# A Study on Oxygenated Fuel Spray Structure Using Laser-based Visualization and Particle Image Velocimetry

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The Oxygenated fuels with higher boiling points such as dimethoxy methane (DMM), dimethyl carbonate (DMC), dimethyl ether (DME) are regarded as hopeful alternative fuels, and they are much different from diesel fuel on physical and chemical properties, which include fuel injection, spray, fuel-air mixture process, and combustion. This paper presents an experimental study on the spray structure of oxygenated fuel by laser-based 2D visualization and particle image velocimetry (PIV). The fuels are injected from a single-hole nozzle at an injection pressure of 40MPa into a room condition. A signal synchronization system is developed to obtain the spray at an arbitrary injection delay time. The spray structures of diesel fuel and DMM are visualized by 2D Mie scattering imaging. A direct cross-correlation DPIV technique is applied to analyze the instantaneous droplet velocity vector field. It is found that the spray of DMM shows an umbrella-shape structure. The spray angle of DMM is larger and the spray tip penetration of DMM is shorter than diesel fuel. Comparing the diesel fuel spray, the large-scale heterogeneity and the branch-like structure of the DMM spray are weak, the fuel droplet of the DMM spray is smaller, the interface between fuel spray and surrounding gas is stronger, and the vortical motion is more violent.

## 1 Introduction

In order to meet the increasingly strict emission regulations, the researchers allover the world are improving the performance of diesel engine at the utmost, which is influenced by the factors, such as in-cylinder airflow, fuel spray, fuel-air mixing and so on. The characteristics of fuel spray play a crucial role on the combustion and emission [1].

Recently, the oxygenated fuels with higher boiling points such as dimethoxy methane (DMM), dimethyl carbonate (DMC), dimethyl ether (DME) are regarded as hopeful alternative fuels, and they are much different from diesel fuel on physical and chemical properties, which include fuel injection, spray, fuel-air mixture process, and combustion

[2].

In practice, both PLIF and Mie scattering have been applied in 2D spray visualization [3]. Because Mie scattering is many orders of magnitude stronger than LIF, less sensitive detectors are sufficient to record the images of scattered light. Laser-based 2D spray imaging by Mie scattering was used to visualize the internal structure of diesel fuel spray by Azetsu et al [4], where the presence of large-scale 'branch-like structures' in the droplet distribution were found.

Particle Image Velocimetry (PIV) is an essentially non-intrusive velocity measuring technique derived from the application of laser speckle photography to a fluid flow [5]. Digital particle image velocimetry (DPIV) is recently developed for the real-time measuring of fluid flow velocity. Measurements of the diesel fuel spray using the PIV technique were reported by Ishikawa et al [6], Wu et al [7], Cao et al [8], and Ikeda et al [9]. But, the research on the spray structure of oxygenated fuel by PIV has seldom been reported.

This paper presents an experimental study on the spray structure of oxygenated fuel and diesel fuel by laser-based visualization and PIV. A signal synchronization system is developed to acquire the spray images at an arbitrary injection delay time. The spray structures of diesel fuel and DMM are visualized by 2D Mie scattering imaging. A direct cross-correlation DPIV technique is applied to analyze the instantaneous droplet velocity vector field.

## 2 Experimental Apparatus

The experimental apparatus includes fuel injection system, spray imaging system, and image interrogating system.

### 2.1 Fuel injection system

The fuel injection system comprised of fuel-pump test bench, injection control system, and pressure vessel (Fig. 1). Fuel streamed from the high-pressure rail was injected to a pressure vessel, where the temperature and pressure of air is room environment in this experiment. The spray of the primary nozzle was controlled by the injection controller, which shut up the assistant nozzle and simultaneous turn on the primary nozzle when the triggering signal arrived. The system can realize the fuel spray of primary nozzle single or time after time, and the pollution of fuel fog to the optics parts can be greatly decreased.

### 2.2 Fuel spray imaging system

The fuel spray imaging system comprised of lasers, transmitting optics system, CCD camera, and signal synchronization system. Two Double-pulsed Nd:YAG lasers were used to emit a frequency-double beam, with a wavelength of 532 nm, 200mJ energy per pulse and 7 ns pulse-width. Through transmitting optics system the beam was shaped into a fanlike laser sheet with a thickness 0.3 mm at the measuring field in the vessel.

The present experiment used a high-definition CCD camera, which has a total of 1008 ×1018 effective photodiode cell with a cell size of $3.4 \times 7 \mu m^2$. A Micro Nikkor lens (f = 105 mm) was used to accompany with the camera.

Fig. 2 shows the signal synchronization system developed in this paper. The timing sequence of triggering pulses is shown in Fig. 3. When the primary nozzle begins spray, the signal of needle lift is input into the delay circuit, which control the delay time of fuel spray. The synchronization processor synchronizes the signals of laser flash, imaging triggering, and laser shining triggering.

### 2.3 Image interrogating system

A direct cross-correlation interrogation method was used to analyses the fuel image as mentioned in references [10]. The interrogation window size is 36×36 pixels with an overlap 25%. In a measuring field of $100 \times 100 mm^2$, a total of about 1722 instantaneous

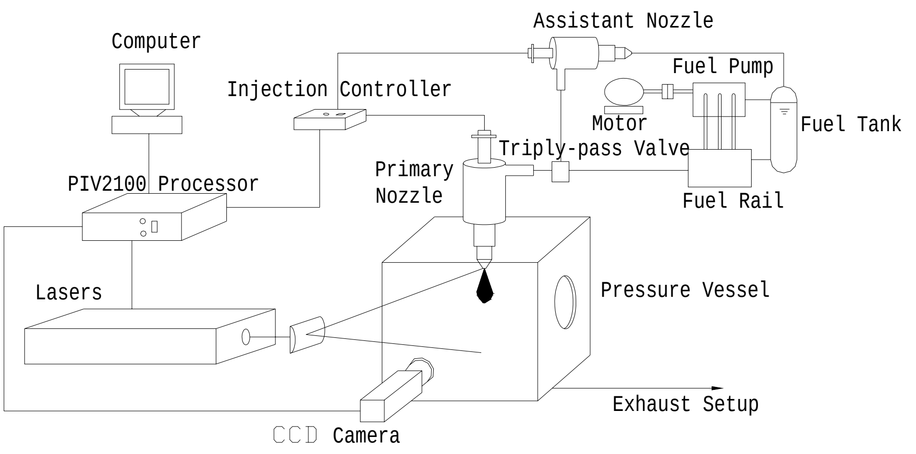



Fig. 1. Sketch of fuel injection system

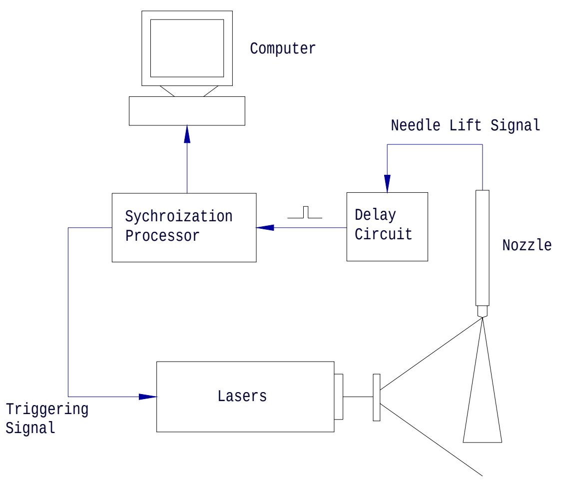



Fig. 2. Signal synchronization system

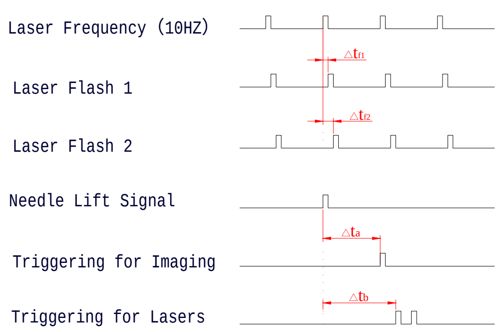



Fig. 3. Timing sequence of triggering pulses

velocity vectors are obtained with a spatial resolution of 3.5×3.5mm$^2$. It should be mentioned that the spatial resolution is subjected to the magnitude of the measuring field. So the measuring field must decrease for a high-resolution image. The threshold for the detection of valid correlation coefficient peak was set to 1.2, and the velocity vectors map corresponding PIV image was filtered by subtracting a uniform average velocity. The large-scale vorticity evaluating the velocity-derivative quantities, which is a fundamental characteristic of turbulence [11], also be presented as well as the streamline of the spray in this paper.

## 3 Result and discussion

Tab. 1 shows the experimental conditions. A single-frame double-image DPIV [12] was applied in this paper and double successive images was obtained in each measuring. Diesel fuel and DMM were used for injecting, and Tab. 2 shows the comparison of physical property between DMM and diesel fuel.

### 3.1 Visualization of structure of fuel spray

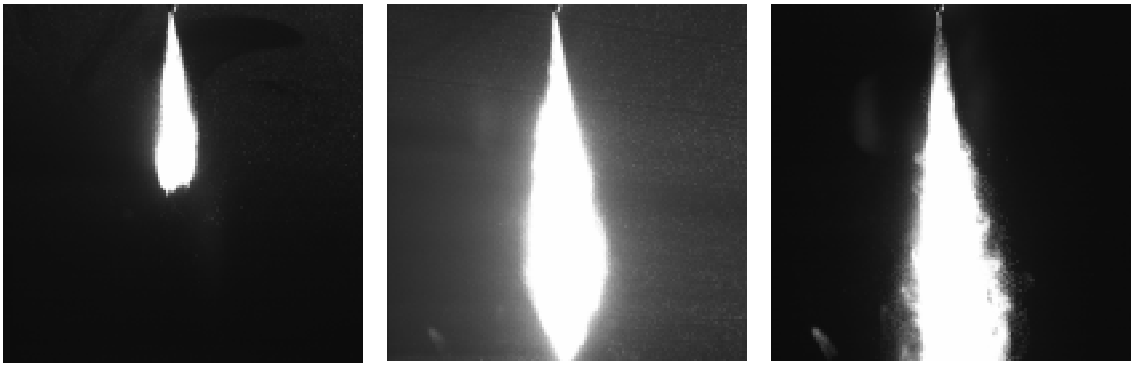
Fuel sprays at various stages were visualized in the viewing area of 100×100mm$^2$. Images were recorded in laser illumination duration of 8 ns, and it pictured the instantaneous shape of fuel spray.

Tab.1 Experimental conditions

| Injection system | Mechanical type injector |
|---|---|
| Nozzle | Single hole |
| Nozzle diameter | 0.37 mm |
| Needle lift | 0.35 mm |
| Spray duration | 4.0 ms |
| Injection pressure | 40 MPa |
| Nozzle open pressure | 20 MPa |
| Fuel | Diesel fuel and DMM |
| Ambient gas | Air |
| Ambient pressure | 1 atm |
| Ambient temperature | Room temperature |

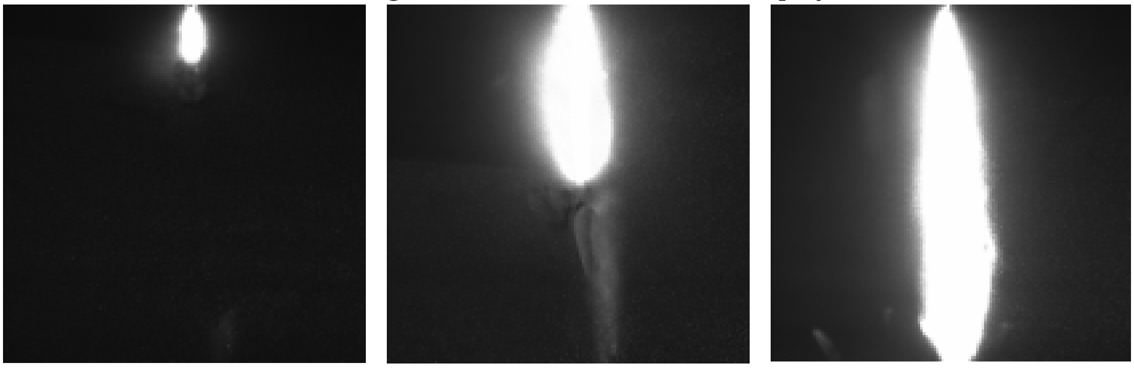
Tab.2 Comparison of physical property between DMM and diesel fuel

| Name | Diesel fuel | Dimethoxy Methane (DMM) |
|---|---|---|
| Molecular formula | / | $C_3H_8O_2$ |
| Molecular weight | >100 | 76.10 |
| Specific gravity (20℃) | 0.84 | 0.8593 |
| Boiling point (℃) | 180~388 | 42.3 |
| Melting point (℃) | / | -104.8 |
| Refractive index | / | 1.3534 |
| Auto-ignition point | 250 | 237 |
| Cetane number | 38~53 | 30 |
| Flash point (℃) | / | -18 |



(a)△t=0.12ms (b) △t= 0.5ms (c) △t=1.2ms

Fig. 4. Visualization of diesel fuel spray



(a)△t=0.12ms (b) △t= 0.5ms (c) △t=1.2ms

Fig. 5. Visualization of DMM spray

Fig. 4 shows the diesel fuel spray at different injection time defined as the time delay △t from the start of injection to the image recording in the viewing area of $100\times100mm^2$, and Fig.5 shows the DMM spray at the same conditions.

It can be seen that fuel droplet spread out around the spray. At the center of the spray, the droplet density is higher and the optical thickness is much greater. It is thus difficult to image droplet in this area even using a laser sheet, and the droplet in the periphery of the spray can be imaged clearly. The spray advancing speed decreases with the increasing of injection time especially in the latter of the spray.

In Fig. 5, it is interesting that the spray of DMM shows an umbrella-shape structure, which is different from the coniform structure observed in the typically diesel fuel spray (Fig. 4), and the spray angle of DMM is larger than that of diesel fuel. Because of the greater resistance of air, the spray-spread speed of DMM is lower than that of diesel fuel, and the spray tip penetration of DMM is also short than that of diesel fuel. The fuel droplet density and size of DMM is respectively smaller than diesel fuel. The fundamental mechanism of this phenomenon is not clear yet, but maybe it is one of the important factors that the boiling point of DMM is greatly lower than diesel fuel, and the further research should be outspread in the future.

### 3.2 Velocity field of fuel droplet

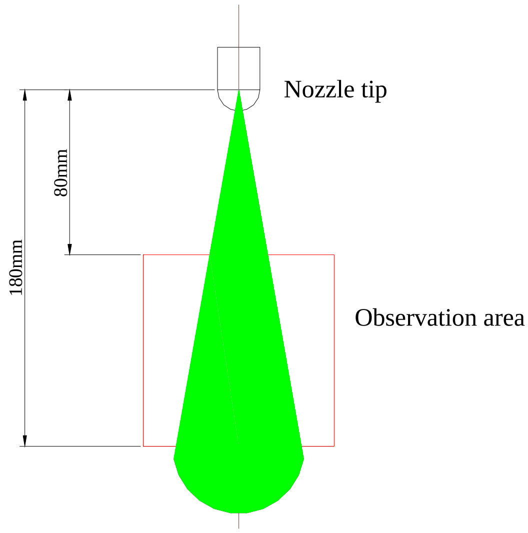



Fig.6. PIV observation area in the fuel spray

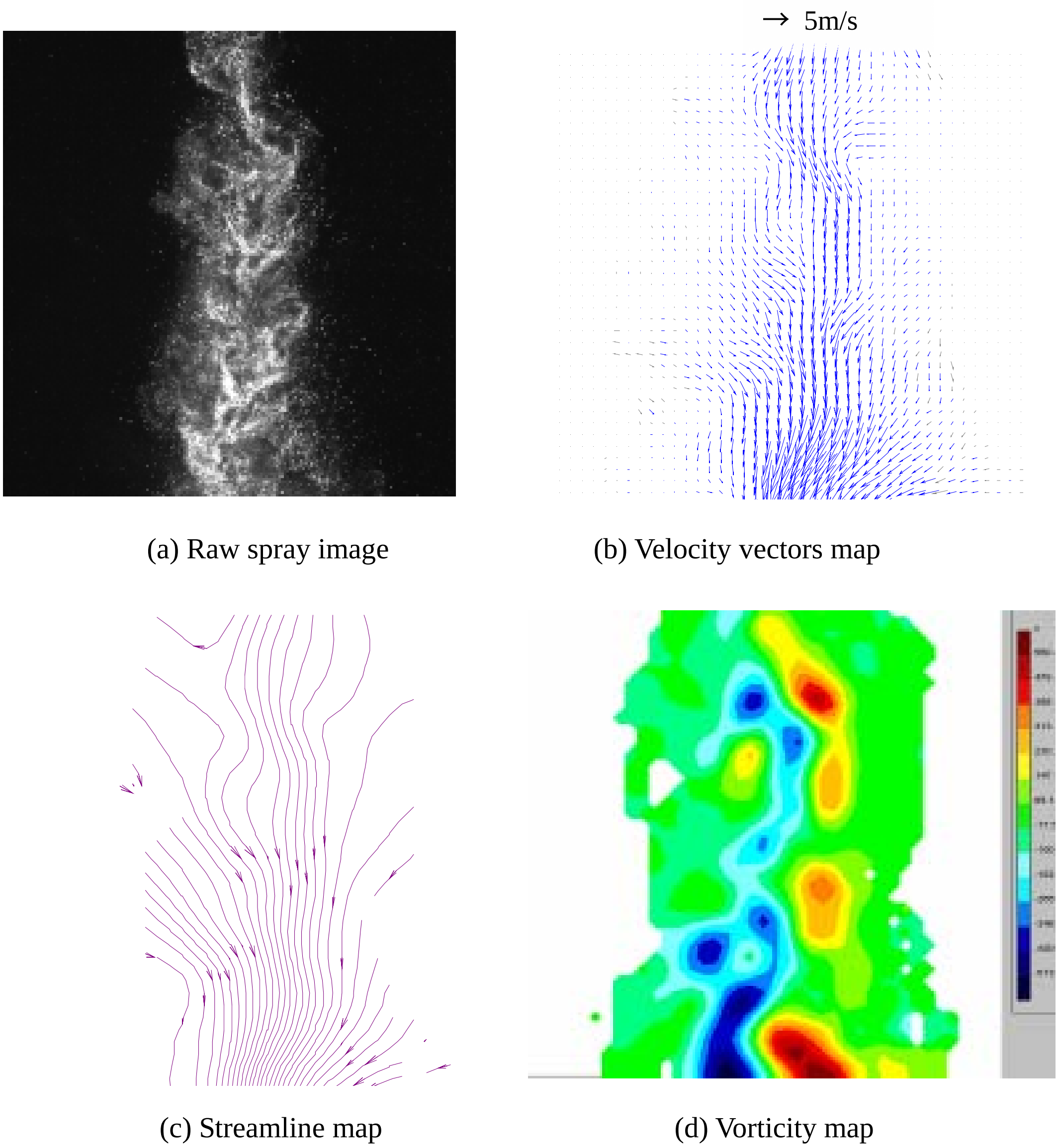
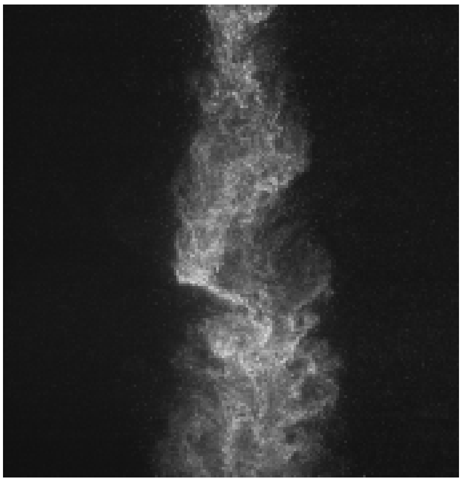
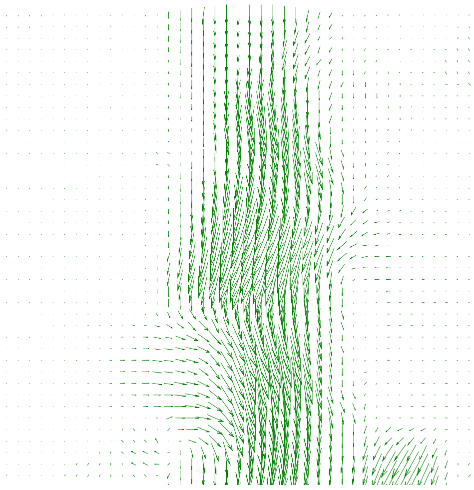
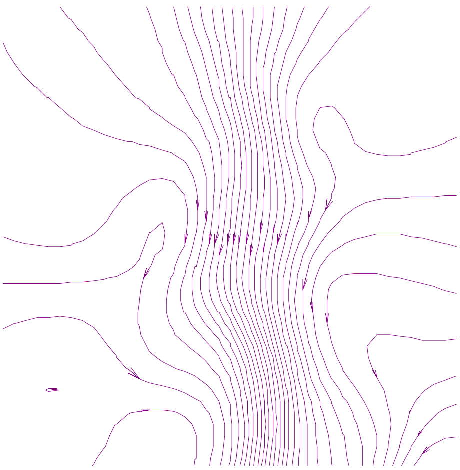


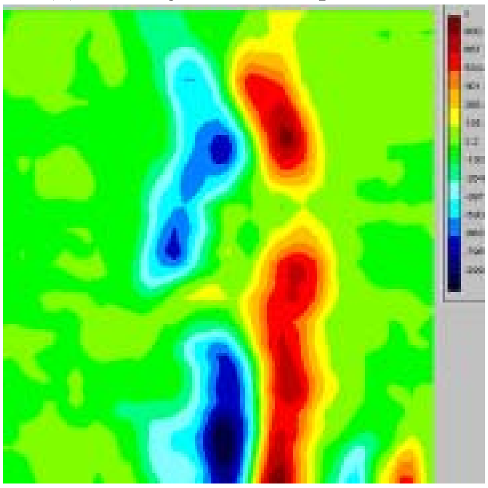

Fig. 7. PIV result obtained from diesel fuel spray images





(a) Raw spray image (b) Velocity vectors map





(c) Streamline map (d) Vorticity map

Fig. 8. PIV result obtained from DMM spray images

Fig.6 shows the observation area of the fuel spray image in this paper. Because of the high density of the fuel droplet in the former of the spray, in this research, the observation area chosen for PIV measuring was in the middle of the spray at the latter injection time, where the fuel droplet density was lower and actual droplet images could be confirmed.

Fig. 7 shows an example of a typical PIV result obtained from diesel fuel spray images at $\triangle t$ = 3.0 ms in the observation area of $100\times100mm^2$. Fig. 7a shows that the spray exhibits a large-scale heterogeneity in fuel droplet density, and the branch-like structure of the spray also is observed clearly as the references [4, 6, 8]. The heterogeneity and branch-like structure of the spray can affect significant the combustion and emission because of the uneven fuel-air mixing locally, and the reason of these phenomena is the interaction between fuel spray and surrounding gas. Fig. 7b shows that the droplet velocity in the periphery is lower than the droplet in the center, and the velocity of the droplet increases along the axial direction. Fig. 7c shows that the interface between the fuel spray and the surrounding gas is observed clearly. In Fig. 7d, it is shown that there are several vortical motion patterns, and the vorticity of the spray increases along the axial direction.

Fig. 8 shows a PIV result obtained from DMM spray images at △t = 2.0 ms in the same area. The large-scale heterogeneity and the branch-like structure of the spray can also be observed clearly, but they are weak than those of the diesel fuel spray because of the better atomization of DMM spray. The fuel droplet of the DMM spray is smaller, and the interface between fuel spray and surrounding gas is stronger. A bigger volume of surrounding gas is absorbed in the DMM spray than diesel fuel spray. The vortical motion is more violent, and the vorticity of the DMM spray is stronger than diesel fuel spray.

## 4 Conclusion

An experimental study on the spray structure of oxygenated fuel and diesel fuel is presented using laser-based 2D visualization and PIV technique. The spray structures of diesel fuel and DMM are visualized, and the instantaneous velocity field of the spray also is revealed. Some interesting features are summarized as follows:

(1) The spray of DMM shows an umbrella-shape structure, which is different from the coniform structure observed in the typically diesel fuel spray.
(2) Comparing the diesel fuel spray, the spray angle of DMM is larger and the spray tip penetration of DMM is shorter.
(3) Comparing the diesel fuel spray, the large-scale heterogeneity and the branch-like structure of the DMM spray are weak, the fuel droplet of the DMM spray is smaller, the interface between fuel spray and surrounding gas is stronger, and the vortical motion is more violent.

The results presented in this paper are useful in better understanding of the mechanism responsible for the fuel-air mixing in diesel engine fueled with oxygenated fuels.

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