Spray Characteristics of Diesel Fuel Containing Dissolved CO_2

M. Karaeen and E. Sher
Department of Mechanical Engineering
The Pearlstone Center for Aeronautical Studies
Ben-Gurion University Beer-Sheva, Israel

Abstract

The effect of adding CO_2 to diesel fuel has been previously studied by several groups that used tailored made injection systems with which remarkable low SMD's were archived. In the present study we use a real commercial fuel injection system and studied the effect of the amount of dissolved CO_2 on the resulted spray characteristics. In this case, when the mixture enters the injector and flows downstream through the variable cross-sections duct, partial nucleation is expected to occur at different locations along the duct and a part of the dissolved gas is transformed into tiny bubbles that grow fast downstream. When the mixture is driven out through the discharge orifice, these bubbles undergo a rapid flashing process resulting a rapid disintegration of the liquid bulk into small droplets. In the present study, an experimental study of steady-state atomization process of diesel fuel containing dissolved CO_2, is presented. An extensive study was performed to map the effect of the CO_2 content on the spray SMD and droplet distribution at different locations downstream the discharge orifice, and also on the spray angle. The spray characteristics (SMD, $D_{0.1}$, and Span factor) were measured with a laser particle size analyzer (Malvern X-Mastersizer), and a digital camera was employed to record the spray angle. An overall analysis has been performed to evaluate the advantage of the proposed method over its counterparts, in terms of the total energy required to produce a desired spray. It is concluded that the atomization of diesel fuel containing dissolved CO_2, is significantly promoted by the flash-boiling phenomenon to result low SMD sprays. It was also found that the spray structure of a fuel/dissolved gas mixture is essentially different from that of a single-component fuel.

Nomenclature

$D_{0.1}$ Drop diameter such that 10% of total liquid volume is in drops of smaller diameter

$D_{0.5}$ Median droplet diameter

$D_{0.9}$ Drop diameter such that 90% of total liquid volume is in drops of smaller diameter

SMD Sauter mean diameter (D_{32})

S_f Span factor

ρ_A Density of Air

U_R Drop velocity

σ Surface Tension

We Weber number

Introduction

The search for new approaches to improve fuel injection, combustion efficiency, and exhaust emissions in internal combustion engines, has been accelerated in the last decade due to the worldwide tightening air pollution regulations. One of the promising ideas is fuel enrichment with dissolved CO_2 prior to injection [1-10].

The effect of adding CO_2 to diesel fuel has been previously studied by several groups that used tailored made injection systems. The downstream part of the injector consisted of an inlet orifice, an expansion chamber, a swirl duct, and a discharge orifice. When the mixture entered the expansion chamber, a part of the dissolved gas was transformed into tiny bubbles that grew inside the expansion chamber. When the mixture was driven out through the discharge orifice, these bubbles have undergone a rapid flashing process that resulted a rapid disintegration of the liquid bulk into small droplets. The effect of the CO_2 content was clearly demonstrated and remarkable low SMD's were archived. In the present study we use a real commercial fuel injection system that is working at 13MPa and studied the effect of the amount of dissolved CO_2 on the resulted spray characteristics. In this case, when the mixture enters the injector and flows downstream through the variable cross-sections duct, partial nucleation is expected to occur at different locations along the duct and a part of the dissolved gas is transformed into tiny bubbles that grow fast downstream. As for the case of the special designed injection system, when the mixture is driven out through the discharge orifice, these bubbles undergo a rapid flashing process resulting a rapid disintegration of the liquid bulk into small droplets.

Zhen et al. [1,2] investigated the atomization behavior of a steady spray of fuel containing dissolved gas; they used diesel fuel containing dissolved CO_2 and air in order to study the effects of the concentration of the dissolved gas, the injection pressure, and the nozzle L/D ratio. They also investigated the injector nozzle orifice flow pattern and pressure

characteristics [3], in order to evaluate their effects on the atomization of fuel containing dissolved gas using scaled up model nozzles and metal nozzles. They observed that atomization occurs almost right at the nozzle exit, the effect of injection pressure on the spray angle is gradually increased, and the Souter mean diameter (SMD) decreased sharply with an increase in the injection pressure.

In order to reduce both NO and soot emissions from Diesel engines while keeping or improving their thermal efficiency, Senda et al. [4, 5] studied the effect of blend of n-Tridecane and liquefied CO_2. The spray penetration was evaluated from shadowgraph photographs. The atomization characteristics were examined for both pure n-Tridecane and CO_2 for different pressures. They found out that indicated thermal efficiency was improved with higher CO_2 mole fraction.

Dissolved CO_2 in gasoline was also studied by Rashkovan et al. [6]. They studied the steady state atomization process of gasoline containing dissolved CO_2, they investigated experimentally the effect of the injector design parameters. The spray characteristics (SMD and D_{90}) were measured. They also observed the flow pattern inside the injector [7]. They found out that the impact of CO_2 is a major effect that not only affects the SMD, but also improves the droplet volume fraction distribution. For high injection pressures the addition of dissolved CO_2 results in an increase in the number of small droplets. They also found that the spray cone angle is nearly independent on the injection pressure, while it depends strongly on the carbon dioxide contained. The shape of the cone is different for these two gases: for pure gasoline injection a hollow cone type was observed, while for an increasing amount of CO_2 contained the cone became closer and closer to solid type. When moving downstream, the opening angle of a pure gasoline spray is rather fixed, while the opening angle of a gasoline-CO_2 mixture decreases. This is attributed to the fast evaporation of tiny droplets (formed by the flashing mechanism) at the periphery of the cone envelope and may explain the apparent small cone angles of the gasoline-CO_2 mixtures as compared to those obtained for pure gasoline.

Xiao et al. studied the droplet size and velocity of fuel containing CO_2 by means of phase Doppler anemometry. They found out that the axial and radial velocities of the fuel spray containing CO_2 is larger than that of conventional diesel fuel spray near the nozzle exit due to explosive flashing phenomena, downstream of the spray, the radial velocity and droplet size of fuel containing dissolved CO_2 is much uniform and smaller than that of pure diesel Spray

[8,9]. They also investigated the process of injecting a bubble jet of transient spray with fuel containing CO_2 using high-speed imaging technology. By visualization of the flashing boiling spray and measurement of spray velocity, three regions are defined in development of flash boiling spray, an acceleration region, a rapid deceleration region, and a slow decline region [10].

In this work, an experimental facility layout had been designed and built in order to study the spray characteristics of a nearly real injection process through a single-hole nozzle commercial Diesel injector. The study was performed by using a high pressure container where the Diesel fuel was enriched with CO_2 at different pressures (mole fractions). A manual injection pump was used to compress the mixture to the desired injection pressure. The SMD, span factor S_f, and the minimum droplet diameters D_{10} were measured along the axial direction. A comprehensive study for the effect of the CO_2 content was performed.

Experimental Apparatus and Test Procedure

Figure 1 shows the schematic diagram of the experimental setup. A 1 liter high pressure bottle was partially filled with commercial diesel (Between 500 and 700 ml), and then a pressurized CO_2 was added to reach the required mixture ratio. In the present study the pressure varied between 1 and 3 MPa. The mixture was left for 12 hrs to reach equilibrium.

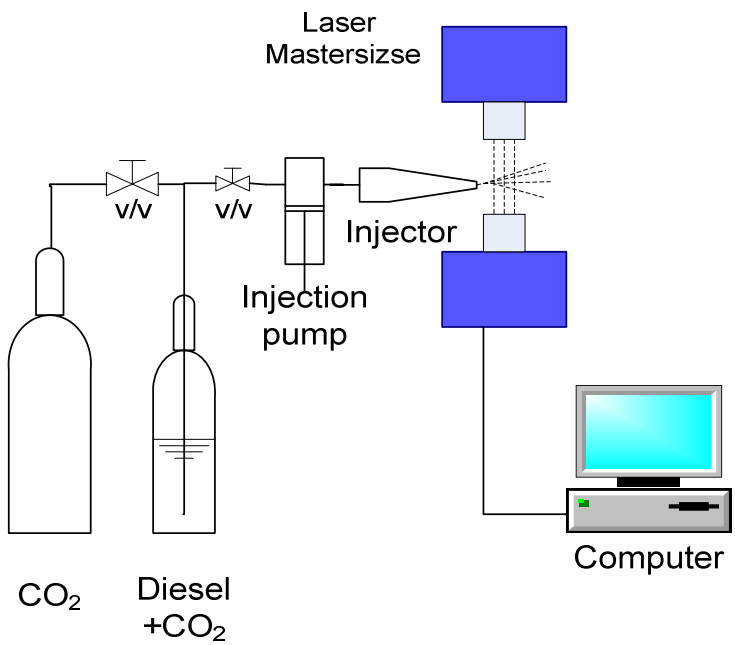

Figure 1: Setup for spray droplet measurement.

A simple procedure to measure the solubility of the CO_2 in the commercial diesel was performed. Figure 2 shows the percent of dissolved CO_2 by mass and mole fractions; as expected, the linear relation follows the Henry's law.

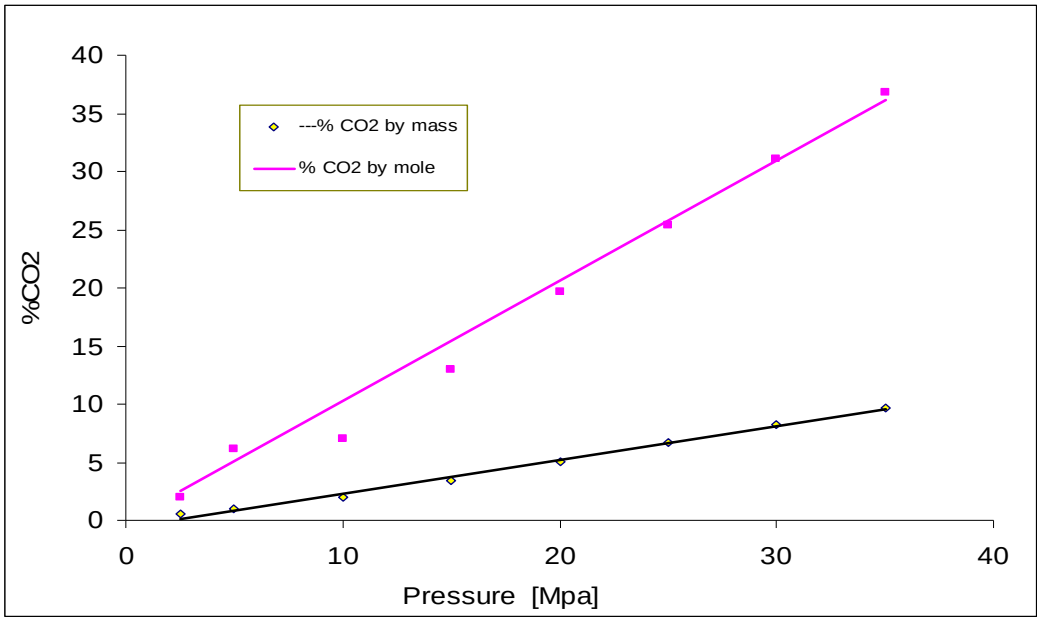

Figure 2: Percent of mass and mole fractions of CO_2 dissolved in Diesel fuel.

A manual working Diesel pump (Bosch nozzle tester Efeb60h) was used to raise the mixture pressure up to the injector opening pressure. A commercial Diesel injector, used for VW Cady 2,000cc Diesel engine, was employed. The injector has a single hole (0.8mm in diameter), and a spring loaded nozzle injector that opens at a pressure of 13 MP. A laser particle-size analyzer, Malvern Mastersizer-X system, was used to measure the atomization spray droplet size and distribution (figure 3). A helium-neon beam crosses the spray pattern and diffracts as a function of their size. The total diffracted light from the different particles is received onto a series of concentric, radial photodiode-array detectors. The fraction of light diffracted to each photodiode detector depends both on the sizes of the droplets and on the volume of droplets of each size. Analysis of the detector's output yields a size distribution by volume, from which a mean size can be derived. The range of spray droplet diameter that could be detected is between 0.1 and 500µm.

Drop size and drop size distribution of the tested spray was measured along the axial distance from the injector nozzle. Each point was repeated eight times to eliminate unavoidable irregular errors.

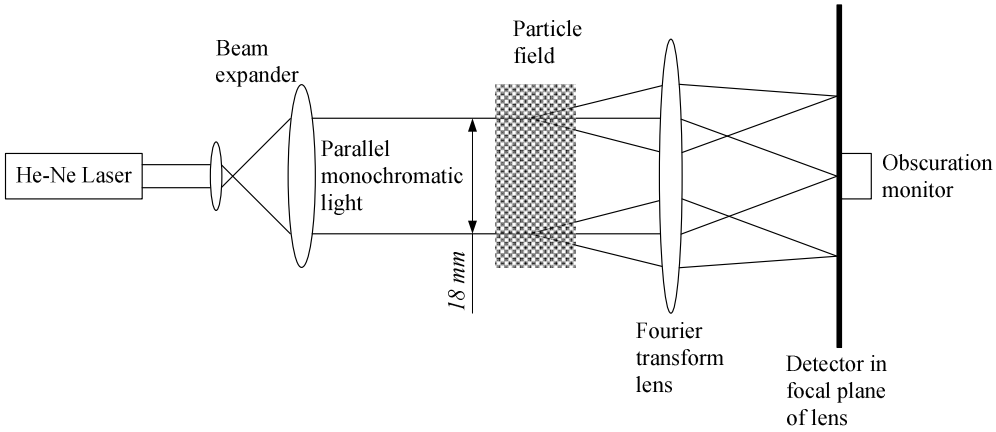

Figure 3: Malvern Mastersizer-X optical setup

The effect of injection process on the structure of diesel spray

Before entering into discussion and comparison of the effect of enriching Diesel with CO_2 on drop size and distribution, it is worth noting drop size evolution downstream. Figure 4 shows how the SMD of a pure Diesel varies along the axial distance. Droplets leave the nozzle with large SMD (59μm at 2cm axial distance), their size decreases along the axial direction from 59μm down to 31μm at 10cm, and then becomes nearly constant. Lefebvre [11] explained that the breakup of drop in a flowing stream is controlled by the dynamic pressure, surface tension, and viscous forces, the deformation of drop is determined primarily by the ratio of aerodynamic forces represented by $0.5\rho_A U_R^2$ and the surface tension forces, which are related to σ/D. Forming a dimensionless group from these two opposing forces yield the Weber number, $We = 0.5\rho_A U_R^2 D/\sigma$.

It follows that the higher the Weber number, the larger are the deforming external pressure forces as compared to the reforming surface tension forces.

Lane [12], and Simmons [13] demonstrated that when a drop suddenly leaves the nozzle to a low pressure region, it becomes increasingly flattened, and at a critical relative velocity it blown out into the form of hollow bag attached to a roughly circular rim. On disintegration the bag produces a shower of very fine drops, while the rim breaks up into larger drops. It was explained by Lane [12] that if the relative velocity is less than the critical, breakup will cease. Arcoumanis and Gavaises[14] showed that other effects such as collisions, droplet turbulent dispersion, droplet evaporation and droplet deceleration, may occur further downstream.

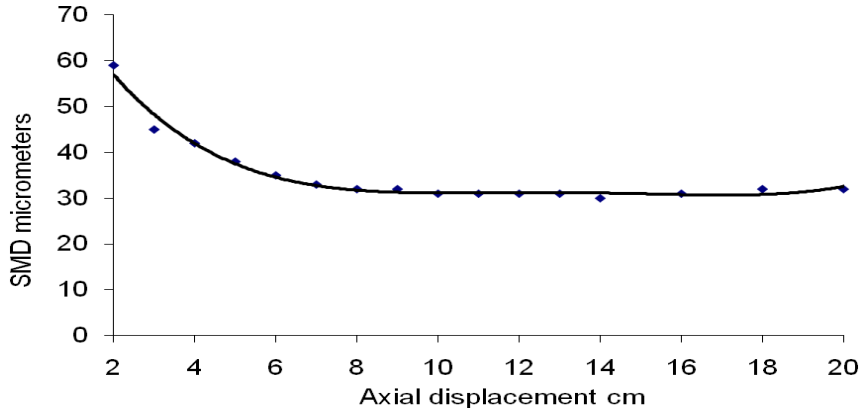

Figure 4: Drop SMD variation for pure Diesel along axial distance.

Results

Measurements of the Souter mean diameter, SMD, span factor, S_f, and minimum droplet diameters, D_{10}, of pure diesel, enriched Diesel with CO_2 at initial pressures of 1, 1.5, 2, 2.5, 3 and 3MPa were performed at the axial horizontal distances between 2 and 20cm from the injector nozzle. The injection and the surrounding pressures were kept constants for all tests; 13MPa and 0.1MPa respectively.

The SMD for pure Diesel and for various concentrations of enriched Diesel with CO_2 is shown in figure 5. It seems that for the pure Diesel the SMD decreases monotonically along the axial direction. For CO_2 enrichments of 2 and 3.4% on mass basis (1 and 1.5 MPa respectively) it is noticed that as compared to the pure fuel SMD, the SMD is higher anywhere, thus showing negative effect of low CO_2 concentrations. A similar results were obtained by Xiao et al [9], they found out that there is a critical value of dissolved CO_2 between mass fraction of 2.72 and 10.59, below this critical value the SMD is larger than that of pure Diesel. At 2MPa and above, the SMD starts at smaller values than in the pure Diesel, and decreases significantly along the horizontal axial distance. The minimum registered SMD happened at a distance of 7cm from the injector nozzle, while it decreases from 33μm to 20μm. After this distance SMD is slightly increases, this might be explained upon the findings of Xiao et al [10], at the beginning of injection spray accelerates which increases Weber number, hence break up of droplets takes its place, then it decelerates which

decreases the effect of aerodynamic forces against surface tension forces, and due to collision of droplets some of them might adhere together which increases droplet SMD.

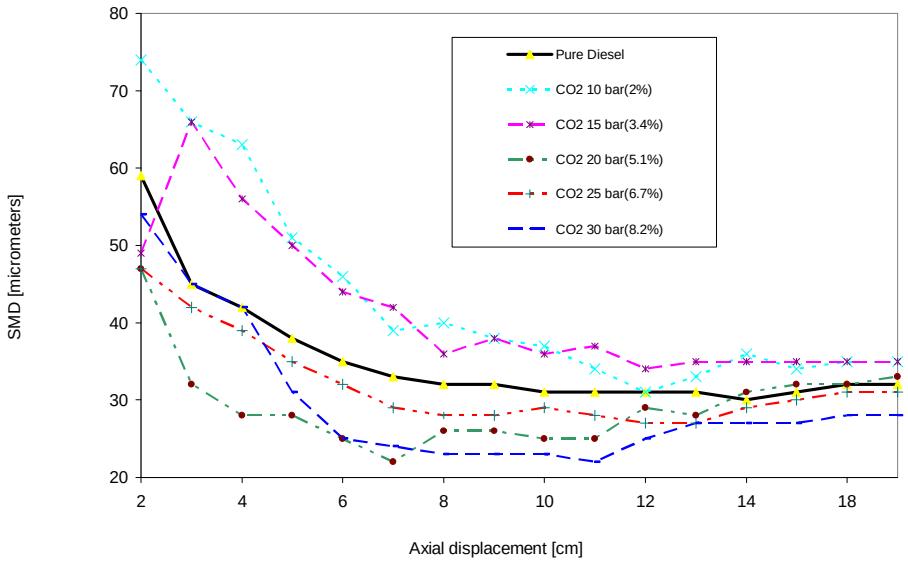

Figure 5: The effect of the CO_2 concentration in diesel on the droplets' SMD

Figure 6 compares the $D_{0.1}$ diameter between the pure Diesel and Diesel-CO_2 enrichment in various degrees. Here again the negative effect for the lower pressures of 1 and 1.5 MPa is clearly shown, but at higher pressures, the $D_{0.1}$ becomes smaller until it reaches a minimum value (about 20% less than that of pure Diesel) at a distance of about 9cm.. Here the $D_{0.1}$ is also started at higher values, break up takes its place through the small axial displacement, then it deformers again, this might be due to the same reason that was explained for the SMD, but here it is noted that the behavior of the curves is slightly different from the SMD, these very smaller diameters might adhere together in a stronger manner than that of the SMD, so along the axial displacement they grow up and up again. The span factor, $S_f = \frac{D_{0.9} - D_{0.1}}{D_{0.5}}$.

It is the measure of the width of the volume distribution relative to the median diameter; it provides a direct indication of the range of drop sizes relative to the mass median diameter.

Figure 7 compares the span factor for the pure Diesel and the span factors for various degrees of Diesel-CO_2 enrichments. It shows that for the low concentrations the span is low, while for high concentrations it is higher than for the pure Diesel, e.g., at higher concentrations of CO_2

the volume distribution relative to the median droplet diameter is higher than that for the pure diesel, which means better droplet distribution.

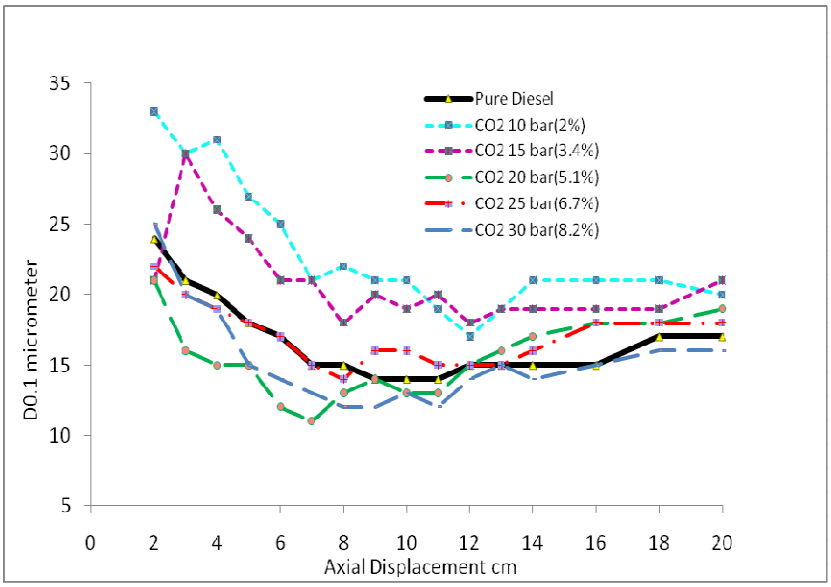

Figure 6: The effect of the CO_2 concentration in Diesel on the droplet $D_{0.1}$

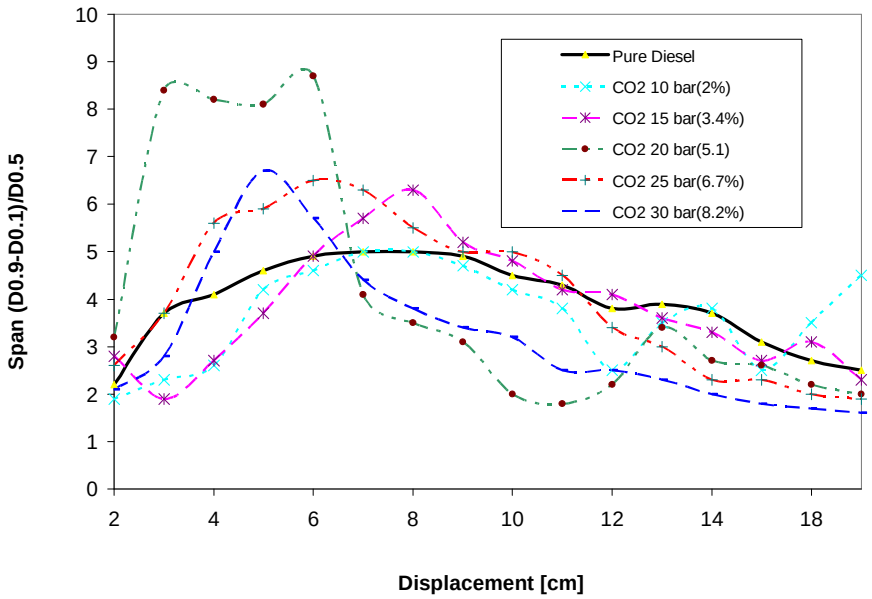

Figure 7: The effect of the CO_2 concentration in diesel on the Span factor of spray droplets

Figure 8 shows an attempt to compare the spray angle of a pure diesel with a CO_2 enriched diesel fuels. A large number of photos was taken at various concentrations, all these photos were similar and didn't show variations for spray angle except for the pure diesel which

showed a larger spray angle, this might be due to the fast evaporation of tiny droplets at the nozzle exit and thus the outer shells of the spray are invisible. Similar results for the gasoline enriched with CO_2 were found by Rashkovan et al [6]; they found that with increasing the amount of CO_2 content, the spray cone becomes closer and closer to a solid type.


Diesel

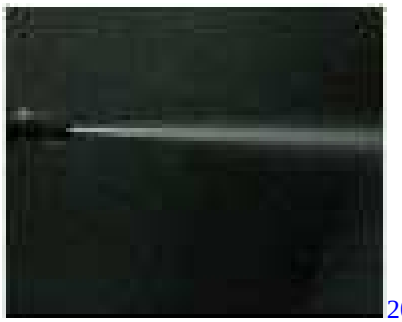
20 bar

Figure 8: Spray angles for pure diesel and enriched diesel with CO_2

Conclusion

An experimental study of the effect of CO_2 concentration in Diesel fuel on the injection droplet size and droplet size distribution is presented. An actual commercial injector was tested. It was shown that introducing CO_2 to Diesel prior to injection has negative effects for small mass fractions (up to 3.4%). At higher mass fractions (up to 8.2%), the SMD was decreased by about 40% (mass fractions, while the D_{10} droplet diameter by about 20%.

The span factor was increased at smaller axial distance that means a more uniform spray droplets size distribution, thus suggesting better chance for diesel droplets to be ignited through the ignition process in the combustion phase.

The spray angle was decreased when CO_2 was introduced, that might be due to the fast evaporation of tiny droplets at the nozzle exit and thus the outer shells of the spray are invisible.

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