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# Spray-tip droplet SMDs of intermittent high-pressure sprays of diesel fuel compared with coal-water slurry sprays

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An experimental study investigated droplet-size characteristics near the spray tip of intermittent sprays of diesel fuel from an electronically controlled accumulator injection system. A modified laser-diffraction particle-analysing technique (Malvern 2600C system) optically synchronised the data taken with the spray penetration, so that the Sauter Mean Diameter (SMD) could be measured at low obscurations without multi-scattering bias. Measurements were made at axial locations 60, 80, 100 and 120 mm downstream of the injector orifice with 0.2 and 0.4 mm diameter orifices. Injection pressures studied were 28, 56, and 83 MPa g, and measurements took place in both pressurised (2.07 MPa g) and unpressurised chamber conditions. The spray-tip SMD increased with ambient gas density and axial measurement location, and fell inversely with injection pressure. Dependence of SMD on nozzle orifice diameter was negligible for fully developed sprays. A regression equation for the SMD ($\mu$m) was found as SMD = $1.402\Delta P^{-0.451}\rho_a^{0.1588}x^{0.8977}$ where $\Delta P$ is in MPa gauge, $\rho_a$ is the ambient gas density in kg m$^{-3}$, and $x$ is the axial measurement location in mm. These results show characteristics consistent with previous studies where coal-water slurry was the atomised liquid. Quantitatively, under identical injection conditions the droplet SMDs of diesel sprays were always smaller than those of coal-water slurry. Parametric comparisons for the two types of injected fuels are presented.

## 1 List of symbols

| | |
|---|---|
| $D$ | diameter of injector nozzle orifice, mm |
| $d_{32}$ | Sauter Mean Diameter, mm |
| $L_b$ | spray break-up length, mm |
| $\Delta P$ | fuel-injection pressure, MPa |
| SMD | Sauter Mean Diameter, $\left(\sum_i N_i D_i\right)/\left(\sum_i N_i D_i^2\right)$ |
| $x$ | axial distance measured from the injector nozzle, mm |
| $\rho_a$ | density of ambient gas, kg m$^{-3}$ |
| $\rho_f$ | density of fuel, kg m$^{-3}$ |

## 2 Introduction

Fundamental understanding of the effects of injection parameters on the atomisation process is a prerequisite to the design of an operational fuel-injection system for a diesel engine. The spray tip or front is the first area exposed to high diffusion rates due to the high temperatures and relative velocities of the compressed gas in the cylinder. Most studies characterise 'whole' sprays, where entire droplets in a single injection are measured, but few focus on measuring droplet diameters in the spray tip. The objective of the present study was to resolve some unknowns of the spray-tip droplet characteristics of high-pressure intermittent diesel-fuel sprays. The droplet sizes were obtained as a function of injection pressure, density of ambient gas, location of axial measurement and diameter of injector orifice.

Hiroyasu & Kadota[1] studied characteristics of 'whole' diesel sprays from high-pressure injection using a liquid-immersion technique; they found that the Sauter mean diameter (SMD) increased with back pressure. This finding

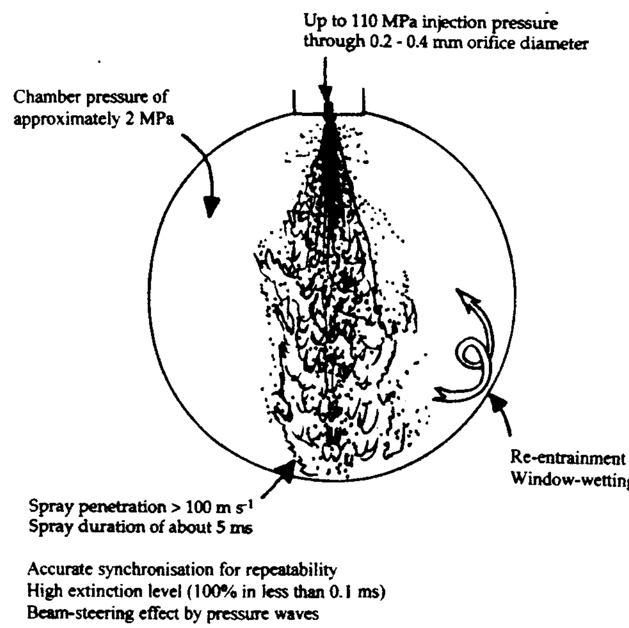


*Fig.1 Expected difficulties in the measurement of droplet sizes for intermittent high-pressure coal-water slurry sprays.*

is the reverse of Taylor's theory[2] that raising the ambient gas density for the case of low-pressure injection (significantly lower than diesel injection pressure) produces smaller droplets because of the greater viscosity and density of the ambient gas. In the previous study of coal-water slurry (CWS) in intermittent high-pressure sprays[3], the spray tip SMD showed an increase with back pressure, as found by Hiroyasu & Kadota[1]. This finding was attributed to the fact that the slower spray penetration and

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shorter break-up length under higher back pressure contribute to the enhancement of droplet coalescence and lead to larger SMDs. This consistency needs to be examined for diesel-fuel (DF2) sprays at similar injection conditions.

Many difficulties have to be overcome in the measurement of droplet diameters near the spray tip (Fig.1). The extremely high injection pressure generates a spray penetrating at a maximum speed above 100 m $s^{-1}$, and the pressure (density) wave generated by such a fast spray may steer the laser beam and bias the laser-diffraction measurement data. For the measurement location closest to the injector exit, where the pressure wave is stronger, the first one or two photo-detector diodes near the beam centre detect the false signal resulting from the steered laser beam; this false signal has to be eliminated carefully.

The central diodes seldom receive scattered signals from real droplets, because the detection range of the central one or two diodes is usually higher than the diameter range of the diesel sprays. Therefore signals detected by the central diodes most likely reflect the beam-steering, and simple elimination of these signals can resolve the problem; this is called a 'kill diode' operation[4]. The chamber must be depressurised and pressurised again after each injection to clean the quartz window thoroughly and prevent any measurement biasing that may occur from window wetting of re-entrained spray droplets. The spray lasts approximately 5 ms and the spray tip penetrates the laser beam rapidly, which results in 100% obscuration in less than 0.1 ms. A precise synchronisation technique is necessary to ensure that the measurement is not made at too high an obscuration level.

## 3 Experimental facility

Fig.2 shows the electronically controlled hydraulic accumulation injector with a pressure chamber to simulate a diesel-engine cylinder, the Malvern diffraction particle sizer, and the optical synchroniser. The injector lifts the needle for 5 ms duration by means of the electromagnetic servo valve. For these experiments, the injector is operated in a 'single-shot' mode, which eliminates the interference of subsequent injections. Nitrogen gas pressurises the chamber, which has quartz windows 25.4 mm thick at both ends to allow optical access for measurement of the drop diameter. The optical probe of the Malvern had been reduced to a 4.5 mm diameter cylindrical shape to enhance the spatial definition of measurement. Distribution of the droplet size is assumed to follow the Rosin-Rammler two-parameter model[5].

Most previous studies have used a specified time delay after the needle lift as a triggering source, in an attempt to match the spray arrival with data-taking. In this study, however, automatic optical triggering is used, since it ensures more accurate synchronisation and repeatability[6]. An instantaneous extinction level of the incident laser beam is monitored from the Malvern detector, and the devised synchroniser unit sends a 5 V square pulse back to the detector for initiation of data-taking, but only if the instantaneous extinction level exceeds a specified value. This allows a one-time single-sweep measurement per spray and achieves highly synchronous measurements for successive sprays under identical injection conditions. SMD measurements for each injection condition were repeated up to 15 sprays for statistical averaging. More detailed descriptions of the electronically controlled accumulator injector system and the optical synchronisation technique are presented elsewhere[7,8,9].

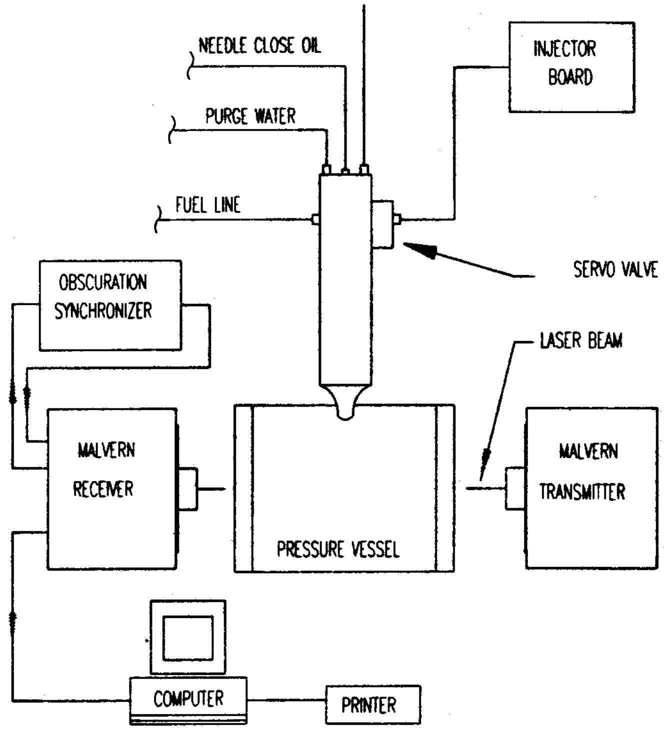


*Fig.2 The accumulator injector and droplet sizing system.*

Yu *et al*[10] measured droplet sizes synchronised with intermittent injection under limited injection conditions, and the results obtained by an LDPA technique were presented for the spray-tip region. The measurements were made for different radial locations at a fixed axial distance from the nozzle, and showed a gradual increase in droplet SMD with radial distance from the spray axis. Droplet SMDs of CWS sprays were larger than the diesel SMDs when the injection conditions were identical. The effects of the chamber-gas density and the axial spray location on the spray SMDs have not been presented in their paper. The geometrical configuration and size of Yu's injectors were different from the present ones, and their measurement was made at different axial locations and at different injection pressures. Nevertheless, comparison of the present results against those data has been attempted wherever possible, and the comparison is discussed in the next section.

## 4 Results and discussion

The first part of this section compares selective results for CWS sprays with those for current DF2 fuel; the previous report[3] presented complete and extensive data for CWS sprays. The second part presents and discusses spray-tip SMD data for DF2 fuel sprays and the individual effects of injection pressure, measurement location, density of ambient gas and diameter of the orifice on the spray development and mean droplet diameters.

Table 1 Experimental test matrix and average SMD for 50% wt coal-water slurry sprays.

| Case | Orifice diameter (mm) | Fuel injection pressure (MPa) | Density of chamber gas (kg m$^{-3}$) | Measurement location (mm) | Average SMD (μm) |
|---|---|---|---|---|---|
| Base case | 0.4 | 83 | 25 | 120 | 49.15 |
| Orifice diameter | 0.2 | 83 | 25 | 120 | 47.22 |
| Fuel injection pressure | 0.4 | 28 | 25 | 120 | 92.50 |
| | | 55 | | | 66.89 |
| | | 110 | | | 31.85 |
| Density of chamber gas | 0.2 | 83 | 1.2 | 120 | 19.37 |
| Measurement location | 0.2 | 83 | 25 | 60 | 15.94 |
| | | | | 80 | 23.81 |
| | | | | 100 | 38.30 |

## 4.1 Summary of coal-water slurry results

Table 1 summarises the tested parametric conditions for CWS sprays and the result of SMDs averaged for up to fifteen individual injections for each parametric condition. The injected liquid was CWS fuel containing 50% weight concentration of micronised coal particles of approximately 5 μm mean diameter. Selected presentation of the size spectrum for each condition follows.

Fig.3 presents light signals detected by the array of ring diodes under different injection conditions. For each injection condition, the detected light energies (in arbitrary scale) versus the ring diodes are shown as in the Malvern computer output. The energy spectrum from a spray with larger SMD establishes a peak at lower-numbered diodes, and a spray with smaller SMD shifts a signal peak at higher-numbered diodes.

The signal peak gradually shifts towards the lower-numbered diode as the measurement location rises from 60 to 120 mm; this shows an increase of SMD with increasing spray penetration. One reason for this would be that larger droplets penetrate deeper than smaller ones. Larger droplets carry higher momentum and inertia, whereas smaller droplets quickly lose their momentum because of their larger drag:inertia ratio; they spread radially outward and fall behind the larger ones. Increased coalescence between droplets with greater travelling distance also contributes to the increase of SMD at downstream measurement locations. Similar trends of droplet SMD were seen for diesel-fuel sprays[11] and were analytically predicted[12].

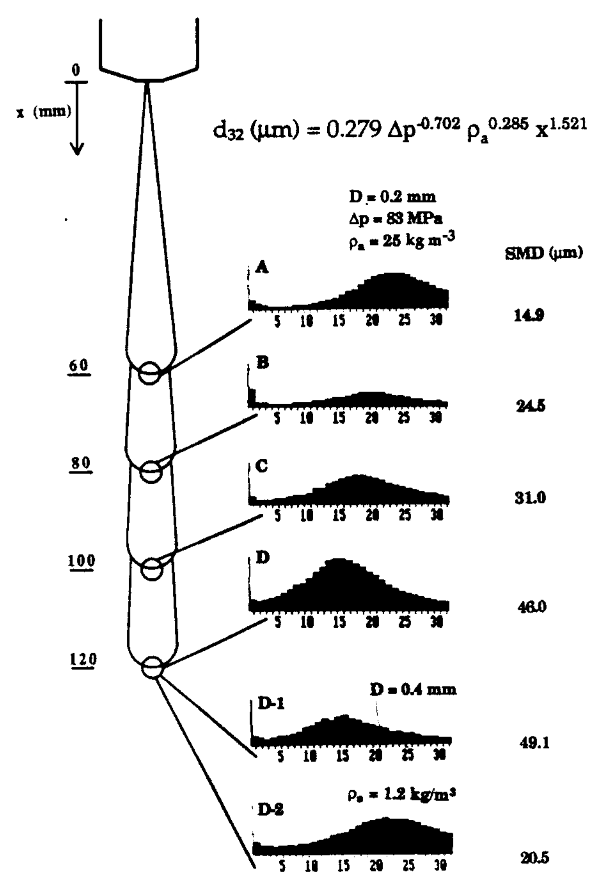


*Fig.3 Light-scattering signals detected at different measurement locations: A to D for 0.2 mm diameter orifice, 83 MPa injection pressure, 25 kg m$^{-3}$ gas density; D-1 for 0.4 mm orifice diameter; D-2 for 1.2 kg m$^{-3}$ gas density.*

With the orifice diameter doubled, the peak and shape of the signal (D-1) did not exhibit a noticeable change compared with the signal (D) taken at the same location but with the smaller orifice. This shows a weak dependence of droplet sizes on the orifice diameter within the tested range of orifice diameters. When the chamber gas density was reduced from 25 kg m$^{-3}$ (D) to 1.2 kg m$^{-3}$ (D-2), the peak moved noticeably toward the outer (higher-numbered) diodes, thereby indicating a significant fall in droplet SMDs. The higher gas density slows the spray penetration and shortens the break-up length, resulting in a longer travel distance for droplets[13]. These two aspects—slower penetration and longer travel distance—contribute to enhanced droplet coalescence and increased SMDs for higher back pressure. Previous studies[1,14] show a similar effect of the gas density on SMD for diesel-fuel sprays.

Table 2 Experimental test matrix and average SMD for diesel fuel no.2 sprays.

| Case | Orifice diameter (mm) | Fuel injection pressure (MPa) | Density of chamber gas ($kg\ m^{-3}$) | Measurement location (mm) | Average SMD ($\mu m$) |
|---|---|---|---|---|---|
| Base case | 0.4 | 83 | 25 | 120 | 25.40 |
| Orifice diameter | 0.2 | 83 | 25 | 120 | 23.28 |
| Fuel injection pressure | 0.4 | 28 | 25 | 120 | 39.19 |
| | | 55 | | | 27.10 |
| Density of chamber gas | 0.2 | 83 | 1.2 | 120 | 12.67 |
| Measurement location | 0.2 | 83 | 25 | 60 | 12.39 |
| | | | | 80 | 16.33 |
| | | | | 100 | 20.96 |

Fig.4 shows the evolution of light signals with increasing injection pressure. All measurements were taken 120 mm downstream from the 0.4 mm diameter orifice, and the chamber pressure remained at 2.0 MPa. The signal peak moved from inner diodes (A) to outer diodes (D), showing a decrease in SMD with increasing injection pressure.

A regression method was used to find a correlation of droplet SMD measured near the spray tip of intermittent CWS sprays. The resultant correlation is expressed as[3]:

$$d_{32} = 0.279 \Delta P^{-0.702} \rho_a^{0.285} x^{1.521} \quad \text{for CWS fuel sprays} \quad (1)$$

where $d_{32}$ is in $\mu m$
$\Delta P$ is in MPa
$\rho_a$ is in $kg\ m^{-3}$
and $x$ is in mm.

A satisfactory agreement was seen when calculated SMDs from this correlation were compared with measured SMDs[3].

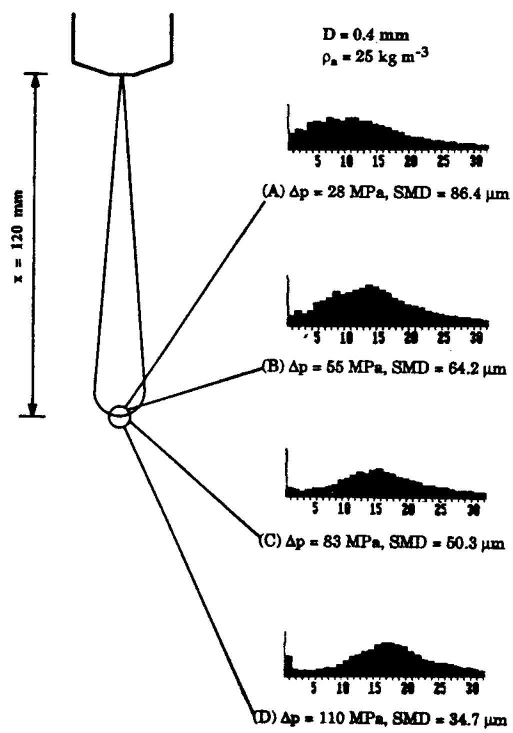


*Fig.4 Light-scattering signals detected for different injection pressures with 0.4 mm diameter orifice and 25 kg m⁻³ gas density.*

## 4.2 Results from the diesel-fuel spray

Table 2 lists the experimental test parameters for DF2 sprays, and summarises the result of SMDs averaged for up to fifteen injections for each parametric condition. Each parameter varied, while the other conditions remained as close as possible to the base case. For the unpressurised chamber gas of 1.2 $kg\ m^{-3}$, the 0.4 mm diameter orifice does not allow acceptable SMD measurement, since the measurement location of 120 mm falls within the spray core region where no spherical droplets form. For the specified conditions, the break-up length for DF2 spray is calculated as 168 mm, based on the correlation suggested in a previous study[15]:

$$L_b / D = 15.8 (\rho_f / \rho_a)^{0.5} \quad (2)$$

where $\rho_f$ represents the density of the fuel (1250 $kg\ m^{-3}$ for 50% CWS fuels and 850 $kg\ m^{-3}$ for DF2 fuels).

Since the Malvern SMD measurement assumes spherical particles, the measurement is significantly biased or impossible within the core region or near the break-up point, where non-spherical drops and irregular-shape ligaments are present. Thus, a diameter of 0.2 mm was used to investigate the effect of different chamber gas densities. For the same reason, a 0.2 mm diameter orifice allowed the measurement ranged down to 60 mm in examining the effect of measurement location.

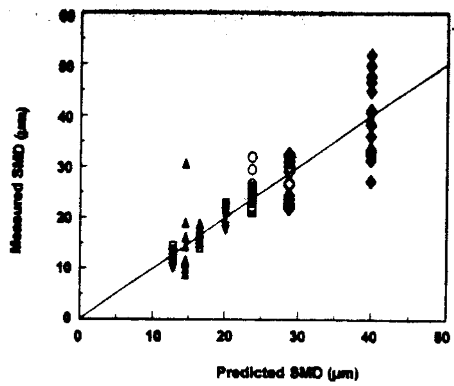


*Fig.5 Comparison of calculated SMDs based on the experimental correlation and measured SMDs for intermittent DF2 sprays. The quantities after each symbol represent respectively $\Delta P$ in MPa; $\rho_a$ in kg m$^{-3}$; x in mm; and D in mm:*

○ 83/25/120/0.4
◇ 55/25/120/0.4
◆ 28/25/120/0.4
□ 83/25/120/0.2
▲ 83/1.2/120/0.2
▼ 83/25/100/0.2
△ 83/25/80/0.2
▽ 83/25/60/0.2

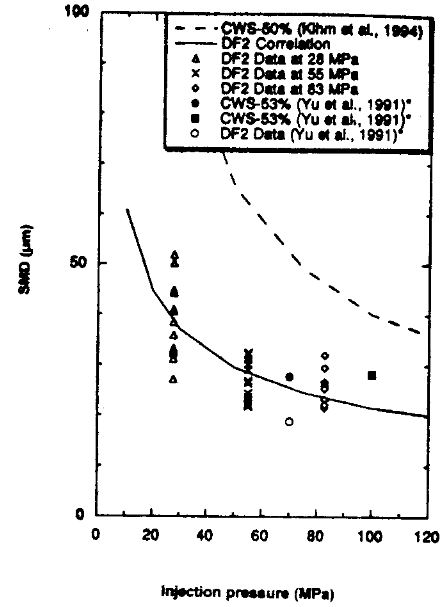


*Fig.6 SMD measured at different injection pressures: D = 0.4 mm; $\rho_a$ = 25 kg m$^{-3}$; x= 120 mm. (*Injection conditions: D = 0.25 mm; $\rho_a$ = 17.5 kg m$^{-3}$; x= 70 mm).*

### 4.2.1 Resultant correlation of SMDs

A regression equation for the spray tip SMD of intermittent DF2 sprays gives:

$$d_{32} = 1.402\Delta P^{-0.4513}\rho_a^{0.1588}x^{0.8977} \qquad (3)$$

where $d_{32}$ is in mm
$\Delta P$ is in MPa
$\rho_a$ is in kg m$^{-3}$
$x$ is in mm.

The regression correlation from all DF2 data presented in this paper was determined by means of the commercially available TriMetrix's Axum program. Fig.5 compares the measured SMD data with their calculated values using the correlation Eqn (3). The Pearson correlation coefficient was 0.89 for the present correlation. (A perfect agreement between the data and correlation equation would yield 1.0 for this coefficient). The individual effects of the injection parameters are presented in comparison with the previous CWS correlation represented by Eqn (1).

### 4.2.2 Effect of injection pressure

Fig.6 shows the spray-tip SMD results for tests where the injection pressures were 28, 55 and 83 MPa (gauge) whereas the other parameters remained constant. The ambient density was 25 kg m$^{-3}$, the orifice diameter was 0.4 mm and the axial measurement location was 120 mm. The dashed curve represents the CWS correlation of Eqn (1) and the solid curve represents the DF2 correlation of Eqn (3). The symbols denoting DF2 SMD data show good agreement with the solid DF2 correlation curve. DF2 spray droplets measured consistently lower than CWS spray counterparts. SMD data for CWS sprays are not included since they are reported elsewhere[3] and show equally good agreement with their correlation of the dashed curve. The range of symbols under identical injection conditions shows the data scatter between sprays.

The lower injection pressure results in larger droplet sizes and wider data scatter, since the injection pressure energy is not sufficient to fully develop spray atomisation. The effect of injection pressure, which reduces spray tip SMDs, falls as the injection pressure rises. Although the injection pressure rises from 55 to 83 MPa, the spray-tip SMD stays nearly identical; this shows that the atomisation of the spray tip is almost completely developed at around $\Delta P$ = 55 MPa and a further increase in the injection pressure can hardly reduce the SMD. This situation can also be referred to as a saturated atomisation state. However, the CWS results show continuously decreasing SMDs for increasing injection pressure of up to 110 MPa (see also Table 1). The high viscosity of CWS (up to several hundred times that of DF2 fuel) requires an injection pressure higher than 55 MPa to reach a 'fully-developed' level of atomisation; in other words, CWS fuels need far more shear energy to achieve the same level of atomisation as DF2 fuels.

The two solid symbols and one circular symbol in Fig.6 represent spray tip SMDs at $r$ = 0 obtained by Yu *et al*[10] for 53% CWS fuel and DF2 fuel, respectively. The DF2 spray SMD data point (hollow circle) at $r$=0 was extrapolated from their measured SMDs obtained at other radial locations. Relative to the present injection their sprays were generated from a smaller orifice of 0.25 mm diameter into an environment of lower gas density of 17.5 kg m$^{-3}$. The axial measurement location of $x$ = 70 mm was closer to the orifice. The smaller orifice diameter can generate smaller droplets, except for saturated sprays under excessively high pressure injection[3,16,17]. According to our findings, which were briefly summarised for the CWS sprays in the previous section and will be discussed for DF2 sprays in the successive sections, both the lower ambient gas density and the closer axial location can reduce the droplet coalescence, because of the longer core length and shorter droplet travel distance. The lower gas density and the closer measurement location of Yu *et al*[10] can explain their smaller SMDs relative to the present data.

### 4.2.3 Effect of the location of axial measurement

Fig.7 shows how the spray tip SMD changes with increasing axial measurement location for both CWS and DF2 fuel sprays. The injection pressure was 83 MPa, the ambient gas density was 25 kg m$^{-3}$, the orifice diameter was 0.2 mm and the location of axial measurement varied in 20 mm increments from 60 to 120 mm. The spray tip SMD rises as the spray travels downstream; this phenomenon was analytically predicted[12] and seen in high-pressure CWS and diesel sprays[3,11]. As explained previously for CWS sprays, the primary reason for the greater SMD is the high inertia of the larger drops carrying them farther and faster relative to the smaller droplets that have promptly slowed because of the dominant drag forces. Aditionally, the increased coalescence of the droplets as they travel downstream contributes to the greater SMD. The exponent of the $x$ term in the correlation equation (Eqn (3)) is approximately 0.9, which shows nearly a linear increase of SMD with $x$.

The exponent of $x$ for CWS sprays (Eqn (1)) is more than 1.5, and the tip SMD shows a more rapid increase with $x$ than for DF2 sprays. Because of its larger fuel densities (1250 kg m$^{-3}$ for CWS fuel and 850 kg m$^{-3}$ for DF2 fuel) the inertia of a CWS drop is about 1½ times that of a DF2 drop of the same diameter travelling at identical speed. This higher inertia of CWS drops makes the more conspicuous penetration of larger drops more pronounced, and a steeper rise of SMD with $x$ prevails in the case of CWS sprays.

The solid and hollow circle symbols in Fig.7 represent respectively the spray-tip SMDs for CWS (53% coal weight) fuel and DF2 fuel under lower injection pressure of 70 MPa from the previous work[10]. Slightly larger SMD values are observed relative to the present correlations. The primary reason for the discrepancies lies in the lower injection pressure. The slightly larger orifice diameter ($D$ = 0.25 mm) may also have contributed to the generation of larger SMDs. In spite of these different injection conditions and different injector geometries, the SMD data from Yu *et al*[10] stay roughly within the data scatter from the present correlations.

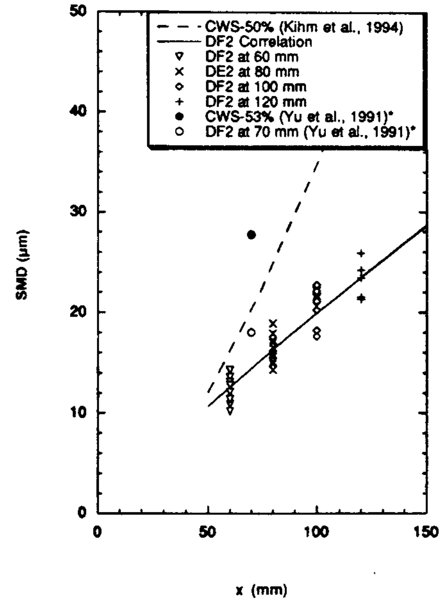


*Fig.7 SMD measured at different axial locations: $D$ = 0.2 mm; $\rho_g$ = 25 kg m$^{-3}$; $\Delta P$ = 83 MPa. (*Injection conditions: $D$ = 0.25 mm; $\rho_g$ = 17.5 kg m$^{-3}$; $\Delta P$ = 70 MPa).*

### 4.2.4 Effect of the density of ambient gas

Fig.8 shows test results of spray-tip SMD measurements for two densities of chamber gas ($N_2$). The densities studied were 1.2 kg m$^{-3}$ (inverted triangle) and 25 kg m$^{-3}$ (diamond), corresponding to 0 and 2.026 MPa g chamber pressures respectively. The other test conditions were injection pressure 83 MPa, orifice diameter 0.2 mm and axial measurement location 120 mm. The injection conditions for the solid and hollow circle data (Yu *et al*[10]) were injection pressure 70 MPa, orifice diameter 0.25 mm and axial measurement location 70 mm.

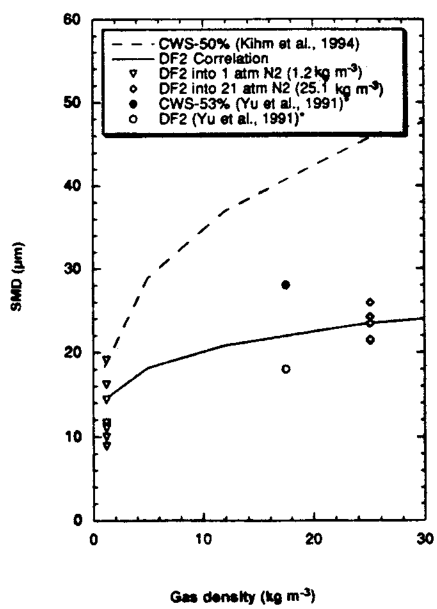


*Fig.8 SMD measured for different densities of ambient gas: $D$ = 0.2 mm; $x$= 120 mm; $\Delta P$ = 83 MPa. (*Injection conditions: $D$ = 0.25 mm; $x$= 70 mm; $\Delta P$ = 70 MPa).*

The results show that the higher ambient gas density produces larger drops and smaller data scatter. Qualitatively similar behaviour was observed with high-pressure injecting CWS sprays[3]. The increased density of ambient gas significantly reduces the break-up length, which is proportional to the inverse square root of the gas density (Eqn (2)). Therefore higher gas density reduces the break-up length and extends the travel distance of droplets, and their enhanced coalescence results in larger SMDs. The trend of increased SMD with increasing gas density is more pronounced for CWS sprays, and is believed to be due to the higher inertia of CWS droplets—as discussed in Section 4.2.3. The slightly smaller SMDs obtained from the previous work[10] (but still within the data scatter of the correlations) is believed to be primarily the result of the closer axial location of measurement.

### 4.2.5 Effect of orifice diameter

Fig.9 shows the results of SMD measurements for orifice diameters of 0.2 and 0.4 mm; the injection pressure was 83 MPa with an ambient density of 25 kg m$^{-3}$ and $x$ = 120 mm. The solid symbol represent CWS spray SMD from the previous work[10] measured at $x$ = 70 mm from a 0.25 mm orifice under 70 MPa injection pressure. The two orifices produced droplets in the same size band within the range of the data scatter. This finding is again consistent with the previous finding for CWS sprays, except that DF2 droplets are about 50% smaller.

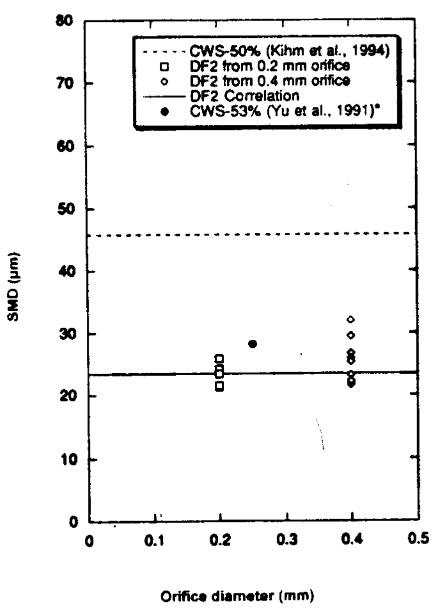


*Fig.9 SMD measured for different orifice diameters: $x$= 120 mm; $\rho_a$ = 25 kg m$^{-3}$; $\Delta P$ = 83 MPa. (*Injection conditions: $x$= 70 mm; $\rho_a$ = 17.5 kg m$^{-3}$; $\Delta P$ = 70 MPa).*

No apparent correlation between SMD and the orifice diameter was observed for high-pressure intermittent sprays. Previous studies[3,16,17] reported similar observation. This insensitivity of SMD regarding the orifice diameter is particularly true for a fully developed atomisation region represented by the measurement made far enough downstream from the break-up point in the case of high-pressure injection.

## 5 Conclusions

An optically synchronised laser-diffraction technique for droplet sizes was used near the spray tip for high-pressure intermittent diesel-fuel sprays. The results were compared with previous findings for 50% wt coal-water slurry sprays.

The conclusions are:

1 Qualitative similarity in spray-tip SMDs was found for CWS and DF2 sprays. Under identical injection conditions, DF2 sprays always produce significantly smaller SMDs than do CWS sprays.

2 Spray-tip SMDs rise with distance downstream from the orifice exit.

3 Spray-tip SMDs fall with injection pressure.

4 Spray-tip SMDs rise with ambient gas density or back pressure.

5 A regression equation has been developed as an experimental correlation of spray tip SMDs (μm) of high pressure, intermittent DF2 sprays:

$$SMD = 1.402\Delta P^{-0.4513}\rho_a^{0.1588}x^{0.8977} \quad (3)$$

where $\Delta P$ is in MPa
$\rho_a$ is in kg m$^{-3}$
$x$ is in mm.


## 6 Acknowledgements

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