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Comparison between background oriented Schlieren (BOS) technique and scattering method for the spray characteristics of evaporating oxygenated fuels

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A B S T R A C T

The purpose of this paper is to compare image measurement of the evaporating spray of oxygenated fuels such as DME and biodiesel spray by using the background oriented Schlieren (BOS) technique and scattering method. In this work, the macroscopic characteristics of oxygenated fuel sprays by using BOS technique were compared with the results of scattering method. In order to analyze the vapor phase images of fuel spray in the constant-volume chamber, the BOS technique is employed to visualize the evaporating fuel spray in a constant-volume chamber with high-pressure injection system. The fuel spray characteristics with evaporating phenomena were visualized to compare the spray macroscopic behaviors such as penetration length and the area of spray axial plane. The results showed that BOS technique is an effective method for the visualization and measurement of macroscopic characteristics of evaporating fuel spray compared to the results of scattering method.

1. Introduction

In the combustion system, the visualization and analysis of injection fuel spray are important to improve the combustion efficiency and clean emissions from the combustion systems such as automotive engine, fuel burning furnace, and various power generating systems. The fuel–air mixing and evaporating performance of liquid fuel sprays play an important role in the understanding of mixture formation. In this point of view, various researches for the spray measuring techniques such as flow visualization, Schlieren photography, Mie scattering method, laser induced exciplex fluorescence, and phase Doppler particle analyzer have been used as diagnostic methods for the mixture formation [1,2]. The spray measurement is very difficult to visualize the evaporating field for the liquefied gas by fast vaporization in the combustion chamber. But backward oriented Schlieren technique proposed by Meier [3,4] can measure the density variation and image displacements in a flow field based on simple Schlieren method. The BOS technique were demonstrated by experimental investigations into the compressible flow field for the blade vortex phenomenon by Refs. [5–7]. In the actual measurement of injection spray, the scattering or shadowgraph is applied to visualization of injection flow and diesel spray. In the case of oxygenated fuel sprays such as dimethyl ether (DME) and biodiesel (BD), it is difficult to visualize the vaporizing sprays using the shadowgraph and scattering technique. In particular, DME spray is different from a spray macroscopic evolution in term of evaporation characteristics of diesel fuel. Idicheria and Pickett [8] report that the results of various diagnostics for the details of diesel spray combustion in an optically accessible chamber by using the high-speed shadowgraph and Schlieren method. Wu et al. [9] investigated the spray structure of oxygenated fuels using laser-based visualization and particle image velocimetry. But these methods for spray visualization are necessary to have the combined optical setup and various laser sources. Also, high-speed image of diesel injection spray includes the combined flows of fine droplets and vaporizing fuels. In the case of spray measurement, it is difficult to capture the flow behavior of vapor phase of the fuel spray.

In this point of view, we investigated for the measurement of spray characteristics of oxygenated DME and biodiesel fuels with evaporating phenomena by using the backward oriented Schlieren (BOS) technique. Also, this work presented the comparison of macroscopic spray characteristics of oxygenated fuels between the BOS technique and the scattering method. Moreover, the results from the experiments showed the distinctive character of BOS method for the visualization of evaporating fuel spray behavior in the density field.

2. Image measurement of evaporating DME spray by BOS technique

The principle of BOS technique is to apply the refractive index according to density gradients in the measuring field. In this investigation, the relation between the density gradient of flow

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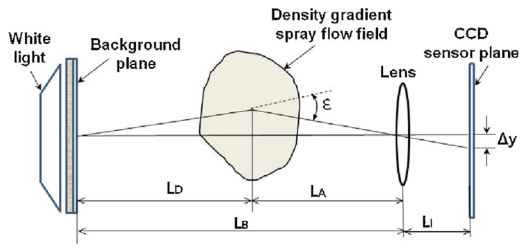


Fig. 1. Optical setup for BOS technique.

field and the refractive index is given by the Gladstone–Dale relation [10,11]

$$\frac{n-1}{\rho} = G(\lambda) \quad (1)$$

where n is the index of refraction, ρ is the density of test field and $G(\lambda)$ is the Gladstone–Dale constant. The constant G depends on the characteristics of the ambient gas and the wavelength λ. The schematic of optical arrangement and BOS diagnostic system for density gradient measurement are illustrated in Fig. 1. From the basic schematic, the governing optical equation is given by [3,6]

$$\Delta y = L_D m \varepsilon \quad (2)$$

In this equation, m is the magnification factor ($m = L_I/L_B$) of background and L_D is the distance from dot pattern to density gradient. In Fig. 1, the deflection of the beams results in displacement of the speckle pattern with respect to reference patterns. The measurement of the spatial gas density distribution in the spray chamber is achieved through the detection of deflection angle of light beams passing through the chamber to be visualized. The focal length of the lens f can be determined as

$$\frac{1}{f} = \frac{1}{L_I} + \frac{1}{L_B} \quad (3)$$

In this work, spray characteristics of DME and biodiesel blended DME fuels are visualized by BOS and scattering technique.

Fig. 2 shows the schematic of BOS system for the visualization of fuel sprays and fuel injection system. For optical measurements of the spray, the BOS system consists of a wavelet noise generated background pattern, metal halide lamp (HVS-SL, Photron), optical lenses, high-speed camera (FASTCAM APX-RS, Photron), and a digital delay/pulse generator. The fuel spray images are obtained from high-speed camera. The synchronization between the spray injector and the high-speed camera was performed by a delay/pulse generator. The captured images were stored in a data acquisition system with image grabber. In order to visualize the spray behavior under the various ambient pressures, a high pressure spray chamber that could pressurize to 4 MPa of maximum pressure was applied. The chamber pressure was controlled by using a high pressure nitrogen gas. The test injector used to visualize the spray behavior and images was an electronic controlled a

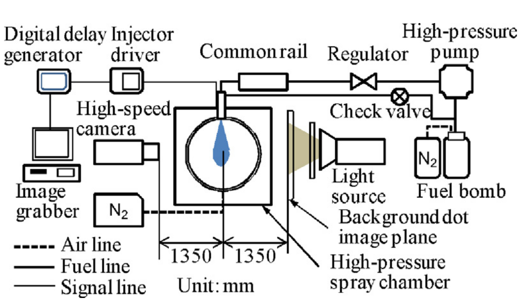
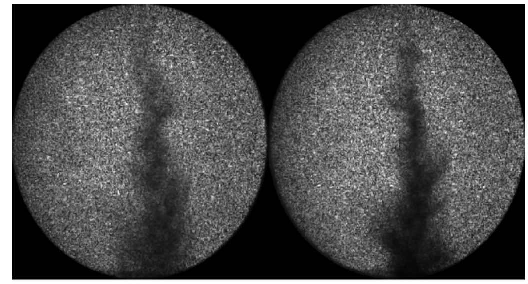


Fig. 2. Schematic diagram of BOS system for fuel spray visualization.



(a) DME spray (b) Biodiesel spray

Fig. 3. BOS images for DME and biodiesel spray after the images processing at 4.0 ms (fuel injection pressure P_{inj} = 41 MPa and ambient density ρ_{amb} = 11.11 kg/m^3). (a) DME spray and (b) Biodiesel spray.

single-hole injector with hole diameter of 0.3 mm. Spray visualization was conducted in a constant volume high-pressure chamber of 250 mm × 250 mm × 250 mm and optical window with 100 mm diameter and 40 mm thickness. Optical window was installed the both side of spray chamber to capture the spray images.

The experiments for the visualization of oxygenated fuels such as biodiesel, biodiesel blended DME, and DME fuel were conducted at 1.0 ms of energizing duration and constant ambient temperature of 303 K. Fig. 3 shows the BOS images for DME and biodiesel spray at 4.0 ms of time after start of injection.

In these two images, the case (a) is the DME spray image which is composed of fuel vapor and small amount liquid droplets. On the other hand, the case (b) is the liquid spray and small amount of biodiesel vapor. In this figure, the energizing time is 1 ms and fuel injection duration is 4 ms. Comparing the fuel properties of DME and biodiesel fuel, two fuels are different because DME is a fuel which is basically in the gas phase at atmospheric condition and biodiesel is a liquid fuel. Therefore, in order to inject liquid fuel into the spray chamber, the fuel system from injection nozzle must be pressurized. The most of DME spray is evaporating during the 4 ms after the injection while biodiesel is not fully evaporating for the same time duration. In the case of biodiesel fuel, the evaporation time of the spray droplets is longer than that of DME fuel due to higher viscosity. The visualization results of BOS technique were compared with the results of scattering method as following Figs. 4–7.

3. Results and discussion

Figs. 4 and 5 show the comparison of spray tip penetration for oxygenated fuels such as DME, DME blended biodiesel, and biodiesel fuel due to the BOS and scattering method at 41 MPa

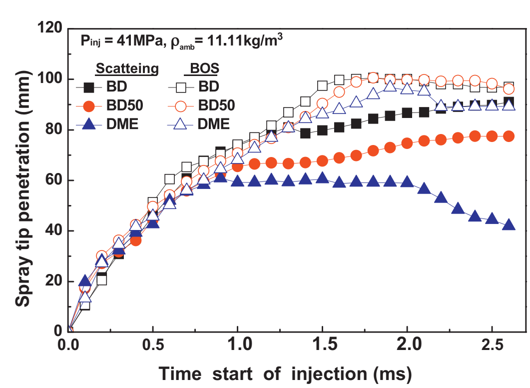


Fig. 4. Comparison of spray tip penetration between BOS and scattering method.