CHARACTERISATION OF HIGH-PRESSURE DIESEL-WATER EMULSION SPRAYS

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ABSTRACT

Combustion efficiency, emissions and fuel economy in diesel engines are strongly dependent on the fuel spray characteristics such as spray penetration, atomization, droplet size distribution and cone angle. The quantitative information on the effect of fuel injection pressures on sprays characteristics is crucial for understanding the process of fuel mixture formation and the effects it may have on the combustion processes. This becomes even more important with the trend of using alternative fuels as a means of reducing emissions. This paper describes a study in a constant-volume vessel aimed at investigating the effect of injection pressure and water content in non-evaporating diesel-water emulsion sprays on droplet size and spray angle using Mie scattering and laser induced fluorescence measurement techniques.

INTRODUCTION

International emission standards from internal combustion engines are increasingly getting more stringent, particularly in regard to particulate matter (PM) and oxides of nitrogen (NOx) emissions in diesel engines. Manufacturers and researchers are continuously looking for means to meet the challenge of reducing both these emissions. The two approaches used for this purpose are in-cylinder control of formation of PM and NOx and implementation of after-treatment technologies. One of the simplest methods of in-cylinder technologies is the use of water-diesel emulsions (DWE) as alternative fuel. This approach requires no significant retrofitting of or modification to the fuel injection system or the engine and provides in many cases a satisfactory resolution of the "diesel dilemma" – the need for trade-off between PM and NOx emissions [1-7]. Work done by the authors' research group [8,9] shows that a direct injection engine with pump-line-nozzle fuel injection system operating on DWE with 15% water content by mass exhibits superior thermodynamic efficiencies and heat release characteristics and lower hydrocarbon and NOx emissions compared with the base engine without any engine retrofitting or modifications. However, little is known about the implication of using high-pressures associated with modern common rail injection systems on spray development and combustion of DWEs. The high injection pressures in the diesel common rail injection system (reaching 200 MPa in modern fourth generation systems) provide much finer atomization of the fuel injected into the combustion chamber, compared with the pump-line-nozzle system, leading to improved combustion process and engine efficiency and reduced particulate emissions [10,11]. It is reasonable to assume that emissions from an engine with common rail injection engine will be reduced if diesel fuel is replaced with water diesel emulsions. However, there are some unknowns such as the effect of the injection pressure (which influences jet velocity and shear stress), the density differential between water and the base fuel and water content on the fuel droplet size distribution in the spray and spray angle.

The quantitative information on droplet sizes and other characteristics of diesel sprays such as spray angles under different injection pressures is crucial for understanding the process of fuel mixture formation and the effects they may have on the combustion process. The traditional techniques for obtaining this information include Laser Doppler Velocimetry (LDV) and Laser Doppler Anemometry (LDA). The techniques are based on the measurement of laser light scattered by seeded particles within a flow. The technique used in the present study is based on a combination of Mie scattering and Laser Induced Fluorescence.

EXPERIMENTAL APPROACH

Figure 1 shows the measurement and experimental setup designed for high pressure spray research. The common rail injector is supplied by fuel from a high pressure pump driven by a single phase, variable speed, variable torque electric motor. The system is capable of developing stable pressures up to 100 MPa and injecting single shot high pressure sprays into a transparent chamber through a single-hole nozzle (0.2 mm diameter) with different preset durations (with an increment of 0.1 microsecond). Standard diesel fuel is used in this study as

both a reference fuel and as the base fuel for the preparation of the emulsified fuels. The emulsified fuels were prepared in-house by mixing the reference fuel, tap water and Sorbitan Monolaurate as a surfactant and subjecting the mixture to vigorous mixing for 45 minutes. Table 1 shows water content and optimum surfactant concentrations in the standard diesel fuel (DL500) and three DWEs used in the study.
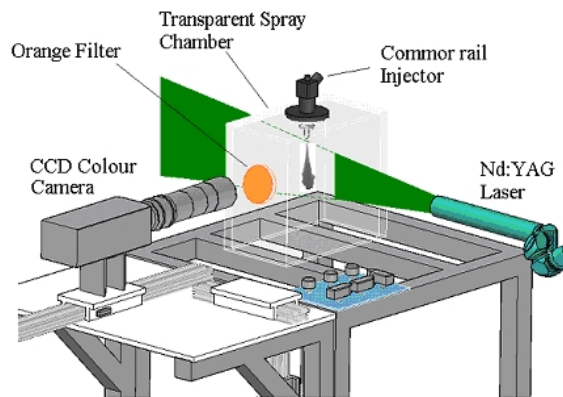

Figure 1 Three external boundary condition types

Fuel Designation	Surfactant (% by mass)	Water content (% by mass)
DL500	0	0
DWE15	0.4	15
DWE25	0.5	25
DWE35	0.7	35

Table 1 Diesel-Water Emulsions

The optical measurement setup for the Mie scattering and laser induced fluorescence measurements system used in the study is illustrated in Figure 1. It comprises a laser (120mJ, 532nm), an optical arm which spreads the laser light into a sheet of 0.8 mm thick and 60 mm wide with the laser pulse width of 6-8ns and a colour CCD camera. The camera is placed at 90 degree angle with the laser sheet to collect the scattering and fluorescence lights from the spray. The experiments are performed in two regimes: without and with a HOYA Orange (G) filter. The latter is installed for the purpose of increasing the laser power in order to get maximum possible fluorescence emission. The common rail injector, the camera and the laser machine are controlled and timed using an electronic control unit linked to a PC.

For the current series of tests, injection duration is kept constant at 5 ms and the laser is triggered 2 ms after the start of injection for the purpose of acquiring the images of the sprays at a steady state. The measurement technique used is based on a combination of Mie scattering and Laser Induced Fluorescence. By using fluoresceins under a laser sheet, the spatial positions of different solvents could be traced. Generally, Fluoresceins are well suited to Laser Induced Fluorescence [12]. Fluorescein

Kiton Red 620 is selected for this study as it exhibits properties, such as solubility in water and insolubility in diesel oil, which allows to investigate diesel-water emulsion sprays. The positions within the spray, at which the images of the DWE droplets are taken, are illustrated in Figure 2. The imaged rectangular detection areas are positioned at different locations, which lie on the boundary between the dense spray core and droplet cloud. The droplet sizes and number of DWE droplets are calculated for every imaged rectangular detection area.
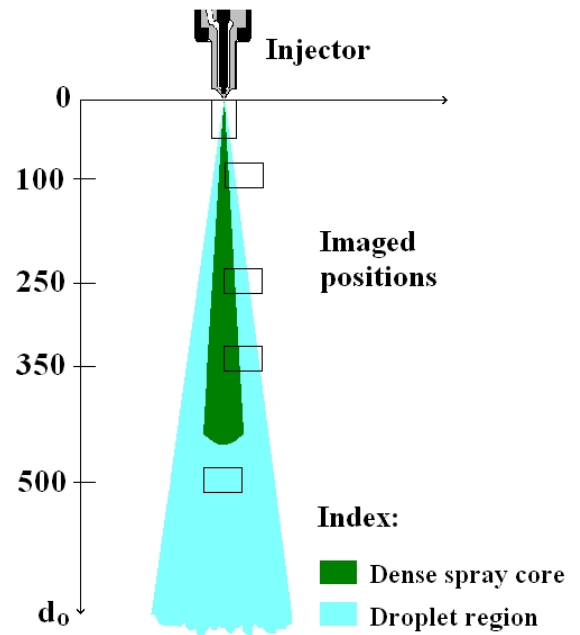

Figure 2 Locations of the captured images downstream of the injector nozzle
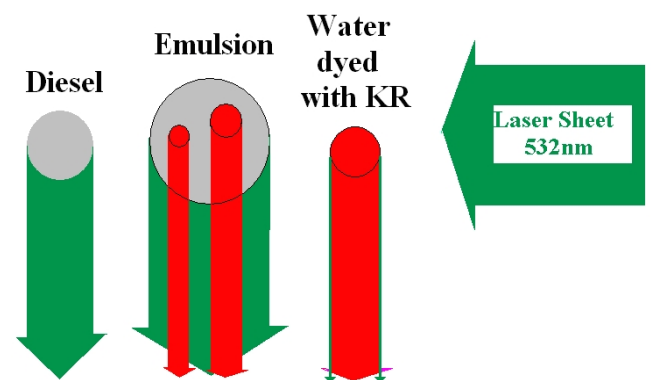

Figure 3 Illustration of the principles of the measurement method

Figures 3 illustrates the principle of the used measurement technique. When a thin laser sheet shines through the centreline of a spray of DWE, a CCD camera, the image plane of which is placed parallel to the plane of the laser sheet, can capture signals from:

- Scattered light (green) with the same wavelength as the laser sheet from pure diesel droplets, the diesel base of DWE droplets and possibly weak scattered light from diesel traces on the surface of water droplets.
- Laser induced fluorescence which is emitted from the dye molecules that have been excited to higher energy levels by absorption of electromagnetic radiation of the laser. Due to the fact that Kiton Red 620 dye is insoluble in diesel, the signal (red) from laser induced fluorescence can be correlated to the water droplets, which dissolved the Kiton Red 620 dye.

A single colour CCD camera equipped with an appropriate optics captures these signals and saves images of the sprays. The distinctive features of the technique are the following:

- The images are taken with magnification number of 1, which means the images are almost true pictures of a part of the sprays. This feature allows measuring the actual sizes of droplets at the examined areas, not the mean diameter of the entire examined area as it is with, e.g., Sauter Mean Diameter measurement technique. It also detects spatial positions of the water droplets in relation to positions of the diesel oil droplets.
- The technique employs only a single, commercial colour CCD camera for simultaneously recording Mie scattering and Laser Induced Fluorescence lights. This is possible thanks to Red, Green and Blue micro-filters installed with every sensor (pixel) of the CCD array of the camera. The setup eliminates the complexity of the optic system if two cameras were to be used. The setup also avoids the laborious task of alignment of two cameras.

A computer program written using GNU Pascal analyses the images, separates the signals into individual Red, Green and Blue intensities, and performs the calculations.

Every colour CCD camera has its unique response characteristics according to the different wavelengths of the light sources. Almost all of the commercial colour CCD cameras have broad-band interference filters (usually Red, Green and Blue filters). As it is shown in Figure 4, there are significant overlaps between colours, which make the recognition of the wavelengths of each light coming to the CCD array more difficult. The relative response curves show that for every scattered light from a laser source of 532 nm the reading in Blue intensity is accompanied by significant readings in Red and Blue channels. The Red intensity reading caused by the 532 nm scattered light could be wrongly recognized as the intensity caused by the fluorescence from Kiton Red 620 under the excitation of the green 532nm laser source (Figure 4). Similarly, the Green reading could be the sum of intensities from two distinct lights since the fluorescence emission from Kiton Red 620 produces green intensity too, besides the "true" green 532 nm wavelength scattered from the diesel droplets. So there is the necessity to differentiate the Red and Green intensity values, which are caused by two different wavelength lights – scattered light of 532nm wavelength and laser induced fluorescence light with predominant 620 nm wavelength.
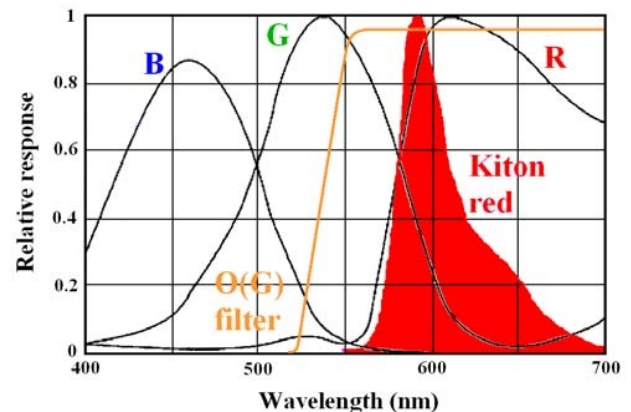

Figure 4 The Hitachi KP-140FD relative response with orange filter and Kiton Red fluorescence

The differentiation is made possible based on the fact that at every wavelength the ratios between responses in Red, Green and Blue sensors are constant, which allows the Red and Green intensities, recorded by sensors from scattering and laser induced fluorescence, to be separated and their values determined. These intensities are then used to reconstruct the separated images of scattered droplets (green colour) and fluorescence droplets (red colour). The next step is to find the pixels with the intensity of the examined colour larger than preset threshold, label the connected pixels and, finally, separate the droplets and calculate their diameters. The connection between pixels is determined using 8-connectivity method or 8-connected component operator [13].

RESULTS AND DISCUSSION

Droplet Sizes

The droplet sizes of DWE in this study are measured in different axial positions as mentioned earlier. Due to the fact that the fuel is injected into atmospheric back pressure, the image positions are farther away than if the fuel was injected under real engine conditions [14]. For the purpose of measurement of droplet sizes, the image positions, as shown in Figure 4, are at $100d_0$, $250d_0$, $350d_0$, and $500d_0$, where d_0 is the diameter of the nozzle hole (0.2 mm).

Figure 5 shows the distribution of DWE15 droplets at the distance of $250d_0$. It is clear that the injection pressure has a significant effect on the sizes of droplets which is similar to diesel fuel injection. The dominant sizes of droplets are in the interval from 5 to 15 microns. As the injection pressure increases, the number of droplets with larger diameters (from 10 to 25 microns) decreases in favour of the number of smaller sizes (up to 5 microns) droplets. Similar trends are observed for the droplet sizes of the injection of DWE25 (not shown) and DWE35 (Figure 6).
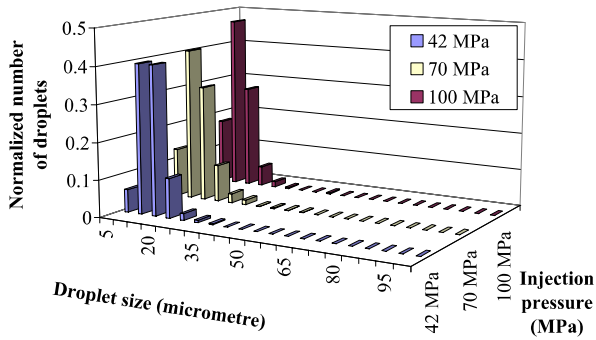
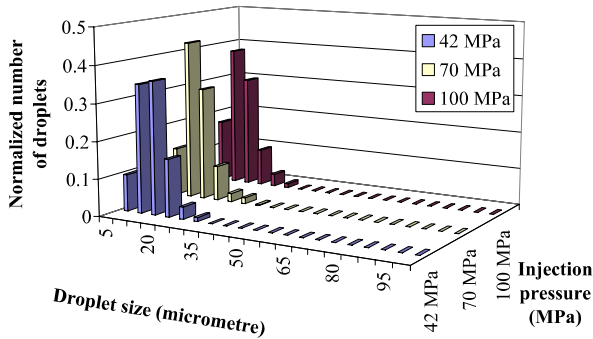**Figure 5** Distribution of DWE15 droplet size at the
axial position of $250d_0$

Figure 6 Distribution of DWE35 droplet size at
axial position of $250d_0$

value corresponding to the fuel with the least water content (15%)
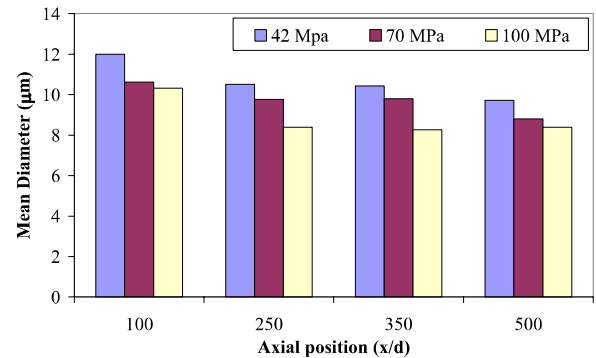
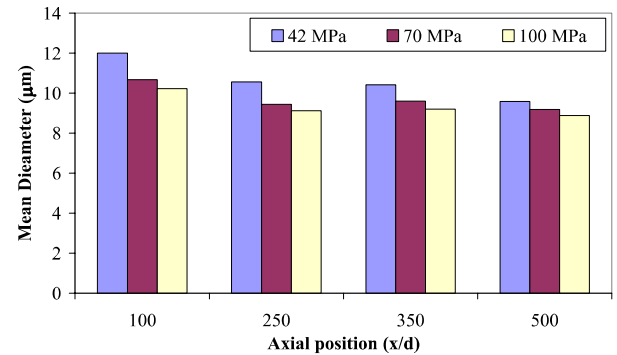**Figure 7** The average droplet size from DWE15 spray

Figure 8 The average droplet size from DWE35 spray

Figures 7 and 8 show the effect of pressure and measurement location on the mean droplet diameter for WDE15 and DWE35, respectively. There is a general trend of decreasing mean diameter with increased distance from the nozzle for all three injection pressures. The injection pressure has a significant impact on the droplet size at all of the measurement points. The influence of injection pressure seems to be more significant at positions closer to the nozzle tip than the positions further downstream.

Spray Angles

The spray angles in this study are measured from the images captured at the nozzle exit. As all the acquired images in the capturing area of 6.4 mm x 4.6 mm have the magnification number of 1, the spray angles are measured at a distance of $22d_0$– about 4.4 mm downstream from the nozzle tip (Figure 9). The angle is calculated based on the number of pixels, which have the intensity above a threshold value and form a continuous arc of the radius of $22 d_0$.

The results from the spray angle measurements of DWEs under different injection pressures are shown in Figure 10. It reveals that the injection pressure has small effect on the spray Angle which varies within the range 23-25° with the higher
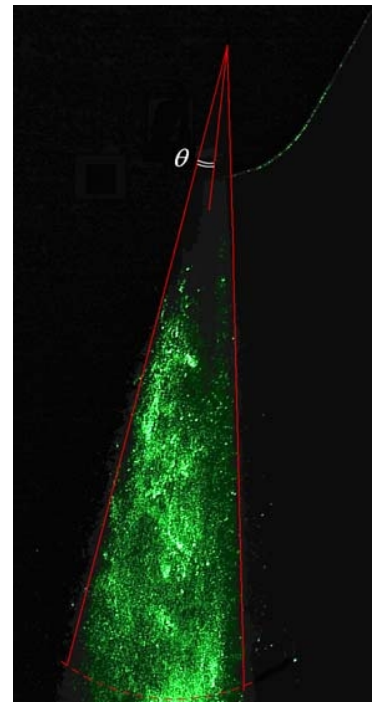

Figure 9 Spray angle measurement

These values are somewhat higher than the values for diesel sprays reported in the literature, which also show weak effect of injection pressure. Hiroyasu et al [15] used much lower injection pressures (up to 25 MPa) in their pioneering work on diesel sprays and found that spray angles ranged between 20 deg to $22°$ at an ambient pressure of 1 MPa. Posrioti and Ubertini [16] report spray cone angle range of 18-22 at 160 MPa injection pressure and Delacourt et al [17] report similar values for an injection pressure range of 80-250 MPa. This indicates that mathematical models designed to predict spray cone angles for diesel fuel can also be used for water-diesel emulsions.
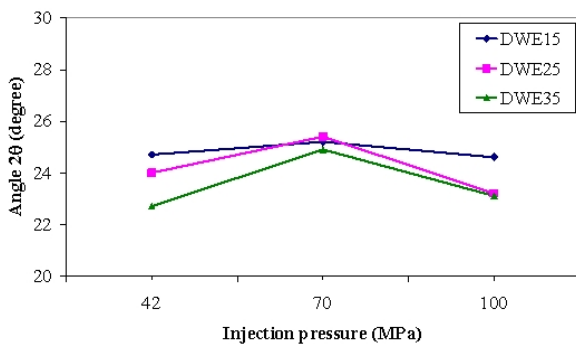

Figure 10 Spray angle measurement results

CONCLUSIONS

Non-combusting DWE sprays are investigated using the laser scattering technique. Specifically, the effect of injection pressure on droplet size and spray angle is examined in some detail. The experiments show that the injection pressure affects the droplet size of DWEs in the same way it affects the diesel fuel. The higher the injection pressures, the smaller the average (both arithmetic and Sauter Mean) diameters of droplets. At all of the measurement points, droplet sizes of less than 10 microns become dominant with the increase of injection pressure. The larger group (15 microns and bigger) reduces considerably with the increase of injection pressure at the measurement points close to the nozzle exit, but at the points further away from the nozzle tip, the injection pressure has little influence on the share of the group, which is already small at these "remote" measurement positions.

The results from the spray angle measurements of DWEs reveal that the injection pressure has little effect on the spray angle. The spray angle varies between $23-25°$ under all test conditions.

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