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Droplet Size Development in a DISI Injector Fuel Spray

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Keywords Droplet Size Distribution, Evaporation, PDA measurement, Joint PDF, Dense Sprays, Internal Combustion Engine.

ABSTRACT

In this work, Phase Doppler Anemometry (PDA) measurements are used to test the hypothesis that the mean droplet size in Direct Injection Spark Ignition (DISI) engine fuel spray increases with distance from the injector due to the evaporation of the smaller droplets. In order to understand the role of evaporation, two velocity components and drop size PDA measurements were performed for one plume of a DISI injector using two fuels with widely differing vapour pressures. The measurements were taken along the plume centreline at four different vertical distances from the injector tip between 20 to 50 mm. on the plume centreline to evaluate the development of droplet size distributions along the plume. Measurements are also made across the plume (perpendicular to the plume centreline) at the 30 and 50 mm locations. Measurements using PDA closer to the injector are more difficult due to the high spray density (particularly apparent at 20mm or closer to the injector). A data fitting process is suggested using joint probability distribution functions (JPDFs) to reduce the effect of statistical significance where data rates are low. This improves the description of the PDA derived drop size distribution in regions where the data validation rate is poor. It is found that the evaporation is not the main cause for droplet size increase along the plume. The most likely reason for the increase of the Sauter Mean Diameter (SMD) with distance from the injector is that the smaller droplets move away from the plume centreline through turbulent diffusion at a higher rate compared to larger droplets. Higher axial momentum of the larger droplets reduces their response to turbulent velocity fluctuations and hence their path-lines are less prone to stray from their initial trajectory.

1. Introduction

Due to the pressure of reducing vehicle CO₂ emissions emphasis in automotive research is placed on development of efficient internal combustion (IC) engines. The employment of the Gasoline Direct Injection (GDI) concept, particularly in downsized turbocharged engines, is a way to reduce CO₂ emissions while potentially not increasing other hazardous gaseous emissions. It has the advantages of precise fuel control, fast response and knock suppression capability. It can however produce increased levels of particulate emission in comparison to a Port Fuel Injected (PFI) engine, due to issues such as the impingement of fuel on the combustion...
chamber surfaces or poor mixing for example. It is therefore important that the break up and atomisation process of the DISI injector spray is well understood to enable successful operation of a GDI engine. Here we focus on an issue related to mixing.

Phase Doppler Anemometry (PDA) is widely used in research to perform non-intrusive measurements on the fuel spray, measuring both droplet size and velocity of individual drops. When analysing the PDA data, it is often noticed that for GDI injector spray the measured mean droplet size increases along the plume centreline as the measurement position moves away from the injector tip. This phenomenon is non-intuitive and it is commonly thought that the mean droplet size would decrease as the plume penetrates further down the stream due to droplet break up and/or evaporation. This phenomenon is also observed by other researchers (Long, 1996, Postrioti, 2012 and Tu, 2014) and the reason for the drop size statistic increasing is usually explained to be the evaporation and hence the disappearance of small droplets in the plume which increase the overall mean droplet size. However, the authors are not aware of published evidence to support this explanation.

The study presented here was carried out in order to gain an initial understanding of this phenomenon by using two fuels with very different vapour pressures. A comparison of the average droplet size as well as the droplet size and droplet velocity distributions of these two different fuel sprays can provide evidence to determine the validity of the common hypothesis that evaporation removes small droplets with increased distance from the injector tip. In this study, the authors also present a reduced order model to represent the joint droplet size and droplet velocity probability distribution function (JPDF). This model could help within modelling as a compact way to describe a spray as an initial condition in a computational prediction for example. More importantly, it could be used to increase the confidence in PDA measurements made at near nozzle regions where the measurement validation rate is not high, hence statistical confidence is low without very time consuming measurement campaigns.

2. Methodology

In order to examine the reason for the increase in droplet size statistic, PDA measurements were conducted along the spray plume of a GDI injector at different axial distances (from 20 to 50 mm). The PDA system has been optimised for accuracy and resolution when applied to typical automotive fuel injectors and is a system that is described fully in other publications such as Wigley et al, 1999, and is not described in detail here.

The measurement locations are shown in Figure 1 and the test matrix explored in this paper is listed in Table 1. Overall, measurements were made at 4 points on the plume centreline in order
to understand the trend of the average droplet size increasing along the plume. Measurements were also made through the plume perpendicular to the plume direction at two distances (30 and 50 mm) in order to understand the droplet spreading in the directions perpendicular to the axis. The injector was operated with a fuel pressure of 20 MPa and injection was into free air under nominal atmospheric conditions. For this study a relatively long injection duration of 5 ms was used, typically yielding around >35,000 individual measurements, but only the data acquired in the ‘steady state’ part of the spray have been analysed where no significant variation of D32 is seen in the running average of 400 samples. Thus each PDF is formed from around 20,000 samples (except at 20 mm). The vapour pressures of the two fuels used to provide different evaporation characteristics, by a factor of around 20, are described in Table 2.

![Fig. 1 The vertical axial locations of PDA measurements.](image)

<table>
<thead>
<tr>
<th>Axial Location</th>
<th>Radial distance to plume centre (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>30</td>
<td>-14 -10 -6 -2 0 2 6 10 14</td>
</tr>
<tr>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>50</td>
<td>-20 -14 -9 -4 0 4 9 14 20</td>
</tr>
</tbody>
</table>

Table 1 Measurement locations.
3. Results and discussion

A trend in PDA results of increasing droplet diameter with plume wise distance from the injector nozzle tip is commonly reported and attributed to evaporation of smaller fuel droplets leading to an increased weighting towards larger droplets the farther the spray has travelled away from the injector (Long, 1996, Postrioti, 2012 and Tu, 2014).

Although n-Heptane and Exxsol D40 have significantly different vapour pressures (described in Table 2) and therefore different evaporation characteristics, both fuels display a similar trend in the relationship between D₃₂ diameter and distance from the injector nozzle tip as shown in Fig 2. Although using the same injector, the initial drop distributions for the two fuels are different due to their differing viscosity and surface tension (described in Table 2). However, despite this initial difference the SMD (D₃₂) statistic increases by approximately 1μm between the 20 mm and 50mm locations along the plume for both fuel types. Since the evaporation characteristics of the two fuels are significantly different, this indicates that it is in fact another mechanism, other than evaporation, that is dominating the observed characteristics.

As the spray becomes less dense the farther it travels from the injector nozzle tip, the measurement of all droplets becomes easier, since there is less optical obscuration within the measurement paths from other passing droplets. At any condition, large droplets within the system measurement volume present the easiest PDA measurement, since they return the largest signal level. Therefore in dense sprays it can be possible for the averages recorded to be biased towards larger droplets, however the fact that the D₃₂ continues to rise here with distance as the spray density decreases gives strong evidence that there is a genuine increase in the number of large droplets compared to smaller droplets as the distance from the injector is increased.

### Table 2 Properties of the test fuels.

<table>
<thead>
<tr>
<th>Property (at 20°C)</th>
<th>n-Heptane</th>
<th>Exxsol D40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vapour pressure</td>
<td>5.3 kPa</td>
<td>0.27 kPa</td>
</tr>
<tr>
<td>Surface Tension</td>
<td>20.14 mN/m</td>
<td>25 mN/m</td>
</tr>
<tr>
<td>Dynamic Viscosity</td>
<td>386 μPa.s</td>
<td>845 μPa.s</td>
</tr>
<tr>
<td>Density</td>
<td>680 kg/m³</td>
<td>776 kg/m³</td>
</tr>
</tbody>
</table>
The arithmetic mean ($D_{10}$) droplet size data for the fuels indicate a less clear relationship than the $D_{32}$ results. Exxsol D40 indicates a slight increase in $D_{10}$ droplet diameter with distance from the nozzle between 20 and 50 mm, whilst the n-Heptane indicates a rise to a peak at around 35 mm plume wise distance before a slight reduction. The level of variation in each example of around 1 µm is considered to be within the noise boundary of the measurements, so the relationship could be considered to be nominally flat.
Fig. 3 Histogram of n-heptane and D40 droplet size at different distances.

Histograms of droplet size for n-heptane and Exxsol D40 at different distances were plotted (Figure 4) in order to understand the effect of droplet distribution on the average droplet size. A similar trend is observed for both fuels; as the measurement distance increases from 20 to 50 mm, the probability of small size droplets (less than 5 µm) increases. This is due to the PDA measurement having higher validation rate in the less dense spray found at this measurement location farther from the injector nozzle. Alongside this increase in the probability of small droplets, the probability of medium size droplets (between 5 µm and 15 µm) decreases. These would actually have a negative impact on the trend of increasing mean droplet size. Thus the real reason for the increase of the average droplet size is the slight increase in the proportion of the large droplets (higher than 15 µm). This compensates the effect of the higher proportion of the small droplets and enlarges the total average droplet size.

In conjunction with the droplet size data, the probability distribution function for each droplet’s velocity perpendicular to the plume direction and size combination were plotted for the central location in the plume at four vertical heights (Figure 5, Figure 6). These JPDFs illustrate that as the spray moves away from the injector, the proportion of larger drops in the sample is seen to increase, in line with the findings of others mentioned earlier. In addition, with increasing distance from the injector, the outward movement of droplets perpendicular to the direction of the sprays is seen to reduce. This indicates that smaller particles are dispersed outwards from the spray centreline close to the injector, whilst the larger particles - with greater momentum - continue in a more plume-wise direction, hence the larger droplet size proportion as the distance from the injector increases. The ‘arrow head’ shape of the JPDF becomes sharper with increasing distance from the injector.
Fig. 5 JPDF of heptane for Droplet velocity (m/s) vs. Droplet diameter (µm).

Fig. 6 JPDF of Exxsol D40 for Droplet velocity (m/s) vs. Droplet diameter (µm)
Figure 7 shows the $D_{10}$ and $D_{32}$ for measurements made across the plume at vertical distances of 30 and 50 mm. Generally the average droplet size at a given vertical height is greatest at the plume centre. This supports the hypothesis that the small droplets are continuously moving outward due to the high rms velocity which results in higher droplet size on the plume centreline.

The JPDFs in Figure 5 and Figure 6 contain rich information about droplet size and droplet velocity distributions, however the data at the near nozzle region is inherently subject to a low validation rate because of the dense spray and hence the difficulty in taking high quality PDA measurements with high statistical significance. Figure 8 shows the three dimensional view (Figure 8 a) and lateral views (Figure 8 b, c, d) of the JPDF. In order to reduce the statistical noise level a mathematic model is created to describe the JPDF. Based upon the plots of the type shown in Figure 8, two assumptions were made: 1) The droplet size distribution function is a log-normal distribution function (Figure 8 b). This assumption corresponds to the commonly
recognised concept that aerosol size distribution is log-normal distribution. 2) The droplet velocity distribution function is a normal distribution function. A model is created to describe the JPDFs of heptane and Exxsol D40 in the centre of the plume based on these two assumptions.

\[
P(v, d) = B(4) \frac{1}{B(2)\sqrt{2\pi}} e^{-\left(\frac{(d-B(1))^2}{2B(2)^2}\right)}
\]

\[
P(v, d) = B(4) \frac{1}{\sqrt{2\pi}} e^{-\left(\frac{\ln^2(v)}{2B(3)^2}\right)}
\]

where \(P\) is the probability of droplets with a specific velocity, \(v\), and diameter, \(d\). \(B(1)\) and \(B(2)\) are the parameters affecting the shape of the log-normal distribution, \(B(3)\) is the parameter affecting the normal distribution and \(B(4)\) affects the magnitude of the fitting model to ensure the JPDF is properly scaled.

It is acknowledged this is an idealised model and may hide some real deviations from theoretical droplet distribution expectation but the spatial distribution of the reduced order model parameters, \(B(n)\), would be expected to vary in a smooth and predictable way. In this way the model presents a methodology to interpolate between spatially sparse measurement sets. The model PDF also offers the possibility of some extrapolation should the parameters have suitably behaved derivatives, providing it did not attempt to move into the primary breakup region for example where significant size redistribution could be happening.

The four model parameters determine the shape and magnitude of the fitting surface. By tuning these four parameters, the model could be adjusted and compared to the JPDF data measured using PDA. Currently a coefficient of determination, \(R^2\), is used to estimate the level of fit of data to the model. Using an iterative solver coded in Matlab, the parameters were optimised to yield the highest \(R^2\) value. (Significant improvements in this approach are possible but not considered further here.) In this way, the large PDA dataset is represented by a significantly reduced set of parameters and can therefore more easily integrated into simulations through algebraic descriptions of the JPDF shape. Moreover, this approach will allow the experimental noise to be reduced in high spray density regions (i.e. in the near nozzle region) where the PDA system struggles to make statistically significant JPDF measurements due to low validation rates.

In this study, JPDF data obtained at far distances (i.e. 30 mm, 40 mm, 50 mm) is used to validate the model, which is then subsequently used to fit to the data obtained at the near nozzle region (i.e. 20 mm) where the data quality is low due to the density of spray. It would be unwise to fit the model to data closer to the nozzle than 20mm since at some point before 20mm the spray is within its primary breakup stage where the formation and tearing of ligaments of spray will not
fit with the model which is based upon data from the second breakup region of formed droplets. The authors are confident that the spray passed through the secondary breakup region beyond 20 mm as the droplet size measured here is smaller than at 50 mm, meaning that the break-up process has finished before the spray reaches the 20 mm location.

![Figure 8](image)

**Fig. 8** Three dimensional view (a) and lateral views (b, c, d) of the JPDFs

Figure 9 illustrates the model’s representation of the raw data presented in Figure 8. It can be seen that, subjectively, the model and raw data look very similar, although increased surface smoothness of the model is clear. The $R^2$ of the fitting process in this case is 0.9403 which indicates a good fit (1 representing a perfect match and 0 no match). Generally, for all the cases, $R^2$ values in less dense spray (> 30 mm) and the fittings for them are higher than 0.9 (Table 3). This demonstrates that this model represents the JPDF data with some fidelity. For the measurements made at near nozzle region (i.e. 20 mm to nozzle), the $R^2$ values are relatively low.
(around 0.7, shown in Table 3). This is due to absorption of the PDA laser signal in the dense spray at the near nozzle region reducing the data rate. Therefore there is higher uncertainty on the JPDF values due to statistical significance as a result of reduced sample population. This appears as a ‘noisy’ surface.

![Fig. 9 Model JPDFs based on experimental data of Fig. 8.](image)

<table>
<thead>
<tr>
<th>Distance (mm)</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-Heptane</td>
<td>0.6952</td>
<td>0.9096</td>
<td>0.9279</td>
<td>0.9403</td>
</tr>
<tr>
<td>Exxsol D40</td>
<td>0.7544</td>
<td>0.8853</td>
<td>0.9476</td>
<td>0.9526</td>
</tr>
</tbody>
</table>

Table 3 R squared values for fittings at different distances.
After validating this model, it was used on PDA measurement made in dense spray. Figure 10 shows the PDA measurement JPDF (a and c) and the model JPDF (b and d). The experimental JPDF data in this plot is ‘noisier’ than that shown in Figure 8 due to sample size reduction. However, as described previously, after the secondary break-up region, the spray drop size and velocity distributions may be expected to have considerable similarity, thus the data could be better interpreted by using the model. The method can also be used to calculate the $D_{10}$ and $D_{32}$ for different distances. In Figure 11 it can be seen that the $D_{10}$ obtained from the model and directly from the measurement statistic are within 0.2 $\mu$m at all locations. This good agreement between model and measurement shows that generally the model has the capability of representing the droplet size distribution with reasonable accuracy. However, a difference is observed between the model calculation and the measurement of $D_{32}$ of heptane. This means that the model does not fit well in some cases. This may be due to particular difficulties in fitting a log-normal distribution to imperfect data, or a few spurious large drops biasing the statistic. More advanced model fitting approaches are available and these may alleviate some of these problems by taking a more rigorous statistical significance based approach.
4. Conclusions

This work has examined the hypothesis that the mean droplet size of a DISI fuel spray measured by PDA increases with distance from the injector tip because of evaporation of smaller droplets. The tests involved taking and comparing PDA measurements of two fuels with differing vapour pressures, to evaluate the validity of this hypothesis. In addition, a model was also created in order to gain more understanding of the droplet size and droplet velocity distribution and improve data interpretation in dense spray regions and providing a method to simplify the representation of the large data set. The following conclusions are drawn after the completion of this study:

1. Fuels with differing vapour pressures were shown to exhibit a similar trend in droplet size development with distance from the injector. Evaporation therefore did not appear to be a consistent explanation for the increase in $D_{32}$ as the distance from the injector increased.

2. A small increase of the proportion of the large droplets compared to small droplets in the measurement distribution is the reason for the overall $D_{32}$ increase.

3. Evidence was provided that suggests the increase in the proportion of larger droplets with distance from the injector is due to different levels of turbulent diffusion for different droplet sizes: smaller droplets move away from the plume centre more preferentially through turbulent diffusion.
4. The reduced order model of the JPDF represents the experimental data well, with correlation coefficients of around 0.9 obtained at far distances from the nozzle. It also produces a good estimation of $D_{10}$ and $D_{32}$, to within 0.2 $\mu$m.

5. Aside from being useful for inferring data in areas where the PDA efficiency is low due to poor validation rates, this tool is also valuable for modellers to understand the droplet size and velocity distribution structure and for convenient and efficient representation of the droplet size-velocity relationship through the spray.

**Acknowledgements**

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