Synchronised droplet size measurements for coal-water slurry sprays generated from a high-pressure diesel injection system

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An experimental study has investigated intermittent sprays of coal-water slurry (CWS) fuel injected from an electronically controlled accumulator injector system. A laser diffraction particle-analysing (LDPA) technique was used to measure the Sauter mean diameter (SMD) near the spray-tip region. To ensure accurate synchronisation of the measurement with the intermittent sprays, a synchronisation technique was developed that uses the lightextinction signal as a trigger for initiating the data-taking. This technique allowed measurement of SMDs near the spray tip, where the light-extinction level was low and the data were free from the multi-scattering bias. Coal-water slurry fuel with 50% coal loading in mass containing 5 gm mass median diameter coal particulate was considered. The studies involved injection pressures ranging from 28 to 110 MPa, nozzle orifice diameters of 0.2 and 0.4 mm, and four axial measurement locations from 60 to 120 mm from the nozzle orifice. Measurements were made for pressurised (2.0 MPa g) and for atmospheric chamber conditions. The spray SMD showed a rise with the distance of the axial measurement location and with the ambient gas density, and a fall with rising injection pressure. An experimental correlation of the Sauter mean diameter with the injection conditions was determined as SMD = $0.279\,\Delta p^{-0.702}\rho_a^{0.285}\,x^{0.521}$, showing satisfactory agreement with the measured SMD data. The results were also compared with previous SMD correlations that were available only for diesel-fuel sprays.

1 List of symbols

D	orifice diameter of injector nozzle, mm
d_{32}	Sauter mean diameter, gin
I	light energy detected by the centre diode with spray presented
I_o	light energy detected by the centre diode without spray
L_b	break-up length, mm
ΔP	fuel-injection pressure, MPa
Q	amount of fuel delivery per stroke, mm^3
x	axial distance measured from the injector nozzle, mm
ρ_a	ambient gas density, kg m^{-3}
ρ_f	fuel density, kg m^{-3}
v	kinematic viscosity of fuel, m^2 s^{-1}
σ	surface tension, N m^{-1}

2 Introduction

The development of coal-fuelled diesel engines[1] has successfully demonstrated the concept of using coal-water slurry (CWS) fuels as a potential substitute for conventional petroleum diesel fuel (DF2). In several studies[2,3] the coal-fuelled operations have been characterised quantitatively by analysis of the combustion process. In a series of previous publications[4,5,6] the characteristics of intermittent CWS sprays have been made for a laboratory injection system, and detailed data have been presented for spray-tip penetration, spray break-up and spray angle.

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However, only a few investigations under limited conditions have been made for droplet sizes of CWS intermittent sprays. The measurement of droplet diameters accompanies many difficulties associated with extremely highpressure injection into a pressurised chamber, and at the same time requires a precise synchronisation technique with the intermittent sprays This paper presents a development of an accurate synchronisation technique for meaningful measurements of droplet diameters of intermittent sprays, and also presents detailed correlations of measured Sauter mean diameters (SMD) of CWS fuel sprays in terms of average injection pressure, ambient air density and measurement location.

Our measurements of droplet diameter were made specific ally for the spray-tip regions for two major reasons:

(1) The droplet-size characteristics near the spray tip determine most important phenomena of internal combustion processes-including combustion initiation, spray penetration and impingement on the cylinder head-and ultimately the pollution behaviours.

(2) Other than at the spray-tip region, CWS fuel sprays are optically very thick, resulting in nearly 100% light-extinction level; the applied measurement technique (the Malvern system) will be irrecoverably biased because of the multi-scattering effect[7].

The disintegration mechanism of liquids is a complicated phenomenon, especially for the high-pressure injection of diesel engines. Nobody fully understands high-injectionpressure intermittent spray behaviours, regardless of the injected liquids. There is little doubtthat the mean and distributions of droplet diameters of fuel sprays play a key role in determining successive combustion and pollution characteristics. Also, precise knowledge of droplet sizes and their distributions can help expedite the progress of the current analytical and numerical research of spray phenomena. A number of studies have been made of high pressure injecting sprays to simulate and investigate the behaviour of diesel sprays, but only a few of those investigators performed droplet-size measurements under high ambient pressure and/or temperature with reasonably acceptable techniques.

Hiroyasu & Kadota[8] developed an empirical correlation between effective injection pressure, air density, the amount of the fuel delivery and the Sauter mean diameter (SMD) d_{32} for diesel fuels:

$$d_{32} = A\ \Delta P^{-0.135}\ \rho_a^{0.121}\ Q^{0.131} \qquad (1)$$

where d_{32} is in μm, A is a geometrical constant ranging from 22.4 to 25.1, depending on the injection nozzle configuration, ΔP represents the mean effective pressure differential across the nozzle (MPa), ρ_a is the ambient gas density (kg m^{-3}), and Q is amount of fuel delivery per stroke (mm^3).

In their study, droplet sizes were measured by means of a liquid-immersion technique where the fuel was injected into immiscible liquid filled at the bottom of the pressure chamber. An interesting aspect of their correlation is that SMD rises with back pressure or the gas density. According to Taylor's theory[9], for low-pressure injecting sprays SMD decreases with back pressure because of the rise in density and viscosity of the ambient gas. Hiroyasu & Kadota[8] explained that in a fully developed high-pressure injection spray the back pressure has opposing effects on the mean diameter, since the reduced spray velocity and increased droplet coalescence, with higher back pressure, result in higher SMD, thereby overriding the decreasing effect of the fluid properties such as density and viscosity on the spray droplet diameter. Note also that the correlation (1) represents the droplet SMD of the whole spray, and is not appropriate for determining the spray-tip SMDs.

The droplet-size distribution and mean droplet diameter for various ranges of injection parameters were measured for petroleum fuel sprays by means of a slide-sampling technique, and a generalised empirical expression for SMD was obtained[10]:

$$d_{32} = 6156\ \ \Delta P^{-0.54}\ \rho_a^{0.06}\ \rho_f^{0.737}\ V^{0.385}\ \sigma^{0.737} \qquad (2)$$

where all the fluid properties are in SI units and the injection-pressure differential is in bars. For this correlation, SMD again rises with ambient gas density. The samplingslide glass was coated with a soot layer, and the size of the crater made by the impinging droplet was measured with a microscope. In addition to any inaccuracies associated with the measurement technique, direct application of the correlation for CWS fuels is difficult, since the viscosity and the surface tension coefficient of CWS fuels generally depend on the shear rate[11].

It was demonstrated that for intermittent sprays, LDPA has many advantages over other available non-intrusive techniques[12]. This is mainly because an ensemble-measurement technique such as LDPA can provide better synchronism tion with intermittent sprays than a single-particle measurement technique such as phase Doppler particle analysing **(PDPA)** or other scattering techniques based on

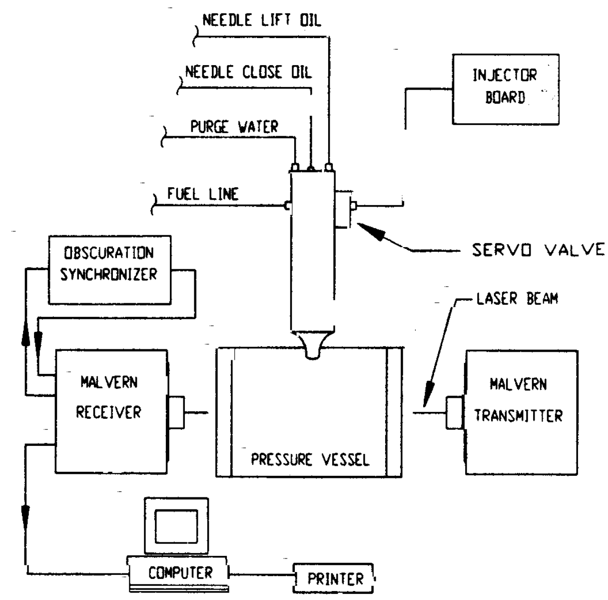


Fig. 1 The experimental system.

accurate synchronisation for intermittent-spray measurement. This was a motivation of the present development of a more accurate synchronisation scheme triggered by a light extinction, which will be discussed in a later section.

In the case of CWS fuels, droplet-size data are scarce. Results of SMD measurement were reported for a continuous CWS injection system[14]: they found that SMDs for CWS fuel sprays are somewhat larger than those for diesel fuels, and the atomisation does not vary significantly with different hole configurations of the injector nozzle. Variations in SMDs under the same injection condition were observed for different types of CWS fuels containing different-size particulate.

Optically synchronised measurement of droplet sizes for intermittent CWS sprays was recently conducted under limited injection conditions[15], and results obtained by an LDPA technique were presented for the spray-tip region. The measurement was made for different radial locations at a fixed axial distance from the nozzle, and showed a gradual increase in droplet SMD away from the spray axis. In identical injection conditions the droplet SMDs of CWS sprays were larger than those of DF2. The effects of the chamber gas density and the axial spray location on the spray SMDs have not been investigated, and the synchronisation technique needs to be refined to enhance the synchronisation accuracy.

The present paper provides droplet SMD data for intermittent CWS sprays using the LDPA technique with an improved synchronisation method. The objectives of this work were two-fold:

1) development of an accurate synchronisation technique for LDPA technique for intermittent spray applications;
2) obtaining an experimental correlation for droplet SMD of CWS intermittent spray-tip regions in terms of related

3 Experimental facility and procedure

3.1 Experimental facility

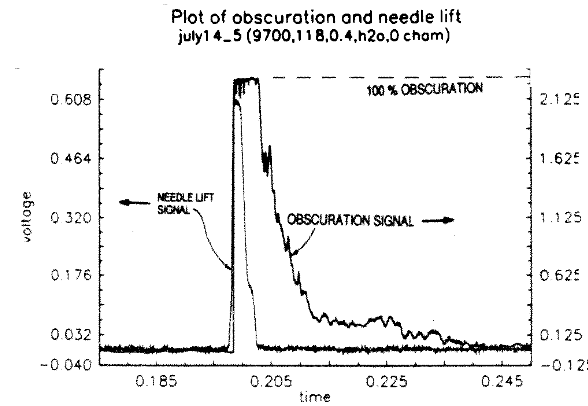
Fig.l shows the experimental set-up of the injector unit, pressure chamber and LDPA (Malvern 2600-C) system. The injector was a state-of-the-art accumulator electronically controlled to lift the needle for 5 ms duration by the electro-magnetic servo valve. The fuel pressure was measured by a calibrated strain gauge attached to the surface of the injector unit, and the needle lift was recorded by the use of a proximity sensor. The spray was injected into the cylindrical pressure chamber which had 25.4 mm thick quartz windows at both ends to allow optical access. Nitrogen gas was used to pressurise the chambei up to 2 MPa.

The basic principle of the LDPA technique is the use of Fraunhofer diffraction theory, where the scattering angle of diffracted light falls inversely with diameter[16,17]. Distributed light energy scattered by individual particles of different diameters is detected by a series of 32 semi-annular ring-shaped photodiodes (31 ring diodes for particle sizing and one centre diode for the extinction measurement) and is converted into a size-distribution function by means of statistical iterations. Light extinction is defined as $(1-I/I_0)$, in which I and I_0 to denote the amount of light energy detected by the centre diode with and without spray, respectively. Measurements were made assuming the Rosin-Rammler two-parameter model[18]. The accuracy of the instrument was checked with a standard calibrating reticule, and the two model parameters of the Rosin-Rammler model were kept within an accuracy better than 5% from the nominal values specified for the reticule.

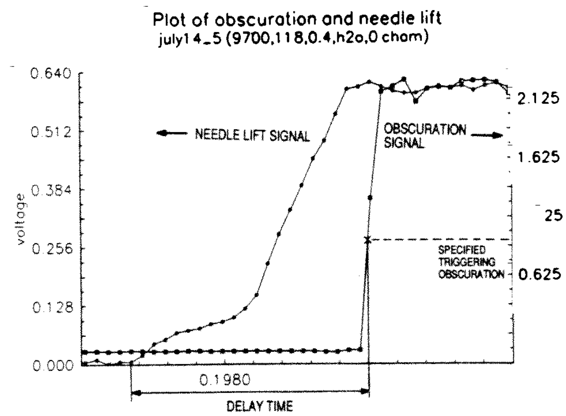
3.2 Synchronisation method

In applying the LDPA technique to intermittent and developing sprays, a precise synchronisation of the data acquisition was necessary, since a free-running integration of the spray measurements gives a smoothed-out result that is of little use. Previous synchronisation techniques[12,13] have utilised a specified time delay as a trigger source after the injector needle was lifted, in an attempt to match the arrival of the spray with data collection. This technique causes unavoidable uncertainties because of difficulty in identifying the precise moment of the needle lift. The spray-tospray variations of the penetration also worsen the accuracy of synchronisation. Therefore optical triggering by the light-extinction level ensures more accurate synchronisation.

Fig.2a presents the needle-lift signal measured for a typical injection of 5 ms duration under 67 MPa injection-pressure differential through a 0.4 mm diameter nozzle. The lightextinction signal was followed within less than 1 ms, which was required for the spray penetration of the laser beam 120 mm downstream of the nozzle tip. The extinction rises quickly to 100% in less than 100 ps, establishing a, fully developed spray, and then gradually returns to zero as the residual spray is diffused and deposited inside the chamber walls. The residual spray formed after the needle is closed has little importance, since it will never exist in the practical case where diesel combustion occurs. When the spray is fully developed with nearly 100% extinction, the multiple scattering of laser light will significantly bias the data[7].



(A) 5 ms resolution



(B) 0.1 ms resolutior

Fig.2 Variations of needle lift and light - extinction signals: (a) for entire spray, and (b) for spray tip in expanded time scale.

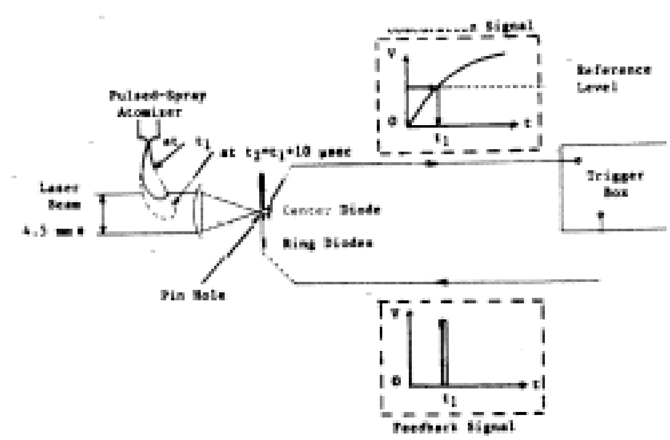


Fig.3 The synchronisation technique that uses laser light - extinction as a triggering source.

Therefore the LDPA measurement must be made within the short period of less than 100 μs while the extinction level is ascending (Fig.2b). This also means that the LDPA technique works best near the spray tip for dense sprays. Such a fast synchronisation can be devised by the use of the light-extinction signal as a feedback triggering source.

An automatic synchronisation for the initiation of datataking was devised by monitoring the extinction signal (Fig.3). The analogue voltage that corresponds to an instantaneous extinction level is sent to a specially designed trigger box, which sends a signal (5-V square pulse) back to the ring diodes for data-taking initiation only if the instantaneous extinction level exceeds the reference level. A single sweep of the data being received by the ring diodes takes 10 μs, and an additional 35 ms is necessary to digitise and send the data serially to the memory of a microprocessor before the diodes become ready for the next data receipt-ie the next sweep. The essential data-transfer time of apprpximately 35 ms limits the measurement to only one sweep per injection. This synchronisation method permits the LDPA technique to be used properly to measure the intermittent spray SMDs within an acceptable accuracy. Further description of the principle and development of the obscuration synchronisation technique has been presented in the previous report[19].

3.3 Experimental procedures

The **LDPA** technique is based on the Fraunhofer diffraction principle, assuming spherical scattering particles. Near the spray break-up region where irregularly-shaped ligaments and non-spherical liquid elements exist[20], the measurement accuracy is significantly lowered. Taylor's theory has led to the concept of the spray break-up length. An experimental correlation for the break-up length as a function of orifice diameter D and the density ratio of the injected fluid to the ambient gas has been previously derived[21]:

$$L_b/D = 15.8\,(\rho_f/\rho_a)^{0.5} \qquad (5)$$

The break-up lengths for both CWS fuel (ρ_f = 1200 kg m^{-3} for 50% coal mass loading) and diesel fuel (ρ_f = 850 kg m^{-3}) were calculated, and Fig.4 shows these results for the atmospheric and pressurised (2.1 MPa) chamber conditions. These results have been verified by experiments for diesel sprays[6]. A correction may be needed for more precise prediction of the break-up length for CWS sprays, to take account of the coal loading effect[22]. The correlation of Eqn. (3), however, provides a good estimate of the break-up length of CWS sprays. The high viscosity and surface tension of CWS fuels slow the atomisation, resulting in narrower sprays; this can be attributed to the longer break-up lengths than those for diesel sprays under the same ambient gas density. The droplet-size measurements had to be made downstream of the break-up point to minimise the presence of non-spherical liquid elements which significantly bias the measurement.

Another difficulty was due to the beam-steering effect that indicated droplet sizes much larger than they actually were. Index-of-refraction gradients created by the pressure waves from the high-speed spray tip cause the beam to bloom and to wander off the centre diode before the spray penetrates the beam. When the injection pressure is verg

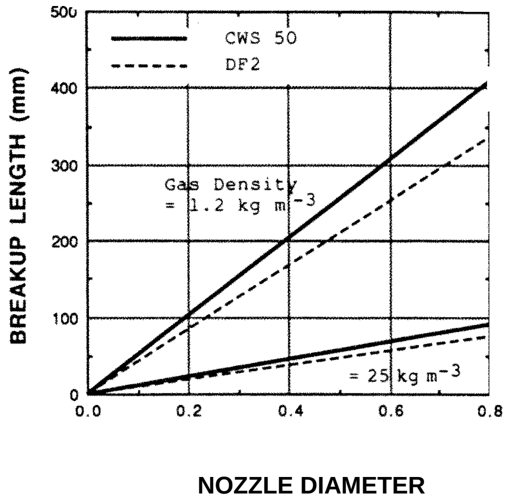


Fig.4 Sprctr break - up length as a functin of the nozzle orifice diameter calculated front the correlation suggested ky fdirouusu & Arai[21].

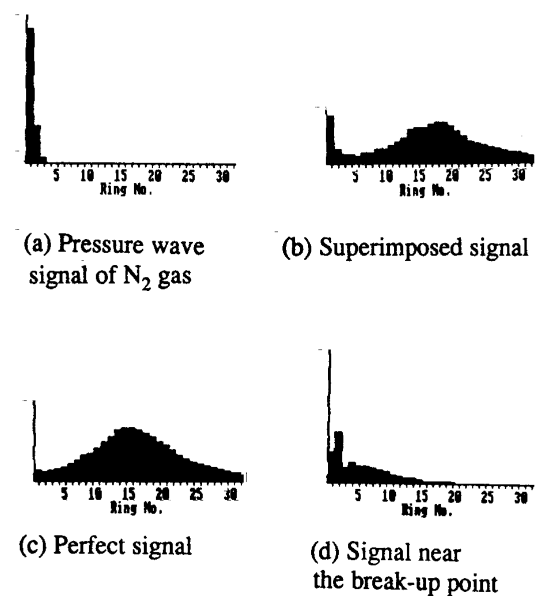


Fig.5 Light - scattering signals detected by the ring diodes of the Malvern instrument: (a) affected signal of the inner ring diodes by the beam steering during the nitrogen gas fill - up to the chamber; (b) affected signal by the refractive index field created from the pressure waves ahead the spray; (c) unaffected signal scattered by CWS spray; (d) false signal affected by both the beam steering and non - spherical particles

beam, the inner ring diodes receive a false signal and the result is erroneous data[24,25]. In order to resolve this problem, the false signals detected by the affected inner ring diodes were 'killed' from the data analysis for the calculation of droplet-size distribution. The inner ring diodes were affected more severely when the measurement location was closer to the break-up region.

Fig.5a presents a typical erroneous signal, which was detected while the chamber was pressurised with nitrogen gas. Index-of-refraction gradients due to the advancement of the high-pressure nitrogen gas into the closed chamber

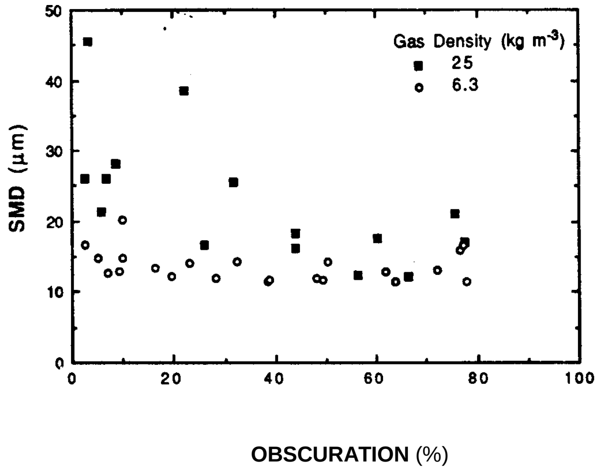


Fig.6 SMD vs obscuration measured for diesel-fuel sprays (D = 0.4 mm, ΔP =68MPa, ρ_a=6.3 and 25 kg m^{-3}, x=120mm).

downstream from the estimated break-up point. The data demonstrate the true signal diffracted by the spray superposed with the affected signal due to the pressure waves. For such cases, eliminating the first one or two diodes resolved the trouble; this was ensured by confirming the log difference to be less than 5.0.

When the measurement location was 70 mm downstream of the break-up point of approximately 50 mm, the strength of the pressure waves was weakened through the slower spray-penetration and the weaker beam-steering effect (Fig.5c). However, when the measurement location was too close to the break-up point (Fg.5d,10 mm downstream of the break-up point), the centre diodes were affected by the beam-steering effect and the diffraction signal was also biased by non-spherical fluid particles. The LDPA measurement must be avoided when the signal is so badly affected and biased, as in the case of Fig.5d.

3.4 Test coal and experimental conditions

The tested CWS fuel was provided by Otisca Industries, and the suspended coal particulate was measured to be 5.0 *μm* in mass median diameter (MMD)[26]. The coal was mined from the Kentucky Blue Gem Seam and was cleaned to 0.8% ash content. The table lists the primary experimental test parameters for the LDPA measurements of droplet diameters of CWS fuel sprays. The coal mass loading was 50% and the injection period was 5 ms for all the investigation. The base case corresponds to the full-load conditions of the GE locomotive engine[27]. The measurement location of 120 mm for the base case is approximately equivalent to the distance from the injection nozzle (multiple holes with slant angles located off-axis) to the cylinder head of the engine. The LDPA technique is highly sensitive to detect any window wetting, so the inner surfaces of the windows had to be cleaned thoroughly after each injection. Once the chamber pressure reached 2 MPa with nitrogen fill, the background signal was carefully monitored until the affected signals in the inner diodes had disappeared as the initial disturbance in the gas density field diminished.

4 Results and discussion

4.1 Effect of light extinction

Light extinction had little effect on measurement of spray SMDs, except when the extinction level became very low. For extinction levels of less than 10%, larger SMDs were measured, as can be seen from the preliminary results for diesel sprays presented in Fg.6. Spray SMDs gradually converged to a constant value with increasing extinction. This measurement was made at 120 mm downstream, for a 0.6 mm diameter nozzle for two values of ambient gas density, 6.3 and 25 kg m^{-3}. A maximum of 55% triggering extinction was used for all experiments, to avoid the multiple scattering effect on droplet sizes at higher extinction. The extinction level of the spray rapidly rises (Fg.2) and it takes less than 30 μs to reach 55% level from 20% extinction level. The spray advancement during this time interval is an order of a few millimetres for the spray-tip penetration velocity of an order of 100 ms^{-1}, and the spray SMD is not significantly varied during such a small advancement of the spray. For each measurement condition in the table, two or three extinction levels were considered-approximately 5, 30 and 55%. The results are presented without discriminating the data taken at different extinction levels.

4.2 Effect of axial measurement location

Fg.7 shows the SMDs for four measurement locations of sprays generated from the 0.2 mm orifice. The injection pressure was kept constant at 83 MPa, and the gas density of the bomb was maintained as 25 kg m^{-3}. For each measurement location, up to ten individual realisations (sweeps) were made, and the black symbols represent the average SMDs. The data scatter can be attributed to the variations of the light-extinction level, ranging from 5 to 550. Another attribution can be made to the irregular nature of intermittent sprays, ie for the same level of light extinction the measurement point may not be identical between sprays. However, the averaged SMDs show a persistent rise with increasine distance from the nozzle.

Table: Experimental test matrix

Case	Injector diameter (mm)	Fuel injection pressure (MPa)	Chamber gas density (kg mm^{-3})	Measurement location (mm)
Base	0.4	83	25	120
Injector diameter	0.2 0.6	83	25	120
Fuel-injection pressure	0.4	28 55 110	25	120
Chamber gas density	0.2	83	.2	120
Measurement location	0.2	83	25	60 80 100

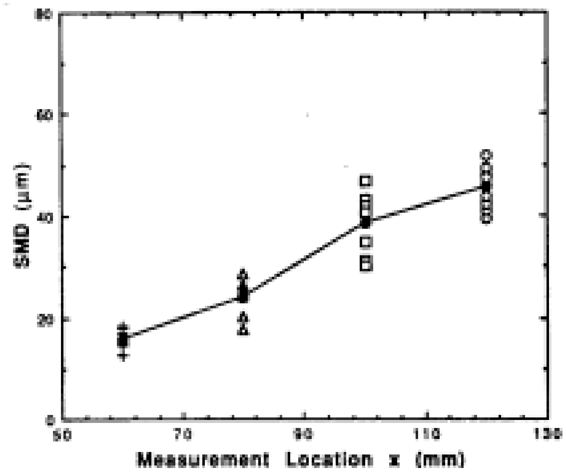


Fig.7 SMD for CWS-50 fuel sprays measured at different axial locations (D=0.2 mm, ΔP=83 MPa, ρ_a=25 kg m^{-3}).

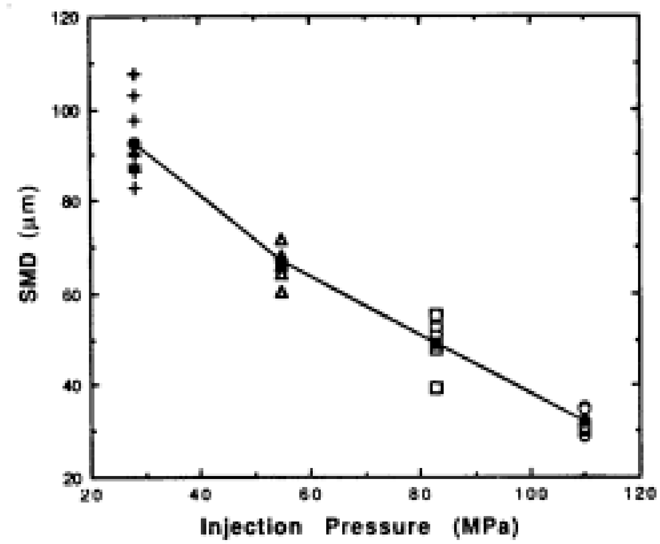


Fig.8 SMD for CWS-50 fuel sprays measured at different injection pressures (D=0.4 mm, ρ_a = 25 kg m^{-3}, x=120 mm).

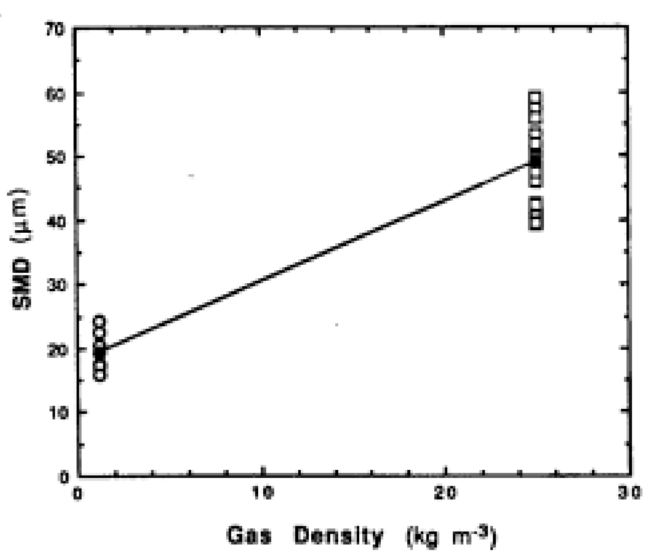
This phenomenon can be explained with the nature of the droplet behaviours. Larger droplets carry higher momentum and deeper penetration than smaller droplets. The smaller droplets quickly lose their momentum because of the larger drag:inertia ratio, and spread radially outwards, falling behind the larger ones. Increased coalescence between droplets with increasing travelling distance also contributes to the increase of SMD for further downstream locations. Similar trends of droplet SMD were seen for diesel fuel sprays[13] and were analytically predicted by Hiroyasu[28].

4.3 Effect of injection pressure

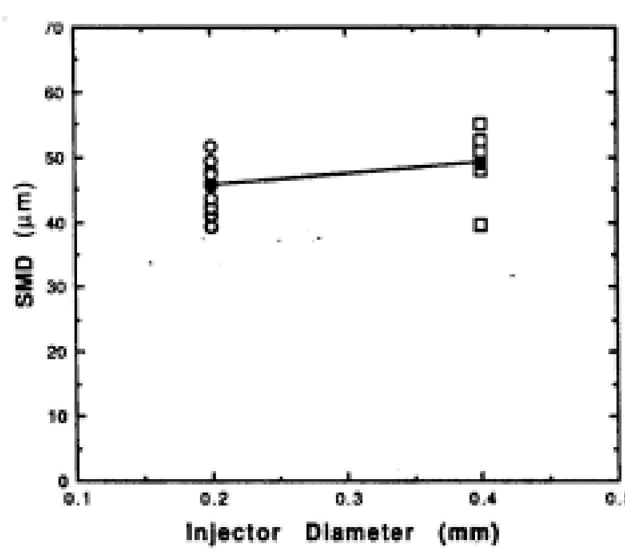
Fig.8 shows the effect of injection pressure on the spray SMD. The measurement was made at 120 mm downstream of 0.4 mm diameter nozzle and for 2 MPa ambient pressure (gas density of 25 kg m^{-3}). Both individually measured and averaged SMDs showed a monotonic fall with rising injection pressure. For injection pressures less than 28 MPa, the current injection system was not able to generate sprays because of the insufficient impulse force for intermittent development of spray.

4.4 Effect of ambient gas density

Measurement was also made at x = 120 mm for unpressurised and pressurised ambient conditions for the 0.2 mm diameter nozzle with 83 MPa injection pressure (Fig.9). The results clearly demonstrate a dramatic rise in SMD with gas density, and this fact agrees with previous findings[8,10]. For the case of high back pressure, spray penetration is slower because of the higher gas density, and the break-up length is significantly shorter (Eqn. 3 or Fig.4) since the spray is developed within a relatively short time after injection[30]. Both aspects-slower penetration and shorter break-up length-contribute to the enhancement of droplet coalescence and lead to higher SMD for higher back pressure. This observation is valid for fully developed high-injection-pressure sprays, but a reversed observation was made for low-pressure-injection sprays[30]: for low-



FiZ.9 SMD for CWS-50 fuel spravs measured for different amhient gas



Fie. 10 SMD for CWS-50 fuel sprays measured for different nozzle

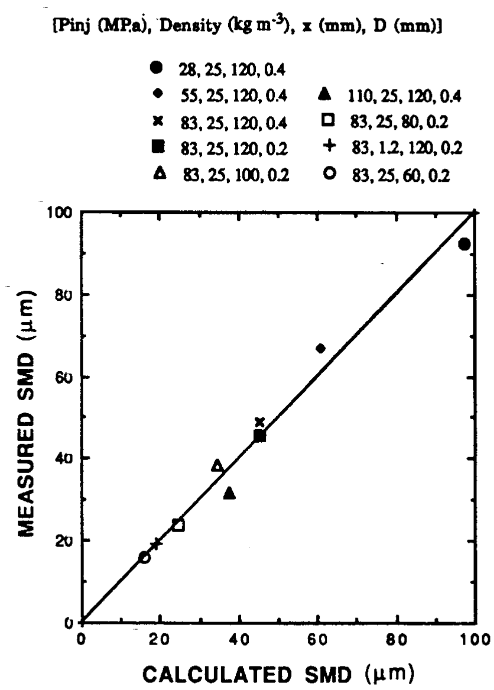


Fig.11. Comparison of calculated SMDs based on the experimental correlation and measured SMDs for intermittent CWS-50 sprays.

pressure injection creating developing sprays, high back pressure acts to reduce the spray SMD since the greater shear action due to the higher gas density and viscosity dominates the atomisation process.

4.5 Effect of nozzle diameter

Fig. 10 shows a weak dependence of SMD on the nozzle diameter for these sprays. Both sets of SMD data measured for 0.2 and 0.4 mm diameter nozzles fall within the range o1 experimental scatter of each other. The average SMDs for the two nozzles differ by only a few percent. For highpressure intermittent sprays, no significantly apparent correlation between SMD and nozzle diameter was observed: this is consistent with previous data for high-pressure diesel sprays[10].

4.6 Resultant correlation

An experimental correlation of SMD for the spray-tip regions of intermittent CWS sprays was determined by means of a regression analysis for the case of 50% loading in coal mass:

$$SMD = 0.279\ \Delta P^{-0.702}\ \rho_a^{0.285}\ x^{1.521} \qquad (4)$$

where SMD is in μm, the injection pressure ΔP is in MPa. the gas density ρ_a is in kg m^{-3}, and the spray-tip (measurement) location x is in mm.
The correlation was determined from all the data obtained from the present work; the characteristics ranged from 28 to 110 MPa for ΔP, 1.2-25 kg m^{-3} for ρ_a, 60-120 mm down stream of the nozzle exit for x, and for CWS fuel provided by Otiscal Industry (5 μm MMD coal particulate with < 1 % ash). A satisfactory agreement is obtained when the correlation is compared with measured SMDs, as shown in Fig.ll. Each symbol represents an average of up to ten measurements for the same injection condition.

The spray SMD falls inversely with injection pressure, and rises with both the gas density and the spray-tip penetration. In the present correlation the dependence of the CWS spray SMD on the injection parameters is consistent with the previous correlations for diesel sprays[8,10,18]. However, SMDs of CWS sprays show a stronger dependence on both the injection pressure and the gas density, relative to DF2 sprays. At present no previous correlations for intermittent CWS sprays are available for comparison.

5 Conclusions

An experimental investigation was carried out to determine a correlation between the CWS spray SMDs and the injection parameters. A laser diffraction technique (the Malvern) was used for measuring the SMD near the spraytip region, where the light extinction was low and the measurements were unbiased and meaningful. A unique synchronisation technique using the light-extinction level as a triggering source for the LDPA measurement was developed to ensure precisely synchronised SMD data with the intermittent sprays.

For each measurement condition three extinction levels were considered-approximately 5, 30 and 55%. Coalwater slurry fuel with 50% coal loading by mass was intermittently sprayed into a pressurised chamber from an electronically controlled accumulator fuel-injection system. The studies involved injection pressures between 28 and 110 MPa, two nozzle-orifice diameters at 0.2 and 0.4 mm, and four axial measurement locations between 60 and 120 mm from the nozzle exit. Both pressurised (2.1 MPa) and unpressurised (0.101 MPa) chambers were considered for the ambient gas density.

The conclusions of this investigation include the following:
1 An automatic and precise synchronisation for the initiation of data-taking was devised by monitoring the extinction signal. This synchronisation method allowed the LDPA technique to be used properly to measure the intermittent spray SMDs within an acceptable accuracy.
2 The average SMD showed an increase with distance from the nozzle. This reflected deeper penetration of larger droplets and increased coalescence between droplets with increasing travel distance.
3 No significant effect of nozzle diameter on SMD was observed for the range of the study from 0.2 to 0.4 mm.
4 The spray SMD fell significantly with increasing injection pressure.
5 The average SMD increased with the back pressure or the gas density. The slower penetration and shorter break-up length enhanced the probabilities of the droplet coalescence resulting in higher SMD.
6 A correlation between SMD near the spray-tip region and injection parameters was determined as SMD = $0.279\Delta P^{-0.702}\rho_a^{0.285} x^{1.521}$ and showed a fairly good agreement with the measured SMDs. This correlation was obtained only for the CWS with 50% loading in coal mass of 5 μm MMD provided from Otiscal Industries. The correlation constants may have to be modified for CWS fuels with different size and loading of coal particulate.

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