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SPRAY CHARACTERISTICS OF DIESEL FUEL CONTAINING DISSOLVED CO_2

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The effect of adding CO_2 to diesel fuel has been studied by several groups that used tailor-made injection systems to achieve notable low Sauter mean diameters (SMDs). In the present study, we use a real commercial fuel injection system and study the effect of the amount of dissolved CO_2 on the resulting spray characteristics. In this case, when the mixture enters the injector and flows downstream through the variable cross-section passage toward the discharge orifice, partial nucleation of the dissolved gas is expected to occur at different locations along the duct, which transforms the mixture into tiny bubbles that grow fast downstream. When the mixture is driven out through the discharge orifice, these bubbles undergo a rapid flashing process that results in an intensive disintegration of the liquid bulk into small droplets. In the present study, we present an experimental study of the atomization process of diesel fuel containing dissolved CO_2 that occurs in steady flow conditions. 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. It is concluded that the atomization of diesel fuel containing dissolved CO_2, is significantly promoted by the flash-boiling phenomenon, which results in low SMD sprays, low $D_{0.1}$ droplets, a faster breakup mechanism, and a more uniform droplet size distribution.

KEY WORDS: *diesel fuel, dissolved CO_2, flash-boiling*

1. 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 worldwide tightening of air pollution regulations. Fuel enrichment with dissolved CO_2 prior to injection is one of the more promising ideas toward reaching these goals (Zhen et al., 1994a,b,c; Senda et al., 1997, 1999; Rashkovan et al., 2004; Rashkovan and Sher, 2006; Xiao et al., 2008a,b, 2009).

The effect of adding CO_2 to diesel fuel has been studied by Zhen et al. (1994a,b,c), who used tailor-made injection systems. In these systems the downstream part of the injector consists of an inlet orifice, expansion chamber, swirl duct, and discharge orifice. When the mixture crosses the inlet orifice, part of the dissolved gas is transformed into tiny bubbles that grow inside the expansion chamber. When the mix-

NOMENCLATURE

$D_{0.1}$	droplet diameter (10% of the total liquid volume is in smaller diameter drops)	SMD	Sauter mean diameter (D_{32})
$D_{0.5}$	median droplet diameter	S_f	span factor
$D_{0.9}$	droplet diameter (90% of the total liquid volume is in smaller diameter drops)	ρ_A	density of Air
		U_R	drop velocity
		σ	surface tension
		We	Weber number

ture is driven out through the discharge orifice, these bubbles undergo a rapid flashing process that results in rapid disintegration of the liquid bulk into small droplets. The effect of the CO_2 content was clearly demonstrated and notable low Sauter mean diameters (SMDs) were archived (Zhen et al., 1944a). However, it is important to note that in real injection systems, the injector tip has to be blocked and sealed at the end of each injection session to ensure no dripping of fuel. Thus, adding an expansion chamber and one more orifice seems impractical. In the present study, we used a real commercial fuel injection system that is designed to work at 13 MPa, and studied the effect of the amount of dissolved CO_2 on the resulting spray characteristics. In this case, when the mixture enters the injector and flows downstream through the variable cross-section duct, partial nucleation is expected to occur at different locations along the convoluted passage and part of the dissolved gas is transformed into tiny bubbles that grow fast downstream. Here, similar to the case of the specially designed injection system, when the mixture is driven out through the discharge orifice these bubbles undergo a rapid flashing process that results in rapid disintegration of the liquid bulk into small droplets.

Zhen et al. (1994a,b) investigated the atomization behavior of a steady spray of fuel containing dissolved gas and used diesel fuel containing dissolved CO_2 and air in order to study the effect of the amount of dissolved gas, injection pressure, and nozzle length-to-diameter (L/D) ratio. Zhen et al. (1994c) also investigated the injector nozzle orifice flow pattern, in order to evaluate its effect on the atomization of fuel containing dissolved gas. Among their other conclusions relating to the atomization distance and the effect of the injection pressure, Zhen et al. (1994c) concluded that the spray angle gradually increases with the CO_2 content. However, this observation is in contrast to two observations by Senda et al. (1997, 1999) and Rashkovan et al. (2004). In order to reduce both NO and soot emissions from diesel engines while keeping, or improving, their thermal efficiency, Senda et al. (1997, 1999) studied the effect of CO_2 content in *n*-tridecane on the atomization characteristics and found that the indicated thermal efficiency was improved with higher CO_2 content. In contrast to the findings of Zhen et al. (1994c), Senda et al. (1997, 1999) found that the spray angle gradually decreases with the CO_2 content. Dissolved CO_2 in gasoline was studied by Rashkovan et al. (2004). They studied the atomization process of gasoline containing dissolved CO_2 that occurs in steady flow conditions and investigated experimentally the effect of the injector design parameters. The spray characteristics (SMD and $D_{0.9}$) were measured while observing the flow pattern inside the injector (Rashkovan and Sher, 2006). Rashkovan et al. (2004) and (Rashkovan and Sher, 2006) found 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. Rashkovan et al. (2004) and (Rashkovan and Sher, 2006) also concluded that the spray cone angle is nearly independent of the injection pressure, while it depends strongly on the carbon dioxide content. They noted that the shape of the cone for pure gasoline injection is hollow, while for an increasing amount of CO_2 content it becomes closer and closer to the 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 was attributed to the fast evaporation of tiny droplets (formed by the flashing mechanism) at the periphery of the cone envelope (Rashkovan et al., 2004).

Xiao et al. (2008a,b, 2009) studied the droplet size and velocity of fuel containing CO_2 by means of phase Doppler anemometry. They found 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 that occur downstream of the discharge orifice. The droplet size of the fuel containing dissolved CO_2 is much smaller and more uniform than the droplet size of pure diesel spray (Xiao et al., 2008a,b). By visualization of the flashing boiling spray and measurement of the spray velocity, three regions were defined in the development of the flash boiling spray: an acceleration region, a rapid deceleration region, and a slow decline region (Xiao et al., 2009).

In the present work, an experimental facility layout has been designed and built in order to study the spray characteristics resulting from a nearly real injection process through a single-hole nozzle commercial diesel injector. The study was performed by using a high-pressure container in which the diesel fuel was enriched with different degrees of CO_2. A manual injection pump was used to raise the mixture pressure to the desired injection pressure (13 MPa). A comprehensive study of the effect of the CO_2 content on the spray characteristics was performed.

2. EXPERIMENTAL APPARATUS AND TEST PROCEDURE

We used a simple procedure to measure the solubility of the CO_2 in the commercial diesel. A 1 L high-pressure bottle was partially filled with commercial diesel and then pressurized CO_2 was added to reach the required mixture ratio—in the present study, between 1 and 3.5 MPa. The mixture was left for 12 h to reach equilibrium. Figure 1 shows the percent of dissolved CO_2 by mass and mole fractions; the linear relation indicates that the mixture follows Henry's law.

Figure 2 shows the schematic diagram of the experimental setup. A manual working diesel pump

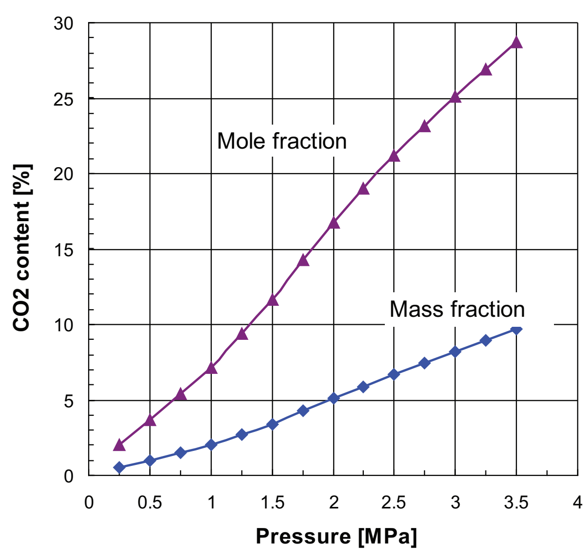

FIG. 1: Percent of mass and mole fractions of CO_2 dissolved in diesel fuel.

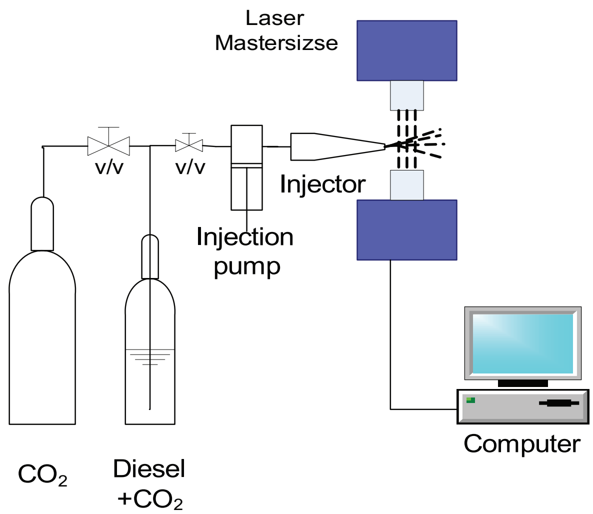

FIG. 2: Setup for spray droplet measurement.

(Bosch nozzle tester model Efeb60h) was used to raise the mixture pressure up to the injector opening pressure. A commercial diesel injector (used for a VW Cady 2,000 cc diesel engine) was employed to spray the mixture into an open space at 100 kPa. The injector had a single aperture (0.8 mm in diameter) and a spring-loaded nozzle injector that opened at a pressure of 13 MP. A laser particle-size analyzer (Malvern Mastersizer-X system) was used to measure the spray droplet size and the droplet size distribution (Fig. 3). In this device, a helium–neon beam crossed the spray pattern and diffracted as a function of droplet size. The total diffracted light from the different particles was received into a series of concentric, radial photodiode-array detectors. The fraction of light diffracted to each photodiode detector depended both on the different droplet sizes 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 can be detected is 0.1–600 μm.

The droplet size and droplet size distribution of the tested spray were measured along the axial distance from the injector discharge orifice. Each point was repeated eight times to eliminate unavoidable irreg-

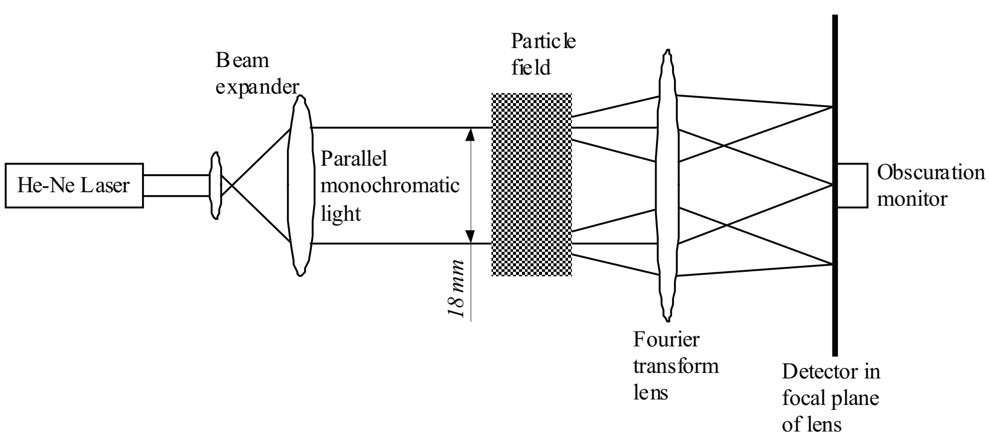

FIG. 3: Malvern Mastersizer-X optical setup.

ular errors and then the average value for each point was considered.

3. RESULTS AND DISCUSSION

3.1 Mean Droplet Size Evolution along the Axial Direction

Figure 4 shows how the SMD of pure diesel varies along the axial distance. Droplets leave the discharge orifice with a large SMD (59 μm at 2 cm axial distance), and their size decreases monotonically along the axial direction from 59 μm down to 31 μm at 10 cm. Lane (1951) and Simmons (1979) 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 is 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 (1951) that when the relative velocity is less than the critical velocity, breakup ceases. Lefebvre (1989) explained that the breakup of a drop in a flowing stream is mainly controlled by the dynamic pressure and surface tension forces. The deformation of the drop is determined primarily by the ratio between the aerodynamic forces, $0.5\rho_A U_R^2$ (where U_R is the droplet relative velocity and ρ_A is the ambient density), and the surface tension forces, σ/D (here, D is the droplet diameter). The ratio is known as 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 compared to the reforming surface tension forces. Along the axial direction, U_R, D, and the Weber number decrease and, thus, the droplet breakup tendency ceases. Arcoumanis and Gavaises (1997), Qian and Law (1997), and Nikolopoulos and Bergeles (2011) showed that other effects such as collisions, droplet turbulent dispersion, droplet evaporation, and droplet deceleration, may occur along the axial direction. These effects explain the moderate decrease further downstream.

The effect of the CO_2 fuel enrichment on the SMD is shown in Fig. 5(a). We notice that for low CO_2 enrichments of 2% and 3.4% (on a mass basis) the SMD is higher than that of pure diesel anywhere along the axial distance, thus showing a negative effect of low CO_2 content. Similar results were obtained by Rashkovan et al. (2004), Rahkovan and Sher (2006), and Xiao et al. (2008b). Xiao et al. (2008b) indicated that the SMD is larger than that of pure diesel up to a critical value of dissolved CO_2 (between 2.72% and 10.59%). Rashkovan et al. (2004) attributed these findings to the balance between the energy needed to evaporate the CO_2 and the required energy to tear

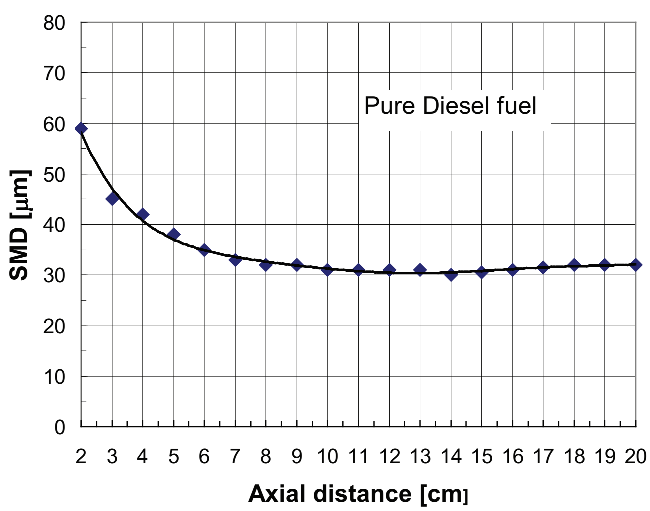

FIG. 4: Droplet SMD variation for pure diesel along the axial distance.

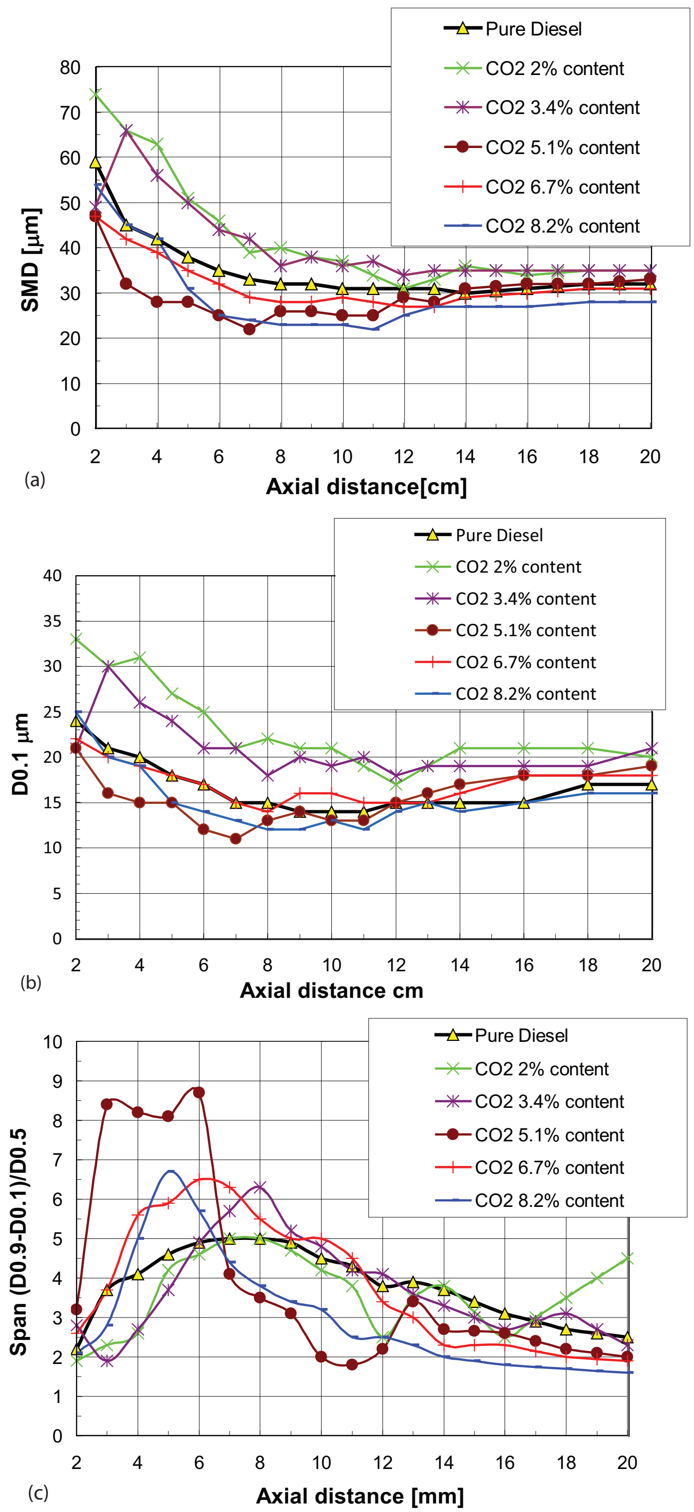

FIG. 5: Effect of the CO_2 mass fraction content in diesel on (a) the SMD; (b) $D_{0.1}$; and (c) the span factor.

the liquid ligaments. For low CO_2 content, the energy needed to evaporate the CO_2 results in a droplet surface cooling effect that increases the surface tension, thus reducing the Weber number. For high CO_2 content (above 14%), the cooling effect is still important but the energy stored in the large quantity of bubbles dominates the breakup process and, thus, lower SMDs are observed.

It is important to note that the minimum registered SMD occurs at a distance of 7 cm while it decreases from 33 to 20 μm, and then seems to slightly increase downstream. Xiao et al. (2009) attributed the SMD increasing to collisions that sometimes lead to droplet adhesion (coalescence). In the authors' opinion, fast evaporation of the smaller droplets is more likely to occur, thus leading to higher SMDs.

Figure 5(b) compares the $D_{0.1}$ diameter between pure diesel and CO_2-enriched diesel at various degrees (where $D_{0.1}$ is the droplet diameter, such that 10% of the total liquid volume is in smaller diameter droplets). Here, again, the negative effect for the lower CO_2 concentrations is clearly shown, while for higher CO_2 contents, the $D_{0.1}$ becomes smaller until it reaches a minimum value at a distance of about 9 cm (about 20% less than that of pure diesel). The rate at which the diameter of the smallest droplets increases along the distance may qualitatively support the idea that the fast evaporation of the smaller droplets is a more important reason leading to higher SMDs [Fig. 5(a)]. With this connection, we recall the classical d^2 evaporation law.

The span factor $S_f = (D_{0.9} - D_{0.1})/D_{0.5}$ is a measure of the width of the volume distribution relative to the median diameter; it provides a direct indication of the range of droplet sizes relative to the mass median diameter. Figure 5(c) compares the span factor for pure diesel and the span factors for various degrees of diesel–CO_2 enrichment. It shows that for low concentrations the span is low, while for high concentrations it is higher than for pure diesel. The value of the span factor indicates how uniform the spray droplets are; a higher number suggests better droplet uniformity.

The spray development history is shown in the three-dimensional (3D) histogram sets depicted in Fig. 6. Figure 7 shows the distribution of the volume fraction for two axial distances, 10 cm and 20 cm, in more detail, which indicate the following:

1. At small distance, for any CO_2 content, the major part of the droplets is large in diameter. As the distance increases, the droplet size distribution approaches closer and closer to a typical log-normal distribution.

2. For low CO_2 content, adding CO_2 demands a longer distance to achieve a log-normal-type distribution. However, for higher CO_2 content, as the enrichment increases, this distance becomes shorter and shorter. This observation is consistent with our above-mentioned observations, in which we noticed that for low CO_2 enrichment (2.0% and 3.4%), the SMD is higher than that of pure diesel anywhere along the axial distance, thus showing the negative effect of low CO_2 content. For high CO_2 content (above 5.1%), the effect is reversed.

3. For pure diesel, about 50% of the droplet volume at a distance of 10 cm is between 30 and 100 μm. At 20 cm, 65% of the droplet volume is within the same diameter range.

4. For the 5.1% CO_2 enrichment and above, the values are somewhat different than those for pure diesel. At 10 cm, more than 60% of the droplet volume is between 30 and 100 μm. As the CO_2 content increases the percentage increases, and even exceeds 70%.

Table 1 compares the corresponding SMD, $D_{0.1}$, and span factor at a distance of 18 cm. When the fuel is enriched by small amounts of CO_2 (2.0%), the SMD seems to increase from 31 to 37 μm. Figure 4 suggests that such an SMD increase is not the sole effect of the shorter distance and, thus, here again the negative effect of low CO_2 content is clear. As the CO_2 content increases above 3.4%, the axial distance at which the volume fraction peaks becomes shorter, the maximum volume fraction increases, $D_{0.1}$ decreases, and the span factor increases.

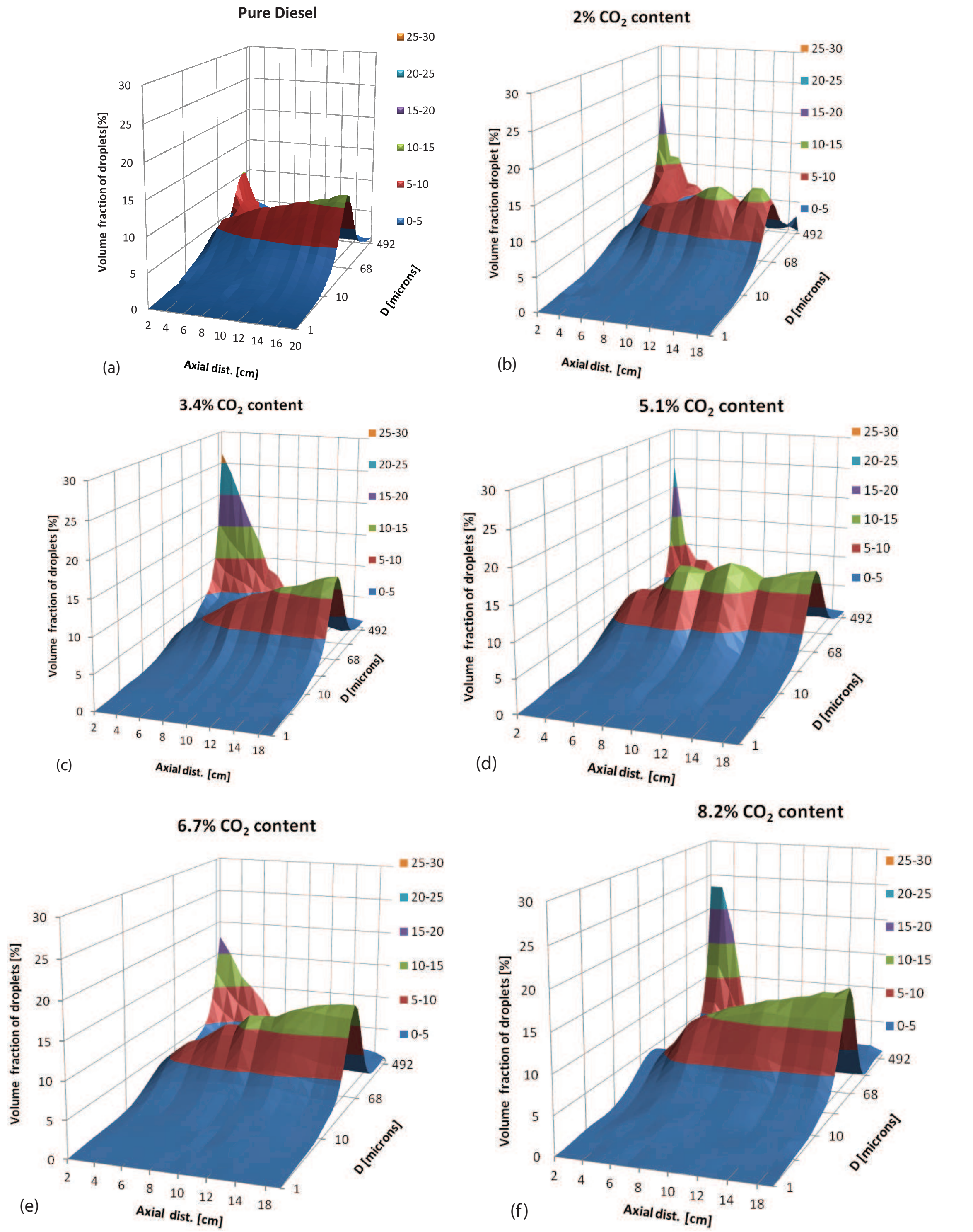

FIG. 6: Spray development for (a) pure diesel; (b) 2.0% CO_2 enrichment; (c) 3.4% CO_2 enrichment; (d) 5.1% CO_2 enrichment; (e) 6.7% CO_2 enrichment; and (f) 8.2% CO_2 enrichment.

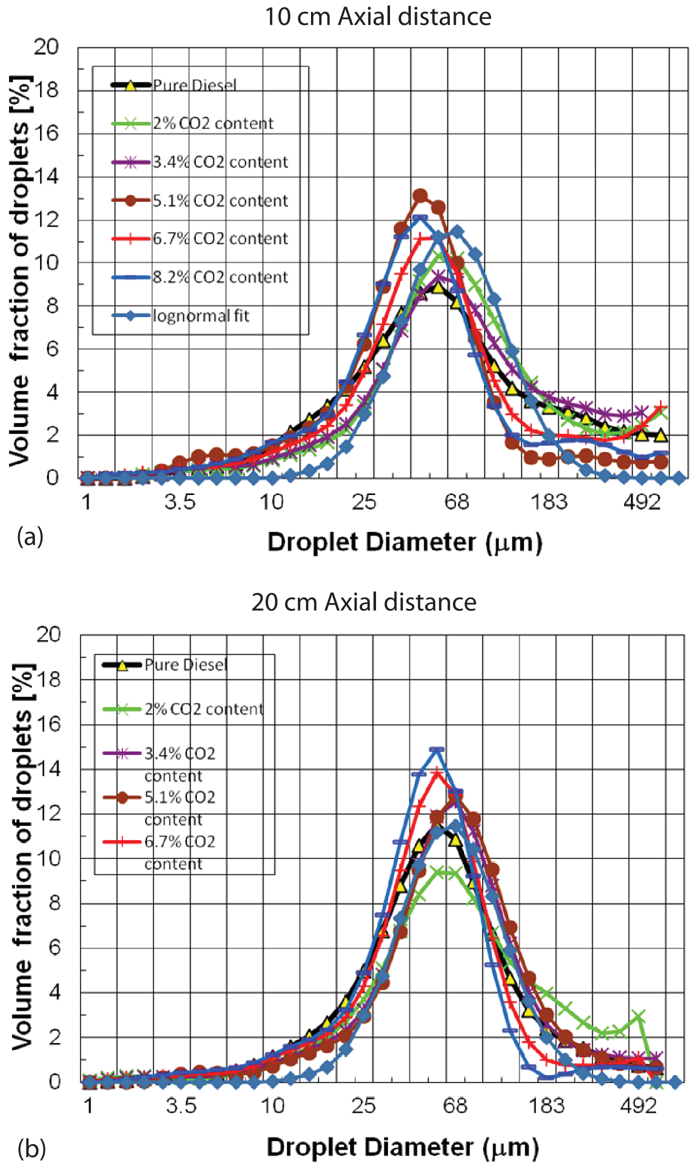

FIG. 7: Droplet size distribution and log-normal distribution for axial distances of (a) 10 cm and (b) 20 cm.

TABLE 1: Effect of CO_2 content on some major spray characteristics at a distance of 18 cm

CO_2 content (%)	Maximum volume fraction (%)	SMD (μm)	$D_{0.1}$ (μm)	Span factor
Pure diesel	11	31	15	3.9
2.0	11	37	21	4.2
3.4	13	37	20	4.2
5.1	14	25	12	8.7
6.7	14	29	15	6.3
8.2	15	25	14	5.7

4. 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. A commercial injector was tested. It was shown that the structure of the 3D histograms of enriched diesel with CO_2 are different from that of pure diesel and the breakup mechanism of droplets is faster, leading to a smaller, higher percentage peak (from 11% for pure diesel to 14% for CO_2 at 5.1% mass fraction), and a more uniform droplet distribution.

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 from 31 to 25 μm (about 20%), while the $D_{0.1}$ droplet diameter decreased from 15 to 12 μm (about 20%). The span factor showed an increasing/decreasing behavior from 3.9 to 8.7 and then, at 8.2%, to 5.5.

The span factor was increased at shorter axial distances, which means a less uniform spray droplet size distribution. However, we noticed [Fig. 5(c)] that for the same axial distance the span factor decreased, thus suggesting a better chance for diesel droplets to be ignited through the ignition process in the combustion phase.

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