our lab [17]. These preliminary experiments yielded promising results, demonstrating that the technique could be used to measure the distribution of fuel between liquid and vapor phases in diesel sprays. All of these tested fuels include an aromatic component that functions as a UV light absorber and is diluted with a non-absorbing alkane to control the degree of absorption because the aromatic component is a strong absorber of UV light.

Commercial diesel fuel is a complex mixture of many hydrocarbon components, most of which are paraffinic, naphthenic or aromatic. Paraffinic and naphthenic hydrocarbons in diesel fuel are almost transparent to UV light with a wavelength above ~ 240 nm. However, the aromatic components in diesel fuel are strong ultraviolet absorbers at wavelengths shorter than 300-360 nm. Commercial Swedish market sold MK1 diesel fuel without added rapeseed methyl ester (RME) contains at most 5% aromatics by volume. This makes it possible to measure the UV light absorption of vaporized diesel sprays. A spray's UV light absorbance is proportional to the concentration of fuel in the vapor phase, and relative fuel concentrations can be measured qualitatively on the basis of absorption in the vapor parts of the spray. Moreover, visible light scattering can be used to qualitatively measure the distribution of liquid phase fuel in a spray.

Main Idea of Light Absorption Scattering

As shown in Figure 1, when a UV light beam passes through a mixture of vaporized diesel fuel (containing aromatics) and liquid droplets, the vaporized fuel absorbs UV light while the liquid droplets scatter and absorb it. Therefore, the transmissivity of UV light in a vaporized fuel can be expressed as:

$$\log \frac{I_0(\lambda_{UV})}{I(\lambda_{UV})} = \left[\log \frac{I_0(\lambda_{UV})}{I(\lambda_{UV})} \right]_{v,ab} + \left[\log \frac{I_0(\lambda_{UV})}{I(\lambda_{UV})} \right]_{l,sc} + \left[\log \frac{I_0(\lambda_{UV})}{I(\lambda_{UV})} \right]_{l,ab} \quad (1)$$

where the subscripts V , UV , l , v , sc and ab signify visible light, UV light, liquid droplets, vapor phase, scattering, and absorption of light, respectively. It has been shown by Zhang et al. [14] that under certain conditions, the transmissivity of UV light due to liquid droplet scattering and absorption can be assumed to be almost identical to the transmissivity of visible light wavelength (λ_v) due to liquid droplet scattering. Consequently, the final two terms on the right hand side of Equation (1) can be expressed as:

$$\left[\log \frac{I_0(\lambda_v)}{I(\lambda_v)} \right]_{l,sc} \approx \left[\log \frac{I_0(\lambda_{UV})}{I(\lambda_{UV})} \right]_{l,sc} + \left[\log \frac{I_0(\lambda_{UV})}{I(\lambda_{UV})} \right]_{l,ab} \quad (2)$$

Combining Equations (1) and (2) yields the following expression for the transmissivity of UV light in a vaporized fuel:

$$\log \frac{I_0(\lambda_{UV})}{I(\lambda_{UV})} \approx \left[\log \frac{I_0(\lambda_{UV})}{I(\lambda_{UV})} \right]_{v,ab} + \left[\log \frac{I_0(\lambda_v)}{I(\lambda_v)} \right]_{l,sc} \quad (3)$$

To obtain the transmissivity resulting from the scattering and absorption of UV light by liquid droplets, the transmission of visible light is measured at the same time as that of UV light. The fuel droplets do not absorb visible light, so visible light attenuation is due to droplet scattering alone. Equation (3) makes it possible to separate the light attenuation signals due to liquid and vapor in light absorption scattering (LAS) experiments.

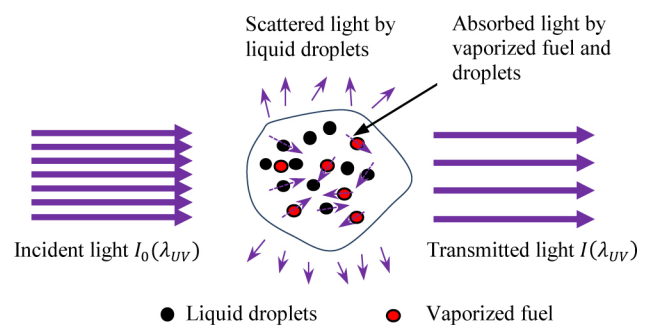


Figure 1. UV light extinction by a cloud of vaporized fuel and liquid droplets.

Detailed derivations of the equations used to describe these processes are presented elsewhere [14, 15, 17], here only the main equations are shown. The vapor concentration can be described as:

$$\overline{C}_v = \frac{1}{\varepsilon(\lambda_{UV})L_v} \left[\log \frac{I_0(\lambda_{UV})}{I(\lambda_{UV})} - G \cdot \log \frac{I_0(\lambda_v)}{I(\lambda_v)} \right] \quad (4)$$

where $\overline{C}_v$ is the vapor concentration (mol/m³); $\varepsilon(\lambda_{UV})$ is the absorption coefficient of vaporized fuel at wavelength λ_{UV} (m²/mol); L_v is the optical path length of light beam in the vapor phase (m); $\log \frac{I_0(\lambda_{UV})}{I(\lambda_{UV})}$ is the transmissivity of UV light; G is the ratio of the optical thickness of the droplet cloud for UV and visible light, and $\log \frac{I_0(\lambda_v)}{I(\lambda_v)}$ is the transmissivity of visible light. The ratio G approaches one as the droplet diameter becomes large relative to the incident wavelength [18], and it was also shown by Zhang et al. [14] that the droplet optical thickness ratio G approaches one when using a UV wavelength of 266 nm and a visible wavelength of 532 nm except in regions where the spray is very dense. In the vaporized fuel spray region, the total extinction is dominated by vapor absorption, which implies that the differences in the droplets' optical thickness at the two wavelengths have little effect on the measured vapor concentrations.

To calculate the vapor phase concentration using Equation (4), it is necessary to determine the transmissivity of UV and visible light, $\log \frac{I_0(\lambda_{UV})}{I(\lambda_{UV})}$ and $\log \frac{I_0(\lambda_v)}{I(\lambda_v)}$, which can be measured with CCD cameras or high-speed video cameras. It is also necessary to determine the absorption coefficient $\varepsilon(\lambda_{UV})$, which can be measured using an optical spectrometer and a high-pressure and high-temperature cell. The optical path length L_v can be measured by assuming the fuel distribution in the spray is axisymmetric. Once these quantities are obtained, the local vapor phase concentration can be calculated.

Qualitative Vapor Concentration Measurement

The approach used for quantitative measurement of the vapor concentration was discussed above to facilitate understanding of the qualitative measurements of vapor concentration used in this work. Because diesel fuel is a mixture of different hydrocarbon components with different boiling points, the lighter components vaporize more rapidly and have higher vapor concentrations during the early stages of vaporization. In addition, the absorption coefficient $\varepsilon(\lambda_{UV})$ depends on the fuel components' molecular structure, the ambient temperature, and the gas density. All these factors make it difficult to quantitatively measure absolute vapor concentrations in a diesel fuel spray. However, qualitative estimates of the vapor concentration can be obtained by making some assumptions:

1. Regions of the spray with negligible visible light extinction can be considered to be fully vaporized.
2. The fuel composition in a fully vaporized spray region is homogenous, i.e. the same distribution of fuel components is present everywhere in a vaporized spray region.
3. Given assumption 2, the absorption coefficient $\varepsilon(\lambda_{UV})$ is the same at all points under fixed experimental conditions.

To approach assumption 1, the evaporating ambient temperature was set to 673 K and the gas density was set to 15 or 30 kg/m³; under those conditions, the diesel fuel will evaporate rapidly. Furthermore, a low threshold was imposed when defining the liquid phase boundary in a

vaporized spray, ensuring that the region defined as containing the vapor spray was free from droplets, and that the measured UV light absorption for this region was due to the vapor alone.

One important factor is that the fuel components do not undergo any changes beyond changes of state as they transition from the liquid to the vapor phase; no ignition or other chemical reactions take place. A constant flow of air with an oxygen concentration of 21% was maintained through the high-pressure and high-temperature chamber (see the Experimental Apparatus section for details). As such, there was a risk that ignition might occur given the high experimental ambient temperature (673 K). However, no ignition was observed during the injection period. If ignition had occurred, we would have expected to see a strong increase in UV light absorption in the vapor phase region due to the carbonyl structure in the aldehydes such as formaldehyde (CH₂O), which are present in cool flames, absorbs UV light between 195 and 275 nm [19]. Sudden increases in UV light absorption in the vapor part of the spray have previously been observed with our apparatus under other experimental conditions, but no trace at any point during this work. An estimate of the ignition delay under the studied conditions supports the hypothesis that ignition does not occur during the injection period.

Ignition delay (i.e. the timing of onset of high-temperature combustion chemistry) has been predicted by Pickett et al. [20] based on extensive experiments in a pre-combustion vessel. Although formaldehyde is produced in cool flames, which develop a few hundred μ s before the start of high-temperature combustion, we considered the ignition delay for the start of high-temperature combustion because values for this parameter are available in the literature. As shown in Equation (5), the ignition delay for a diesel spray can be fitted to the Arrhenius expression [21]:

$$\tau_{ig} = A \exp\left(\frac{E}{RT_a}\right) \quad (5)$$

where

τ_{ig} = the ignition delay;

A = the pre-exponential constant [ms];

E = the global activation energy;

R = the universal gas constant;

T_a = the ambient temperature [K];

The coefficients of the Arrhenius expression A , E/R and T_a are as referred to the work of Pickett et al. [20]. Figure 2 shows the ignition delay predicted for gas densities 14.8 kg/m³ and 30 kg/m³ and nozzle outlet diameters of 0.1 and 0.18 mm from the datasheet [20]. By interpolation, the ignition delays estimated for our experimental conditions, i.e. gas densities of 15 and 30 kg/m³ with an ambient temperature of 673 K, and an outlet nozzle diameter 0.14 mm were 5.25 and 2.94 ms, respectively. Our experiments were performed using commercial Swedish market sold MK1 diesel without RME whose cetane number and distillation temperature (initial and final) are close to those of the #2 diesel fuel used by Pickett et al. It is therefore

reasonable to suppose that the predicted ignition delays for the two fuels should be similar at a given fuel temperature. However, it is expected that ignition delay under our experimental conditions is slightly longer than predicted ignition delay. Since it was shown by Payri et al.[22] that there is a relationship between ignition delay and fuel temperature(T_f) as $\tau_{ig} \propto T_f^{-0.38}$. The body of injector nozzle was cooled continuously with cold tap water (temperature $\sim 288\text{K}$) in our case and it is much lower than the fuel temperature of 436 K which was used by Pickett et al. In addition, the ignition delay increases with decreasing injection pressure. The injection pressure of 1380 bar was used in prediction model, so it should underpredict the ignition delay for two of the injection pressures (800 and 1200 bar) and slightly overpredict it for the injection pressure (1600 bar) in our experiments.

Results for vapor phase images recorded up to 2 ms after start of injection (ASOI) (of the total recording time 2.6 ms ASOI) are presented. During this period, as shown in Figure 2, only at gas density 30 kg/m³, there is a risk of ignition. If it is assumed that formaldehyde is formed at this condition, strong additional UV absorption would occur and later disappear, because the formaldehyde is consumed by subsequent high-temperature combustion. This experimental observation was shown by Kosaka et al. [23]. However, this type of phenomena was not observed during the injection period in our cases. In addition, as shown in Figure A1, it further justifies that the formation of CH₂O is not expected during 0-2.0 ms ASOI, see details in Appendix. Overall, during injection event in our case, it can be assumed that the fuel composition remains constant in all of the studied cases.

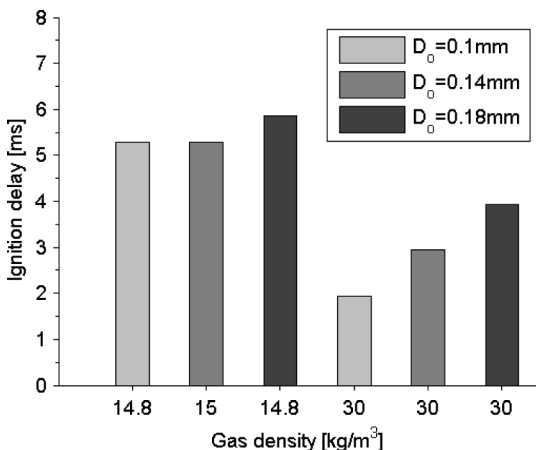


Figure 2. Predicted ignition delay based on the Equation (5). Data for gas density $\rho_a = 14.8 \text{ kg/m}^3$ and 30 kg/m^3 , nozzle outlet diameter $D_o = 0.1$ and 0.18 mm is taken from the reference [20]. Ignition delay is interpolated for $D_o = 0.14 \text{ mm}$, $\rho_a = 15$ and 30 kg/m^3 and ambient temperature 673 K. Orifice pressure drop: 1380 bar, #2 diesel fuel, fuel temperature: 436 K, ambient oxygen concentration: 21%.

Because the absorption coefficient $\epsilon(\lambda_{UV})$ is expected to depend on the ambient temperature and gas density, comparisons of estimated vapor phase volume fractions generated by the different injectors under different ambient conditions would be of questionable value. Therefore, we only compare results obtained under identical ambient conditions.

Qualitative Description for the Liquid Phase' Optical Depth

When visible light crosses the liquid droplets, the Lambert - Beer law can be used to express the liquid concentration $\bar{C}_l$ as

$$\bar{C}_l = \frac{1}{\sigma_{ext}(\lambda_v) L_l} \log \frac{I_0(\lambda_v)}{I(\lambda_v)} \quad (6)$$

where $\bar{C}_l$ is the liquid concentration; L_l is the optical path length of the liquid phase spray and $\sigma_{ext}(\lambda_v)$ is the extinction coefficient of droplets at wavelength λ_v . Since the absorption of liquid droplets in the spray can be neglected, the extinction cross section is reduced to the scattering cross section, $\sigma_{ext} = \sigma_{sca}$. The scattering cross section of the droplets depends on their diameter, and the diameter distribution should be determined for fuel concentration measurements. We did not attempt quantitative measurement of liquid phase concentration; instead, we used the optical depth (OD) to describe different region of the liquid phase spray. Three different regions were defined: the high density, the mildly diluted, and very thin liquid phase zones. For details, see the image processing section.

EXPERIMENTAL APPARATUS

A Scania XPI injector with a single-hole nozzle was mounted in the bottom part of a previously described continuous-gas-flow type high-pressure/high-temperature (HP/HT) chamber [24], and the injected fuel spray was directed upwards against the direction of air flow. The air flow rate was limited to $\sim 0.1 \text{ m/s}$, so the gas conditions inside the chamber were considered quiescent compared to the initial fuel spray velocity of over 100 m/s. The fuel temperature was controlled by cold tap water flowing around the injector head. The injection frequency was 0.2 Hz, and the fuel was a standard diesel fuel sold in Sweden (with no RME), designated MK1. A common rail fuel supply system was used together with three solenoid type single-hole injectors with nozzle geometries specified in Table 1. The conicity of the nozzle is described by the k-factor, which is calculated as $(D_i - D_o)/10 \mu\text{m}$, where D_i and D_o are the inlet and outlet diameter in μm , respectively. The nozzle configurations were selected to test the effect of conicity while maintaining a constant outlet diameter (nozzles N1 and N2), and the effect of conicity while maintaining a constant mass flow rate at the applied fuel pressure of 137.9 bar, or 2000 psi (nozzles N1 and N3). As shown in Table 2, the ambient temperature was kept constant in all cases. In each case, the energized injection pulse was set for 2.0 ms, but the actual injection duration (determined by high-speed video recordings) was about 2.6 ms.

Table 1. Nozzle specifications

Nozzle	Outlet diameter	k-factor	Hydro-grinding	Flow rate at 137.9 bar
N1	140 μm	0	30%	1.90 mg/ms
N2	140 μm	2	30%	2.09 mg/ms
N3	136 μm	2	30%	1.90 mg/ms

Table 2. Experimental conditions

Ambient temperature (K)	Gas density (kg/m ³)	Ambient pressure (bar)	Injection pressure (bar)	Injection duration (ms)
673	15	29	800, 1200, 1600	~2.6
	30	58		

Optical Setup

Figure 3 shows the optical setup for capturing liquid and vapor phase images simultaneously. Diffuse background illumination was achieved by illuminating a ground quartz plate, with the light from two halogen lamps for broadband visible light extinction, and one mercury arc lamp with strong emission at 254 nm for UV light extinction. Diffuse illumination can reduce the influence of beam steering effects. A dichroic mirror reflecting 248 ± 25 nm directed the UV light towards one camera system, and it was further filtered using a UV filter centered at 254 nm with 40 nm FWHM. The camera system consisted of one Phantom V7 high-speed video CMOS camera and a Hamamatsu C9548-04 image intensifier with a Nikon UV 105 mm lens with f/5.6. The intensifier gate time and camera exposure time were set to 25 μ s, the camera's pixel resolution was 336×136 and its spatial resolution was 3.65 pixel/mm. One Phantom V1210 high-speed video CMOS camera was used to capture visible light images with pixel and spatial resolutions of 256×640 and 6.5 pixel/mm, respectively; its exposure time was set as 10 μ s. A Nikon 50 mm lens with f/5.6 was used with the V1210 camera. Both Phantom cameras were synchronized by a Stanford Research DG645, and the frame rate was set to 36,000 Hz. One Stanford Research DG535 was set as the master, triggering both the injector driver and the DG645 at 0.2 Hz. The focus of both cameras was set on the plane normal to the nozzle tip.

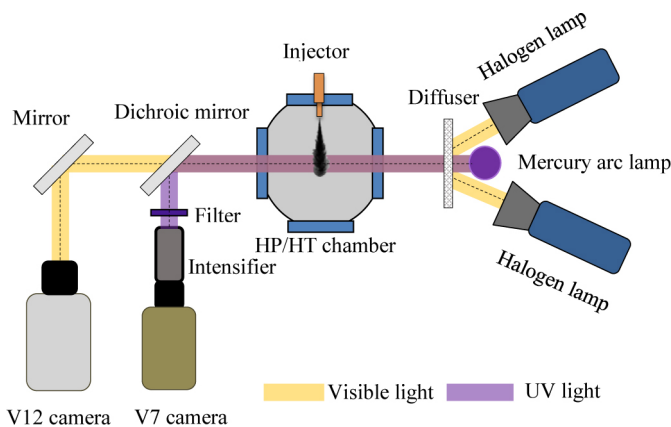


Figure 3. Optical setup for liquid and vapor phase distribution measurement.

IMAGE PROCESSING

Stability of Visible and UV Light Intensity

Given the instability in the light intensity of both the mercury arc lamp (UV light) and the halogen lamps (visible light), the light intensity varied over the course of each injection event period, especially for the UV light. The light intensity varied by less than

2.5% over an injection period in the visible images but variation of up to 30 - 40% occurred in the UV images. Consequently, it was necessary to introduce a correction term when calculating the light transmissivity (I/I_0) of the spray. It was found that although the light intensity differed in different areas of the visible or UV images, the magnitude of the change in intensity with time was identical at all points in the image, see details in Figure A2 in the appendix. In other words, the light intensity varies simultaneously and proportionally across the whole image area. To account for this variation in the light intensity, a pixel block that was not affected by the spray was selected as shown in Figure 4. The correction coefficient for each time step is calculated by normalizing the mean light intensity of selected block in the spray image against the mean light intensity of selected block in the background image. This correction was applied to all of the processed images presented below.

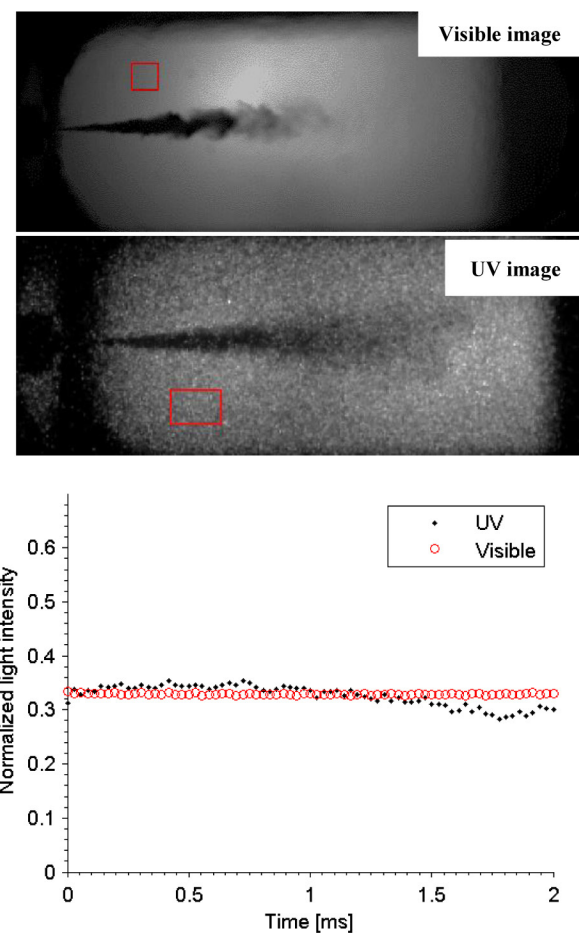


Figure 4. Normalized (by 255) the mean light intensity of selected block in visible (top) and UV (middle) images as a function of time (after the trigger signal) during one injection event shown in the graph at the bottom. Selected blocks are shown as red color squares in the visible and UV spray images. Conditions: ambient temperature 673K, ambient gas density 30 kg/m³, injection pressure 1600 bar, nozzle N2. Visible and UV images are taken at 1.418 ms ASOI.

Processing of Liquid Phase Images

The signal-to-noise ratio for the liquid phase images (taken with visible light) was higher than that for the UV images and their processing was relatively straightforward. Only one threshold value

was generally used to extract the liquid phase boundary. For example, the threshold could be defined as the midpoint of a relative light intensity slope with a logarithmic scale [6]. The spray image in Figure 5 (a) has been normalized against a background image in which no liquid spray is present, and shows the light extinction level in the liquid spray (darker colors correspond to greater optical depths). The three different liquid phase zones are indicated with red lines - the high density liquid phase zone A, the mildly diluted zone B, and the very thin density liquid phase zone C.

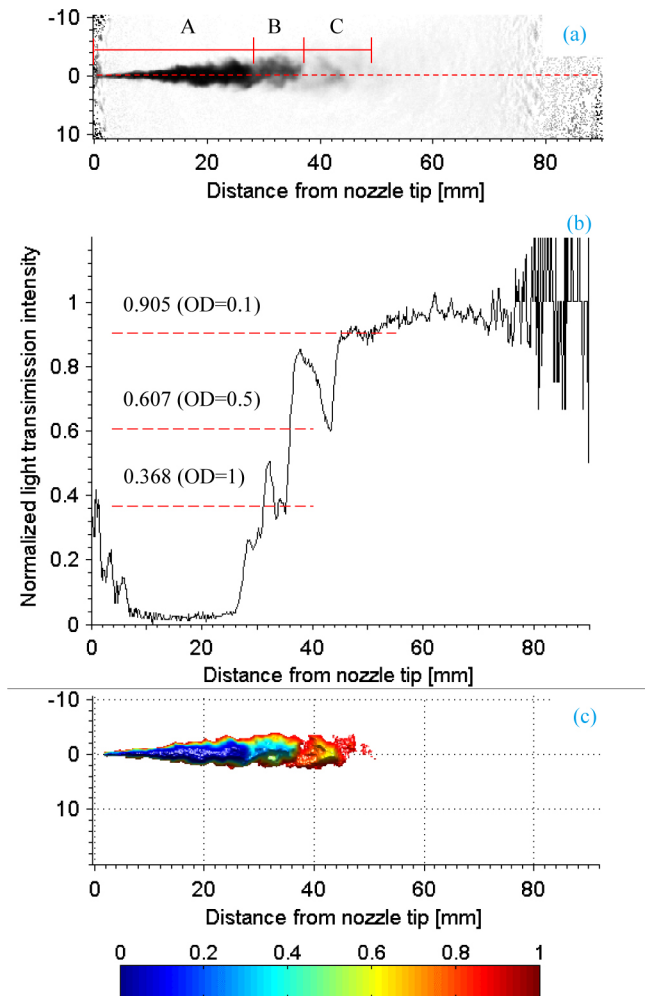


Figure 5. Liquid phase image processing. Experimental conditions: Ambient temperature 673 K, gas density 30 kg/m³, injection pressure 1600 bar, 1.418 ms ASOI, and nozzle N2. (a): Normalized spray image, red dot line is along the nozzle tip axis. Zone A: high density liquid phase zone. Zone B: mildly diluted zone. Zone C: thin density liquid phase zone. (b): Normalized light transmission intensity along the nozzle tip in the image (a). (c): Converted color map image from image (a).

These three zones are defined by three different levels in the light transmission intensity curve as shown in Figure 5 (b). In our case, to extract the whole area with the liquid droplets present, a threshold corresponding to 0.905 (i.e. 231 out of 255 or OD=0.1) was used. Pixels with values above the threshold 0.905 (corresponding to an OD below 0.1) are considered as part of ambient gas, because the light attenuation in the corresponding regions is very low and the liquid droplet density is only a small fraction of that in the vapor phase regions of the spray. When selecting the lowest threshold value,

it is important to recall that the results are not influenced by noise and other effects not related to droplet scattering, such as the schlieren effect of the vapor phase in front of the spray head (see at the right edge around 75 mm from the nozzle tip in Figure 5 (a)). Liquid lengths shown in figures below measured for optical depths of 0.1 and 0.5.

After the lowest threshold is determined from a plot such as that shown in Figure 5(b), the normalized image is displayed as a color map image as shown in Figure 5 (c). Figure 5 (c) clearly shows that the high density liquid phase zone is in the center of the spray (corresponding to the light and dark blue regions), while the low density liquid zone is shown in red.

Processing of UV images

The UV images were processed using a five-step process involving: 1) normalization against a background image recorded immediately before the injection event - a representative normalized image is shown in Figure 6 (a); 2) masking the normalized image to extract only the interesting spray region; 3) filtering the masked image using a median filter with matrix 8×8, which proved suitable for our purposes - the normalized light intensity along the spray axis with different median filter matrix sizes is shown in Figure 6 (b); 4) converting the filtered image into a binary image with a threshold value of 0.8 (OD=0.22) to detect the fuel-containing spray region; 5) determining the binary image area in the originally normalized images by filtering with a median 5×5 matrix filter to yield a final image as shown in Figure 6 (c). Note that the term 'UV image' refers to an image acquired using UV light that might contain both liquid and vapor phases, whereas 'vapor images' depict only the vapor phase that obtained through excluding liquid phase from the UV images.

Because of the fluctuation and the weakness of the light intensity at the UV wavelength of 254 nm in the mercury arc lamp, UV spray image exhibited salt-and-pepper noise as shown in Figure 6 (a). The normalized light transmission intensity along the nozzle tip central line is drawn as shown in Figure 6 (b).

Except for the area close to nozzle tip, there are two distinct light intensity slopes A and B as shown in Figure 6 (b). These two slopes correspond to the edges of the dense liquid core and the vaporized fuel, respectively. Based on slope B, a threshold value can be chosen to extract the area of the image in which both the liquid and vapor spray are causing light attenuation. As can be seen in Figure 6 (b), the original normalized light transmission intensity fluctuates strongly, and the relatively noisy character of the UV image is due to the comparatively weak light source and the use of the image intensifier. To reduce the influence of such fluctuations, median filters with different matrixes were tested. With matrix 3 (3×3), there are still strong fluctuations, and a risk of identifying noise outside of the fuel cloud. However, matrixes 5 (5×5) and 8 (8×8) make the normalized light intensity much smoother while preserving the image's dynamic information; the larger matrix 10 (10×10) removes some dynamic information and introduces a risk of measuring out the border between the spray and the surrounding air. The 8×8 matrix is

considered most suitable for edge identification in the current set of images because it can remove noise effectively without significantly distorting the spray edge.

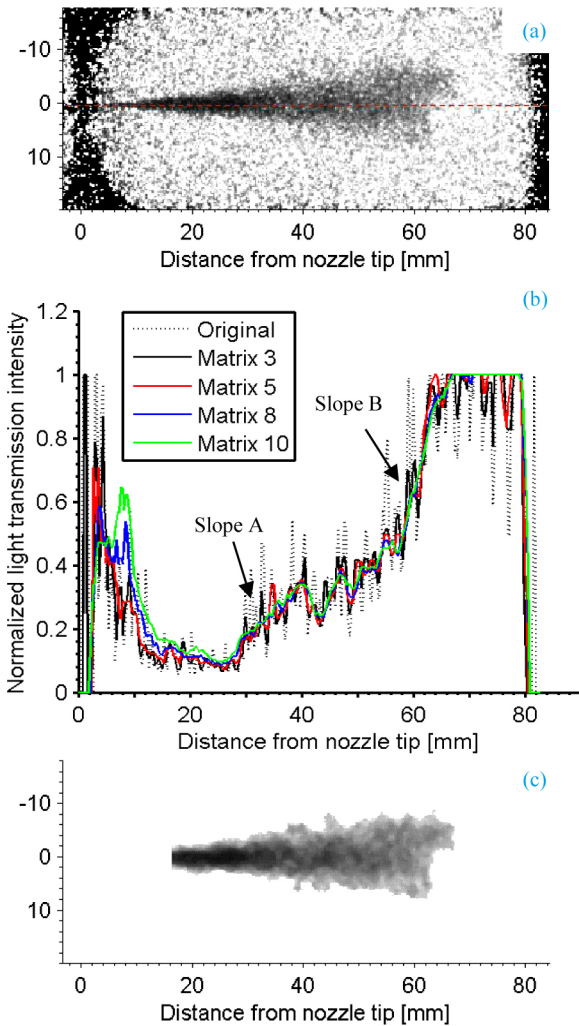


Figure 6. UV image processing. Experimental conditions: Ambient temperature 673 K, gas density 30 kg/m³, injection pressure 1600 bar, 1.418 ms ASOI, and nozzle N2. (a): Normalized raw image, red dot line is central line along the nozzle tip. (b): Light transmission intensity along the central line of image (a). (c): Processed image from image (a).

The selected threshold level is based on analyses of the normalized light transmission intensity with different median filter matrixes. As shown in Figure 6 (b), slope B is steep and a threshold value anywhere between 0.6 and 0.9 could reasonably be selected. With a low threshold of 0.6, regions of the UV image with low light attenuation (including some parts of the vapor phase regions) might be removed, whereas a high threshold of 0.9 may not be very effective at eliminating noise. Based on these considerations, an intermediate threshold of 0.8 was used to determine the spray edge.

The normalized image is masked to eliminate regions that are obviously not part of the spray and include areas where fuel is present. As can be seen in Figure 6 (b), the light transmission intensity near the nozzle tip is low, but not as low as in the visible image, which it should be in reality. Furthermore, applying a median filter in the area where the spray has a small width may result in overly high

transmission in the filtered images. Therefore, the regions of the UV images corresponding to the distances of less than 16.4 mm from the nozzle tip were not further analyzed. The removal of this area does not affect the vapor phase dominated area further downstream.

After the relevant part of spray has been defined, the original normalized image is filtered with a 5×5 matrix using a median filter in order to preserve the dynamic information in the image as much as possible, while still smoothing it and reducing noise.

Combining Visible and UV Images

The visible and UV images shown in Figures 5 (c) and 6 (c) were acquired simultaneously, and Figures 5 (c) and 6 (c) were combined as shown in Figure 7 (a). This image clearly shows that the vapor phase region in the UV image is not detected by the visible light shadow imaging technique used to generate the liquid phase image, implying that the vapor phase region of the vaporized spray can be captured successfully by using UV light and an image intensifier. Moreover, the vapor phase boundary is larger than liquid phase boundary in Figure 7 (a), indicating that the detection of the vapor phase boundary is not affected by the liquid phase.

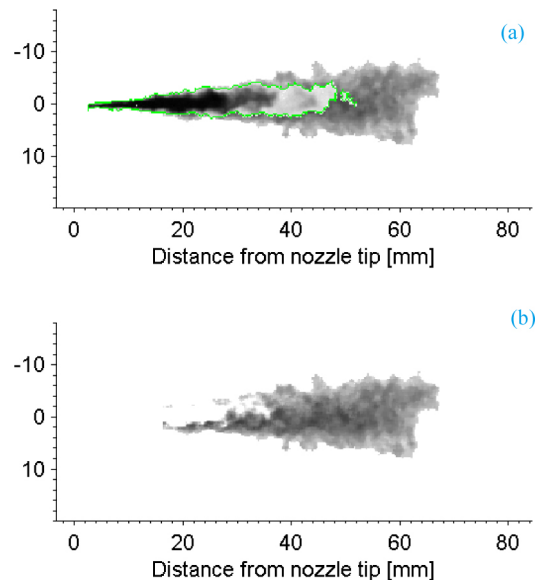


Figure 7. (a): Combined visible and UV images. Green line is liquid phase boundary of Figure 5 (c). (b): Vapor phase image where the light attenuation by droplet scattering in the UV images has been compensated. Images are based on the UV image Figure 6 (c) and liquid phase image of Figure 5 (c).

Based on Equation (3), the light attenuation intensity of the vapor phase can be calculated as:

$$\left[\frac{I(\lambda_{UV})}{I_0(\lambda_{UV})} \right]_{v,ab} = \frac{I(\lambda_{UV})}{I_0(\lambda_{UV})} / \left[\frac{I(\lambda_V)}{I_0(\lambda_V)} \right]_{l,sc} \quad (7)$$

Light attenuation in the UV image is partially due to the liquid phase scattering. Therefore, to extract the light attenuation due to the vapor phase alone, the processed UV image is normalized against the processed liquid phase image. Figure 7 (b) shows the light attenuation due to the vapor phase. Comparing Figures 7 (b) and 6 (c), it can be