LDV Measurement of Spray of Diesel Fuel Containing Dissolved Gas

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Exhaust gas recirculation within the spray (EGRWS) promises to develop into a new technique for controlling diesel combustion and exhaust emissions. The primary objective of this paper is to present a study of atomization behavior of a steady spray of diesel fuel containing dissolved gas (FCDG). The solubility of CO_2 and air in diesel fuel and $C_{14}H_{30}$ was measured respectively according to perfect gas equation of state and the feasibility of gas-blasting method for dissolving gas into fuel was verified. Using diesel fuel containing dissolved CO_2 gas, experiments were performed under atmospheric conditions on a diesel hole-type nozzle. The atomization process and spray characteristics were investigated by laser Doppler velocimetry (LDV). The effects of the injection pressure were examined. The results show that the injection of diesel fuel containing dissolved gas can greatly improve the atomization and produce a paraboloid-shaped spray. As compared with diesel fuel, CO_2-dissolved diesel fuel engenders larger radial velocity and more uniform velocity distribution. That is attributed to greatly enhanced liquid-gas mixing resulting from flash separation of gas phase from liquid.

1. Intruduction

In order to meet stringent emission standards, the reduction of NOx and soot from direct injection diesel engines has been a focus of research in recent years. One of the effective means for controlling NOx formation is exhaust gas recirculation (EGR). Researchers have observed 30 % to 75% reduction in NOx by using 5% to 25% EGR rates. Unfortunately, EGR also has some negative effects including increased engine wear and high soot emission, especially under high load due to the inherited trade-off between NOx and soot. Huang et al. proposed a new concept for reducing diesel exhaust emissions—— exhaust gas recirculation within the spray (EGRWS), by means of injecting diesel fuel containing exhaust gas[1]. Their research results show that the dissolved CO_2 within the spray will not only enhance fuel atomization and promote mixture formation but also exhibit substantial reduction of NOx levels. Meanwhile, smoke levels are lower than those of the base engine in the whole range of the test. The mixed fuel is expected to undergo flash boiling or gas separation when being injected into cylinder, which improves spray atomization and thus suppresses soot formation. NOx emission can be reduced due to internal EGR by the CO_2 gas. So EGRWS may possibly develop into a new technique for controlling diesel combustion and exhaust emissions. In this work, in order to examine the atomization characteristics of the mixed fuel and determine how the dissolved CO_2 affects the spray behaviour, the drop velocity distribution in the spray of CO_2-dissolved diesel fuel as well as diesel fuel was investigated by using LDV technique.

2. Experimental Technique and Apparatus

In preparing gas-dissolved fuel by gas-blasting method, the dissolved amount of gas in fuel was measured according to perfect gas equation of state. A schematic of the experimental system is shown in Fig1. For comparison, measurements were made with CO_2-diesel fuel system, CO_2-$C_{14}H_{30}$ system, air-diesel fuel system and air-$C_{14}H_{30}$ system.

In the spray measurement, the CO_2-dissolved diesel fuel in the pressure vessel was pressurized by high-pressure air and was injected into quiescent atmosphere at room temperature 23? under constant injection pressure, as shown in Fig.2. A hole-type diesel nozzle with single hole on its axis was used. The nozzle orifice diameter is 0.27 mm and the L/D ratio is 3.15. LDV technique was used to measure the drop velocity distribution. The measuring point grid is shown in Fig.3, where the origin of rectangular coordinate system is set to the center of the injection hole exit, here z- and x- axis indicate the axial and radial direction of spray respectively. So (x, z) expresses the measuring position. The LDV system is operated with a 40MHz-frequency shift and forward scattering mode is adopted with a 36° scattering angle. For comparison, the conventional spray of diesel fuel was also measured under the same experimental conditions.

3. Experimental Results and Discussions

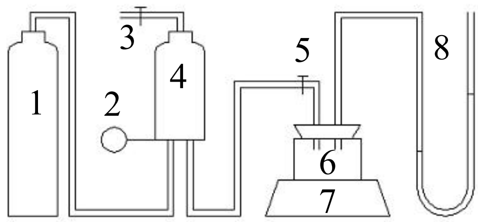


Figure 1 Schematic of measuring apparatus for dissolved amount of gas

1. Gas bottle 2. Pressure gage 3.Valve 4. Pressure vessel 5.Valve 6. Measuring vessel 7. Electronic balance 8. U-shaped tube

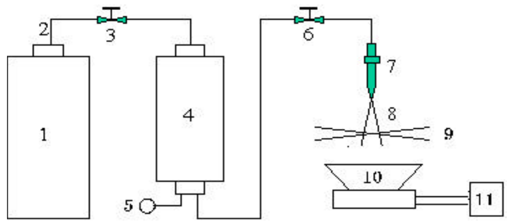


Figure 2 Schematic of spray measuring apparatus

1.Compressed air bottle 2. High pressure line 3.Valve 4. pressure vessel 5. Pressure gage 6. Valve 7. Diesel nozzle 8. Spray 9. Laserbeams 10. Spray collector 11. Ventilator

Fig.4 and Fig.5 compare the dissolved amount of CO_2 and air between in $C_{14}H_{30}$ and in diesel fuel respectively at room temperature 23? . It is found that the dissolved gas amount increases with dissolving pressure. CO_2 has a high dissolubility in diesel fuel, which is a prerequisite for injection of diesel fuel containing dissolved gas (IFCDG). For example, under 3 and 5 MPa dissolving pressures, the CO_2 dissolubility is 0.0937 and 0.2133g(gas)/g(diesel) separately. CO_2 dissolubility in diesel fuel is lower than in $C_{14}H_{30}$. Finally, air dissolubility in diesel fuel or $C_{14}H_{30}$ is below that of CO_2. Gas dissolubility in liquid depends on Van der Waals bond to a great extent.

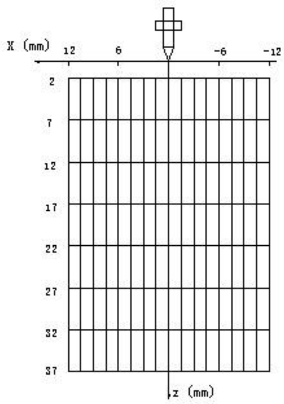


Figure 3 Measuring point grid

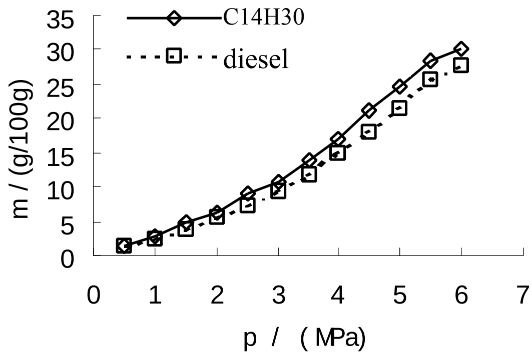


Figure 4 Comparison of dissolved amount of CO_2 between in $C_{14}H_{30}$ and in diesel fuel

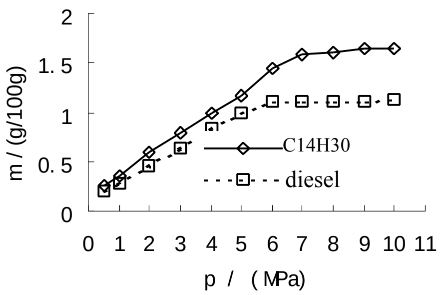


Figure 5 Comparison of dissolved amount of air between in $C_{14}H_{30}$ and in diesel fuel

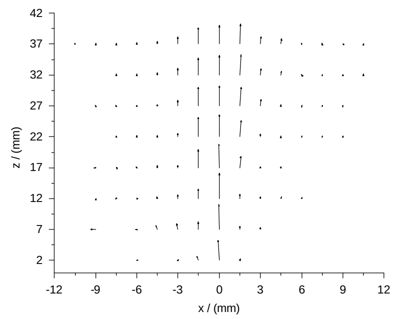


Figure 6 Vector diagram of CO_2-dissolved diesel spray under 4 MPa injection pressure

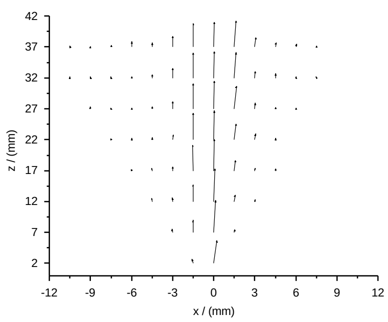


Figure 7 Vector diagram of CO_2-dissolved diesel spray under 6 MPa injection pressure

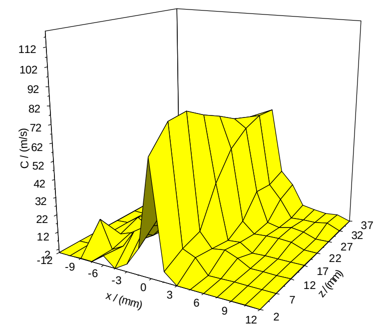


Figure 8 Mean velocity distribution in CO_2-dissolved diesel spray under 4 MPa injection pressure

Fig.6 and Fig.7 show the mean velocity vector diagrams of CO_2-dissolved diesel spray with

3 MPa dissolving pressure under 4 and 6 MPa injection pressure respectively. Fig.8 and Fig.9 illustrate the spatial distributions of the corresponding mean velocity C ($C = \sqrt{U^2 + V^2}$, where U and V are mean axial and radial velocity respectively). It can be seen that both flow fields appear non-axisymmetric. The jet of CO_2-dissolved fuel expands suddenly on the liquid coming out of the injection hole and produces a parabolic-shaped spray with a large spray angle. That indicates a good atomization right at the nozzle exit.

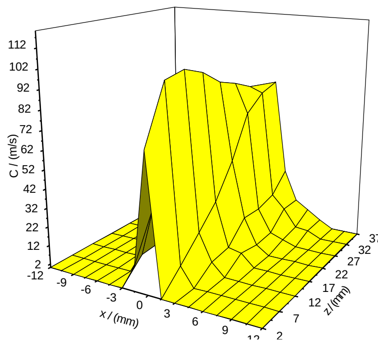


Figure 9 Mean velocity distribution in CO_2-dissolved diesel spray under 6 MPa injection pressure

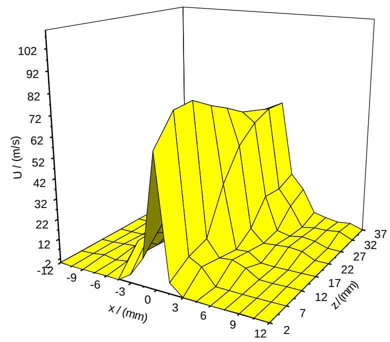


Figure 10 Mean axial velocity distribution in CO_2-dissolved diesel spray under 4 MPa injection pressure

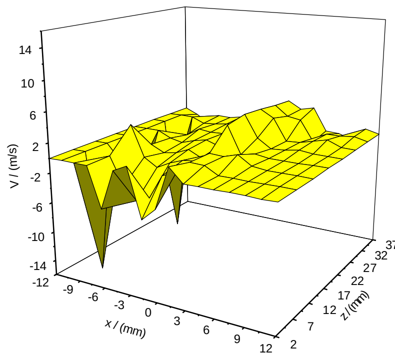


Figure 11 Mean radial velocity distribution in CO_2-dissolved diesel spray under 4 MPa injection pressure

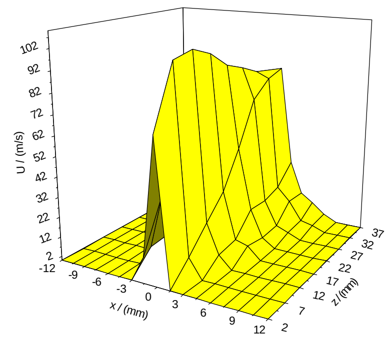


Figure 12 Mean axial velocity distribution in CO_2-dissolved diesel spray under 6 MPa injection pressure

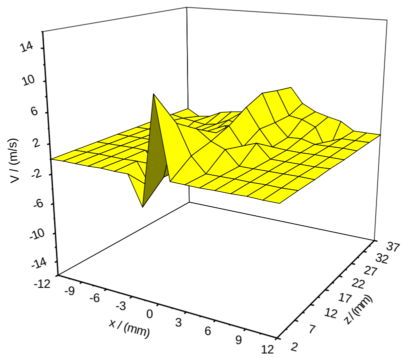


Figure 13 Mean radial velocity distribution in CO_2-dissolved diesel spray under 6 MPa injection pressure

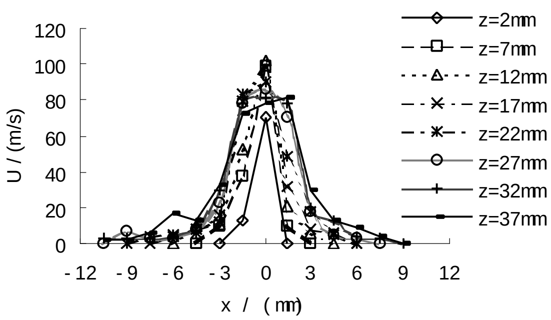


Figure 14 Radial distribution of mean axial velocity in CO_2-dissolved diesel spray under 6 MPa injection pressure

As shown in Fig.10, 11, 12, 13,14 and 15, the axial velocity of spray is far bigger than the radial velocity due to the leading of injection hole. Drop velocity in central zone increases evidently with injection pressure. The case in outer zone is not the same. So the higher the injection pressure is, the bigger the difference is in axial velocity between the dense spray core and outer atomized droplets. The distribution of radial velocity appears double peak

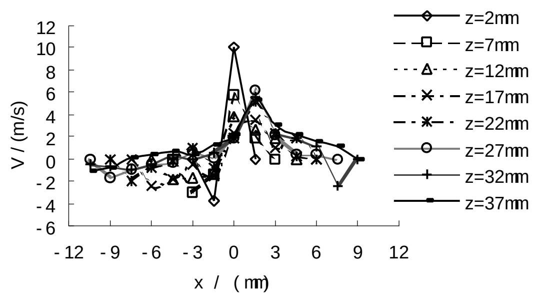


Figure 15 Radial distribution of mean radial velocity in CO_2-dissolved diesel spray under 6 MPa injection pressure

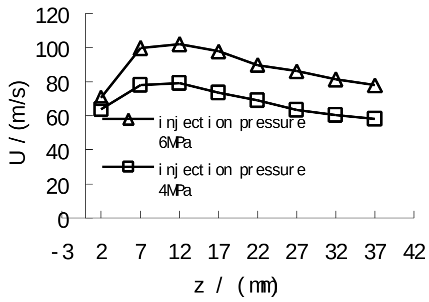


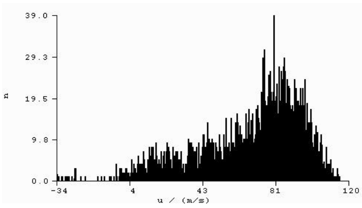
Figure16 Effect of injection pressure on mean-velocity variation along spray enterline

numerically. With the increase of axial distance, the peak point of radial velocity moves outwards and radial velocity tends towards zero.

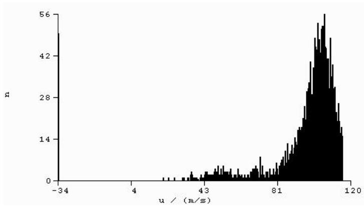
Fig.16 shows the variations of axial velocity along the nozzle centerline under 4 and 6 MPa injection pressure. As expected, the axial velocity rises with injection pressure. It is of interest to note that with increase in distance between the nozzle and measuring point, the mean axial velocity is first increased near the nozzle exit and is gradually decreased beyond a certain z value afterwards in both cases. The possible reason for relative low initial axial velocity and initial increase in axial velocity near the exit, is LDA measuring error caused by dense core of the spray near the exit. It has been well established that the examination of the microscopic characteristics of a dense diesel spray is difficult, especially within the inner core of the spray near the nozzle. LDV measurements do not prove to be the exception.

The probability distribution of on-axis FCDG velocity varies along spray centerline, as shown in Fig. 17 (in which, n expresses drop number). It is obvious that the velocity distribution near the nozzle exit is non-axisymmetric with a great number of low drop velocities, leading to low mean velocity. This coincides with Fig. 16. With the increase of axial distance, the probability histogram tends to an axisymmetric single peak pattern, which is ascribed to improved atomization.

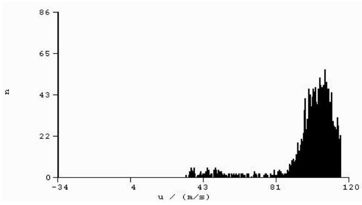
In the experiments, the spray patterns observed are indicated in Fig.18. As expected, the spray of diesel fuel containing dissolved CO_2 gas (FCDG) rapidly expands immediately upon the liquid leaving the orifice and forms a characteristic parabolic-shaped pattern of flash boiling injection. The atomization occurs almost right at the nozzle exit with large spray angle. This phenomenon arises from the impact of CO_2 gas on the jet, which causes big radial velocity and spray spread, as indicated in Fig. 19 and 20. In the case of diesel fuel, the spray forms a typical sharp cone-shaped pattern with a dense spray core surrounded by clouds of atomized droplets. The relatively uniform mean velocity of FCDG corresponds to well-dispersed spray. For the diesel fuel, the big difference between central velocity corresponding to the spray core and outer velocity related to the spray mantle is verified.



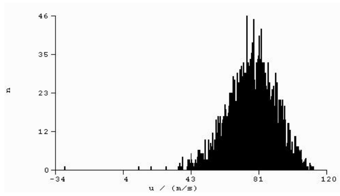
(a) Measure point (0,2)



(b) Measure point (0,7)

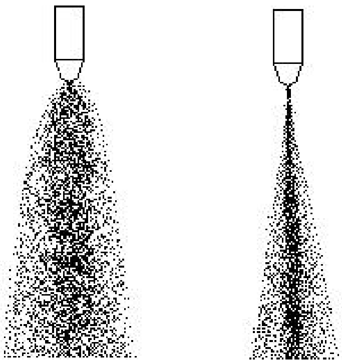


(c) Measure point (0,12)



(d) Measure point (0,37)

Figure17 Probability histograms of on-axis velocity under 6 MPa injection pressure



(a) FCDG spray (b) Diesel spray

Figure 18 Comparison of spray patterns between FCDG and diesel fuel

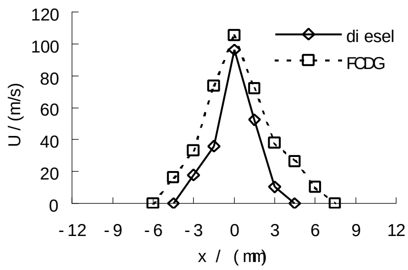


Figure19 Comparison of mean axial velocity between FCDG spray and diesel spray (z=7mm)

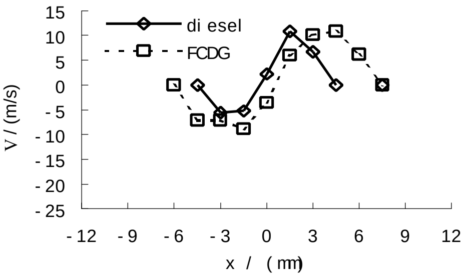


Figure20 Comparison of mean radial velocity between FCDG spray and diesel spray (z=7mm)

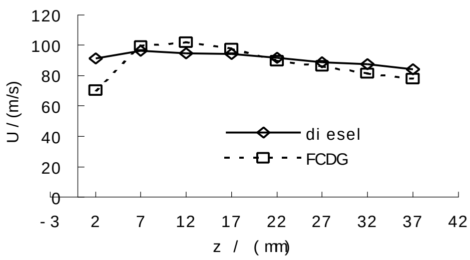


Figure 21 Comparison of mean-velocity variations along centerline between FCDG spray and diesel spray

Fig.21 compares the variations of axial velocity along the nozzle centerline between FCDG spray and diesel spray. It is indicated that the axial velocity of FCDG is slightly larger than that of diesel fuel in the initial part. This is due to the fact that the density of FCDG liquid is a little less than that of diesel fuel. Beyond a certain z value afterwards, the case is just the opposite, which signifies an intense decay of central momentum in FCDG spray resulting from greatly improved atomization by the impact of CO_2 gas. Moreover, this figure also shows an initial increase in axial velocity near the nozzle exit as Fig. 16.

4. Conclusions

1) CO_2 has a high dissolubility in diesel fuel, and the dissolved amount increases with dissolving pressure.
2) The jet of CO_2-dissolved diesel fuel expands suddenly on the liquid coming out of the injection hole and produces a paraboloid-shaped spray with a large spray angle. That indicates a good atomization right at the nozzle exit. In contrast, the conventional spray of diesel fuel takes a typical sharp cone-shaped pattern with poor atomization.
3) For CO_2-dissolved diesel fuel or diesel fuel spray, the measured on-centerline velocity first increases and then decreases with increase in distance between the nozzle and measuring point. The possible reason is the LDV measuring error caused by dense spray core.
4) The radial velocity of CO_2-dissolved diesel fuel is larger than that of diesel fuel. It is assumed that the rapid separation of gas from the mixed fuel adds extra radial momentum to drops. Both radial velocities tend to zero as axial distance increases. In addition, radial velocity assumes a double-peak distribution in radial direction.
5) CO_2-dissolved diesel fuel forms more uniform velocity distribution than diesel fuel. That is attributed to greatly enhanced atomization and liquid-gas mixing resulting from flash separation of gas phase from liquid.
6) Under the experimental conditions here, drop velocity in central zone increases evidently with the rise of injection pressure. The case in outer zone is not the same.
7) The investigation results will contribute to a better understanding of injection of CO_2-dissolved diesel fuel for application to diesel engine.

5. Acknowledgements

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6. References

[1] Huang Zhen. Zhang Shunyuan. Zhang Lianfang. *Evaluation of the Effect of Injection of Fuel Containing Dissolved Gas on Diesel Combustion and Emissions [J] .Journal of Combustion Science and Technology*,1996 ,vol.2 (No.4):p299-306