

Article

Visualization of Injected Fuel Vaporization Using Background-Oriented Schlieren Method

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Abstract: In this experimental study, ethanol, an eco-friendly fuel used to reduce harmful exhaust emissions from internal combustion engines, was blended with gasoline. To optimize the combustion and the shape of the combustion chamber, the spray development and spray behavior of ethanol and gasoline were visualized and compared. Droplets of injected fuel were visualized using a high-speed camera. Because it is difficult to experimentally observe fuel vaporization using only high-speed cameras, the vaporization characteristics of the spray were compared and analyzed by using the background-oriented schlieren (BOS) method with density variation and image displacement in the spray flow field to visualize the vaporized fuel. The experimental results indicate that the fuel vaporization phenomenon could be observed during the spray development and that more fuel vaporization occurred at higher ambient temperatures and lower ambient pressures. Additionally, the dependence of the differences in the vaporization characteristics of the fuel and the wall-wetting phenomenon caused by the vaporized fuel was analyzed.

Keywords: fuel spray characteristics; spray visualization; background-oriented schlieren (BOS); wall wetting; ethanol–gasoline blended fuel



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1. Introduction

Methods of reducing exhaust emissions from internal combustion engines are being investigated by numerous groups. Concerns over environmental pollution and limited petroleum resources have resulted in tightened regulations on exhaust emissions and fuel economy and the active development of engines that use various power sources, such as electric hybrids and hydrogen fuel cells. Moreover, the development of vehicles utilizing alternative fuels, such as biodiesel and bioethanol, to reduce the dependence on petroleum is ongoing. In particular, the amount of research on using ethanol as an alternative fuel to reduce exhaust emissions is gradually increasing. Using ethanol can reduce exhaust emissions because of its simpler chemical structure compared with that of gasoline or diesel [1]. Ethanol has the advantage of including oxygen atoms in the fuel, which facilitates engine combustion. When ethanol is mixed with gasoline for combustion, a higher ethanol mixture ratio tends to decrease the amounts of hydrocarbons and CO produced. Because of its high latent heat of vaporization, ethanol has a higher charge efficiency compared with that of gasoline [2,3]. These considerations have driven the development of engines that use a mixture of ethanol and gasoline. The United States has more than seven million flexible-fuel vehicles (FFVs) on its roads [4]. Fuels with a 10% ethanol mixture (E10) are commonly used, and fuels with 85% denatured ethanol

(E85) can also be used [5]. In Brazil, the annual production of ethanol exceeds 6.5 billion gallons [6] and most of the cars sold are FFVs [7]. In Brazil and Europe, the production of FFVs is increasing and infrastructure has been established to allow drivers to adjust the ethanol–gasoline mixture ratio based on their driving patterns.

Residual fuel in fuel tanks can change the fuel rate and other characteristics, leading to variations in the combustion characteristics. To overcome these disadvantages, it is necessary to develop engines that can detect the ethanol fuel components and optimize the combustion process according to the mixture ratio. To optimize the combustion in target engines utilizing gasoline direct-injection (GDI) systems, it is necessary to evaluate the fuel spray.

FFV engines are following the global automobile industry trend of using smaller turbocharged engines to improve fuel efficiency. The aim of engine downsizing is to maintain engine performance while reducing exhaust emissions. Turbocharging and direct-injection systems are the most common techniques employed in engine downsizing. Direct-injection systems, which inject fuel directly into the combustion chamber, require more precision than port injection methods. Research on injection characteristics is essential in engine development in order to improve their combustion characteristics and to reduce exhaust emissions. Even with environmentally friendly fuels, excessively long fuel spray penetration can result in wall wetting in the combustion chamber, which adversely affects combustion and impacts the output and exhaust emissions. To prevent these problems, extensive research has been conducted on spray visualization to measure spray patterns and behaviors. However, it is difficult to visualize fuel vaporization using the common Mie scattering spray visualization technique at high ambient temperatures or in similar conditions. Therefore, considerable research has been conducted on the use of schlieren techniques and lasers to visualize vaporization phenomena [8,9].

Payri et al. studied diesel spray characteristics using Mie scattering, double-pass schlieren imaging, and CH radical chemiluminescence [10]. These measurement techniques were used to analyze the liquid and vapor phases of diesel sprays and to study the impact of the injector nozzle's shape on combustion.

Montanaro et al. conducted a comprehensive characterization of fuel spray behavior to increase the thermal efficiency of gasoline engines [11]. The spray studies were conducted using a hybrid Mie scattering and schlieren optical technique. The spraying experiments were carried out with isooctane using a GDI injector, during which the liquid and vapor phases were separated and the diffusion and evaporation parameters that characterize the fuel spray were extracted.

Laser measurement equipment and the schlieren method are commonly used to distinguish between the vapor and liquid phases of sprayed fuel. However, schlieren studies can be costly because of the experimental equipment required. To overcome this problem, research has been conducted on replacing the traditional laser-based schlieren method for analyzing the liquid and vapor phases of the spray.

Lazzaro conducted a study on spray characteristics using a multi-hole GDI injector with isooctane [12]. The spray characteristics were distinguished using schlieren, shadowgraph, diffuse back-illumination (DBI), and Mie scattering methods. The results proved that the shadowgraph image can be used by itself to clearly distinguish between the liquid and vapor phases of the spray.

Bang et al. studied the spray characteristics of dimethyl ether (DME), DME blends, biodiesel, and diesel using the background-oriented schlieren (BOS) method [13]. By using the BOS method, the liquid and vapor phases of the spray were observed, and the variation in the spray's depth and area with the DME mixing fraction was studied.

As demonstrated in these earlier studies, using the schlieren method to visualize the liquid and vapor phases of a spray requires the use of complex optical devices and laser sources. In contrast, the BOS method [14,15] can be used to observe the flow of vaporized fuel easily [16]. In this study, we investigated the spray characteristics to optimize the spray in direct-injection FFV engines. By using the BOS method to visualize the spray, we

experimentally analyzed the spray characteristics based on the fuel mixing ratio of the ethanol–gasoline mixture.

2. Experimental Setup and Procedures

The spray images of E0, E50, and E100 blended fuels comprising ethanol and gasoline at different volume ratios were analyzed. The physical and chemical properties of these fuels are listed in Table 1. The test injector was a gasoline direct-injecting injector with six different-sized holes and a maximum injection rate capacity of 250 mg/min. The injector was controlled using an injector driver (CompactRIO, National Instruments, Austin, TX, USA) and a LabVIEW (2020 SP1) program. The experimental conditions were based on the SAE J2715 Standard Test Conditions [17].

Table 1. Characteristics of gasoline and ethanol.

Property	Gasoline	Ethanol
Chemical formula	C_4-C_{12}	C_2H_5OH
Molecular weight (kg/kmol)	114.15	46.07
Oxygen (wt%)	0	35
Octane number	86–94	98–100
Density at 20 °C (kg/m ³)	732	792
Latent heat of vaporization (kJ/kg)	289	854
Autoignition temperature (°C)	257	423
Lower heating value (MJ/kg)	43.47	26.87
Air–fuel ratio	14.7	9

A schematic of the Mie scattering experimental setup for measuring the liquid spray pattern of the blended fuels is shown in Figure 1. To obtain a Mie scattering image, spray images were acquired using a metal halide lamp (MID-25FC, Lighterrace, Osaka, Japan) as the light source and a high-speed camera (V7.0, Phantom). The injector and high-speed camera were synchronized to capture the high-speed spraying behavior during injection. A constant-volume chamber with the dimensions of $300 \times 300 \times 300 \text{ mm}^3$ was used for the comparative analysis of the spray shape according to the blending ratio. The spray penetration, spray angle, and spray area were analyzed using MATLAB (R2022b). During the analysis, each captured image was converted into a black-and-white grayscale image. To reduce the errors between images, the threshold values for the spray images were matched by fixing their threshold values.

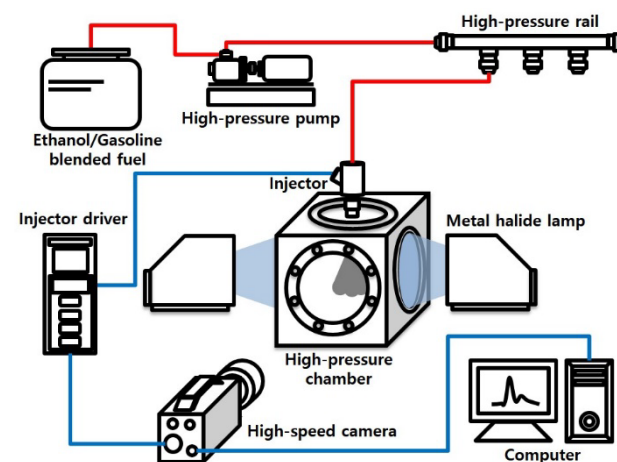


Figure 1. A schematic of the Mie scattering experimental setup.

To quantify the spray characteristics, the spray penetration was defined as the distance from the injector tip to the spray tip; the spray cross-section area as the pixel area in the acquired image; and the spray angle as the angle between the spray cross-section area and

the half-point of spray penetration, as shown in Figure 2. The calculations were performed by comparing the ratio of the actual image to the spray image. The spray's start time was defined as the time in the image at which the spray was first observed. The collision phenomenon between the spray and piston was observed.

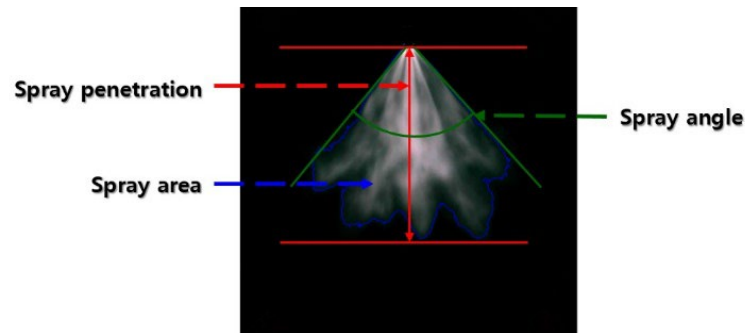


Figure 2. The definition of the spray penetration, spray angle, and spray area.

To observe the vaporization of the fuel in different ambient conditions, the temperature in the chamber was varied. Because fuel evaporation is expected to accelerate at higher temperatures, the temperature of the chamber was raised to 120 °C to determine the differences in evaporation. The chamber was heated to increase its temperature and the differences in vaporization at different ambient temperatures were compared by injecting fuel under the same conditions but at the atmospheric temperature of 20 °C. In addition, the injector was positioned at 90° from the piston to observe the effect of fuel collision with the piston directly on the cylinder's wall. By applying these experimental conditions, images can be obtained using the Mie scattering and BOS methods to predict wall wetting by the vaporized fuel.

Figure 3 shows a schematic of the BOS method for capturing images of the evaporative spray shape. The BOS method exploits the dependence of the refractive index on the density gradient of the measurement field in the Gladstone–Dale equation, relating the refractive index to the gas density [18,19]:

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

where n is the index of refraction, ρ is the density of the test field, and $G(\lambda)$ is the Gladstone–Dale constant.

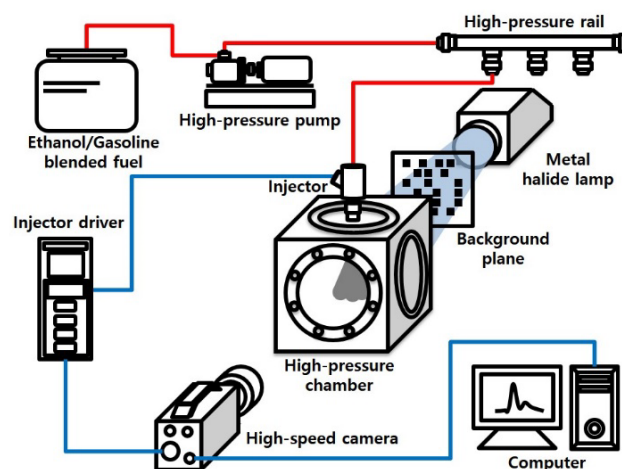


Figure 3. A schematic of the BOS experimental setup.

In the BOS method, the schlieren speckle pattern is replaced with a background pattern. This pattern should have a high spatial frequency and contrast and should consist mostly of randomly distributed dots. The pattern image is first measured in the absence of flow, before the start of the experiment, and the displaced image of the background pattern by the spray flow in the test field is subsequently measured. The two images are then analyzed using the correlation method.

The image displacement Δy in Figure 4 is defined in Sharma and Doric's theory as follows [20,21]:

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

where $m = Z_i / Z_B$ is the magnification of the background, and Z_D is the distance.

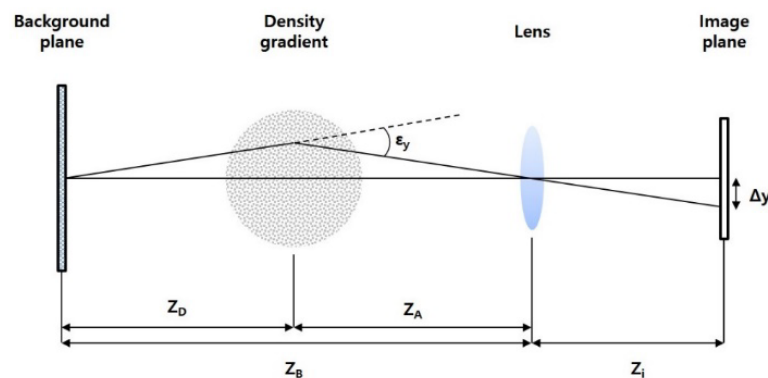


Figure 4. A schematic of the BOS method optical setup.

This can be rewritten as

$$\Delta y = f \left(\frac{Z_D}{Z_D + Z_A - f} \right) \varepsilon_y \quad (3)$$

where Z_A is the distance from the lens to the object and f is the focal length of the lens.

The deflection of the beam results in the displacement of the speckle pattern. The focal length of the lens f is defined as

$$\frac{1}{f} = \frac{1}{Z_i} + \frac{1}{Z_B} \quad (4)$$

A larger Z_D and smaller Z_A yield a larger image displacement.

For postprocessing, the background must be focused on as shown in Figure 5 to obtain the maximum contrast at high spatial frequencies. The focal length for a clear image is defined as

$$\frac{1}{f} = \frac{1}{Z'_i} + \frac{1}{Z_A} \quad (5)$$

The blur degree d_i in Z_A can be obtained by substituting the values of the lens diameter d_A and the magnification of the density gradient image $M' = \frac{Z'_i}{Z_A}$ [22].

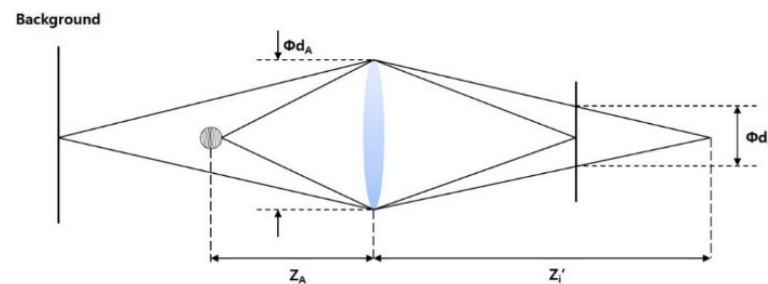


Figure 5. The focusing position and image blur in the BOS method.

For accurate comparative analysis with the Mie scattering results, the BOS images were captured by fixing the positions of the experimental apparatus, moving the light source to the opposite side of the camera, and placing the background plane between the test field and the light source. The experimental conditions and definitions of the spray penetration and spray angle were the same as those used for Mie scattering. The use of the same experimental conditions and image ratios allowed for an accurate comparison and analysis of the Mie and BOS imaging results. Tables 2 and 3 show the specifications of the visualization experimental apparatus and the experimental conditions.

Table 2. The specifications of the experimental setup.

Test Apparatus	Specification	
High-speed camera	Frame rate (fps)	10,000
	Shutter speed (s)	1/10,000
	Resolution	464 × 456
	Spatial resolution (μm/pixel)	254.11
Light source	Light source	Metal halide lamp
	Power (W)	250
	Cooling method	Air cooling
Injector	Injector type	Gasoline direct injection
	Number of holes	6
	Injection flow rate (g/min)	250

Table 3. Experimental conditions.

Test Item	Condition	
Test fuels	E0	Ethanol 0% + Gasoline 100%
	E50	Ethanol 50% + Gasoline 50%
	E100	Ethanol 100% + Gasoline 0%
Spray visualization experiment	Injection pressure (bar)	250
	Energizing duration (ms)	1.5
	Ambient pressure (bar)	1, 5, 10
	Ambient temperature (°C)	20, 120

3. Visualization Results

3.1. Comparison of Spray Behavior Obtained via Mie Scattering

Figure 6 shows the spray images of the blended fuel obtained via Mie scattering and Figure 7 shows the results for the spray penetration and spray angle of the blended fuel, which were obtained after the spray images were analyzed using MATLAB (R2022b). The differences in the spray shape at different ethanol–gasoline blended fuel injection temperatures are shown in Figure 6. As the ambient temperature increased, the edge of the spray shape became blurred and the spray angle tended to decrease. As shown in Figure 7, the initial spray behavior exhibited long spray penetration for the E100 fuel, which has a high density. However, it was visually observed that the spray penetration for the E0 fuel became longer than that for E100 after approximately 0.5–0.8 ms. One reason for this is the effect of aerodynamic drag forces [23,24], which reduced the spray rate of fuel particles with large diameters. Another reason is the difference between the gasification rates of gasoline and ethanol, which resulted in the vaporization of E100 fuel as the spraying progressed. To confirm this, a BOS experiment was performed to measure the vapor.

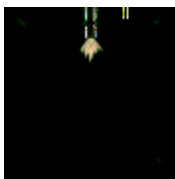
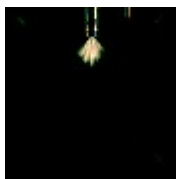
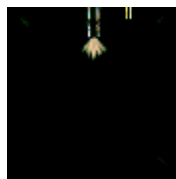
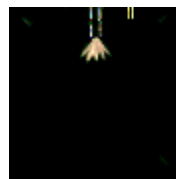
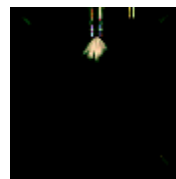
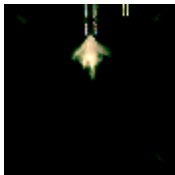
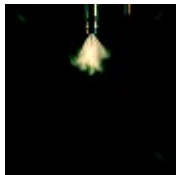
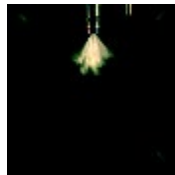
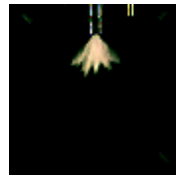
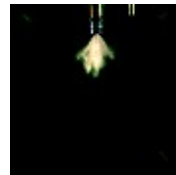
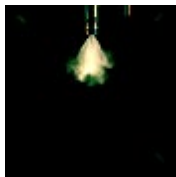
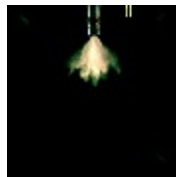
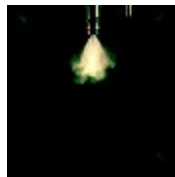
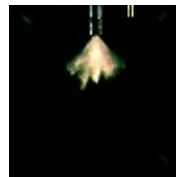
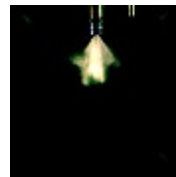
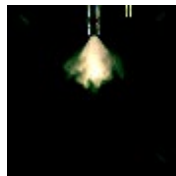
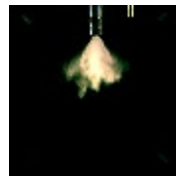
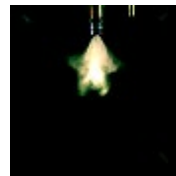
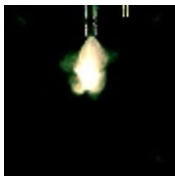
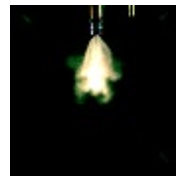
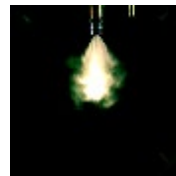
Test fuel	E0		E50		E100	
ASOI (ms)	Ambient temperature					
	20 °C	120 °C	20 °C	120 °C	20 °C	120 °C
0.2						
0.4						
0.6						
0.8						
1.0						
1.2						

Figure 6. Cont.

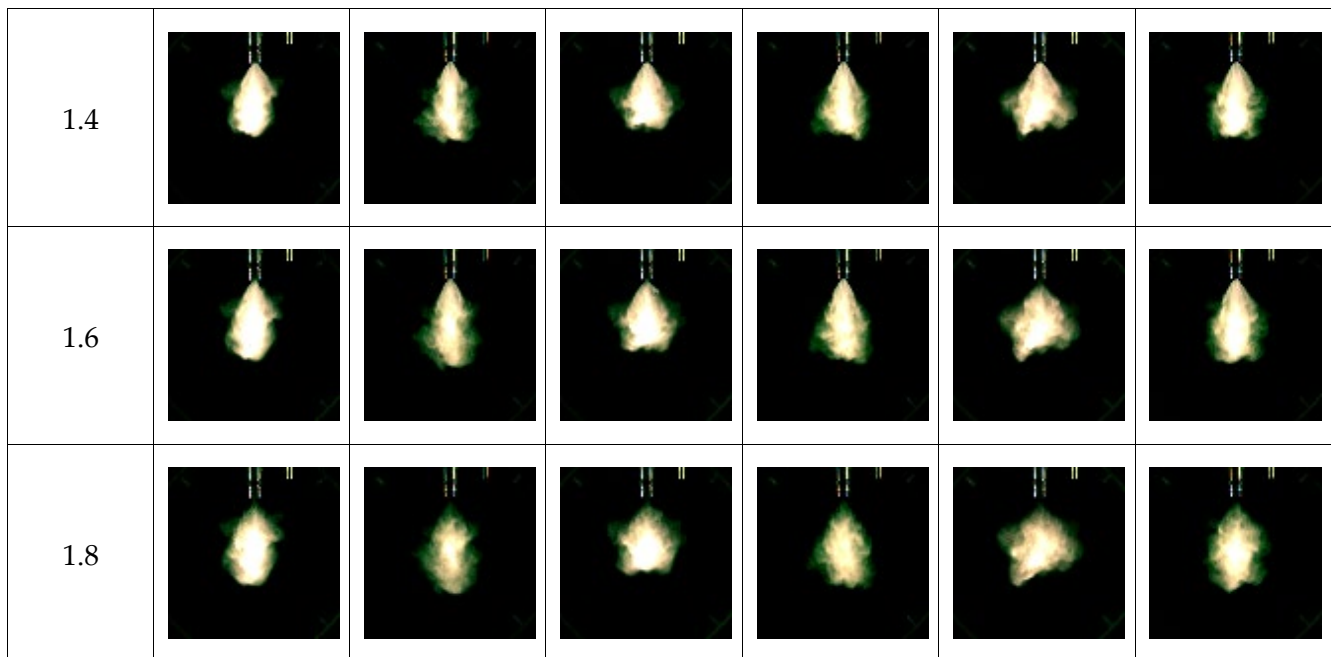


Figure 6. Mie scattering images of blends (P_{inj} : 250 bar; P_{amb} : 5 bar).

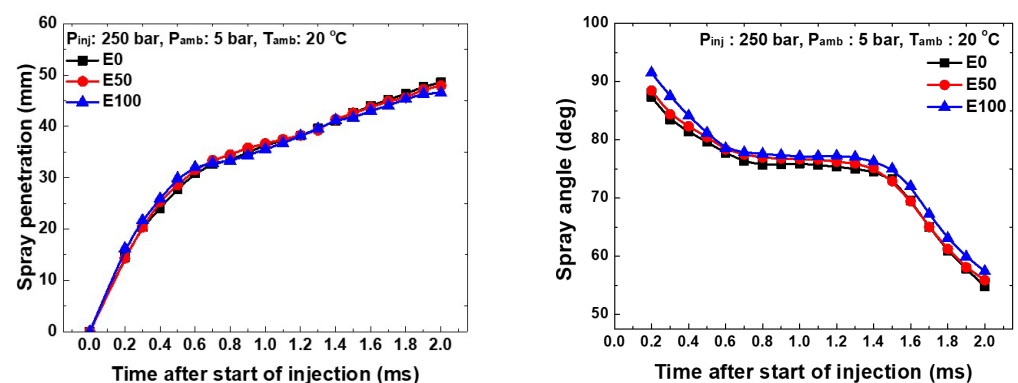


Figure 7. The results for the spray penetration and spray angle of the blends.

3.2. Comparison between Mie Scattering and BOS Method

Figure 8 shows a comparison of the Mie scattering images with the images obtained using the BOS method under the same conditions. The red line indicates the edge of the spray shape in the BOS image, which is larger than that in the Mie scattering image. While only liquid fuel was observed in the Mie scattering images, the BOS images exhibited a density change and image displacement caused by vapor flow due to fuel vaporization. In agreement with these tendencies, a comparative analysis of the spray penetrations and spray angles in the Mie scattering and BOS images reveals that the spray penetrations and spray angles measured using the BOS method are larger than those measured using Mie scattering over the entire range, as shown in Figure 9. In addition, the differences between the measurement methods tend to be greater at higher ambient temperatures. The spray penetration differences between the Mie scattering and BOS images at 2.0 ms after start of injection (ASOI) for the same start conditions range from 2.1 to 5.1 mm, depending on the ambient temperature. The corresponding spray angle differences range from 6.2° to 14.2° . Based on the differences in the Mie scattering and BOS results, as well as the larger differences at higher ambient temperatures, it can be concluded that fuel vaporization progressed as the spray progressed. The differences between the spray penetrations and spray angles can be attributed to differences in the vaporization degree of the blended fuel.

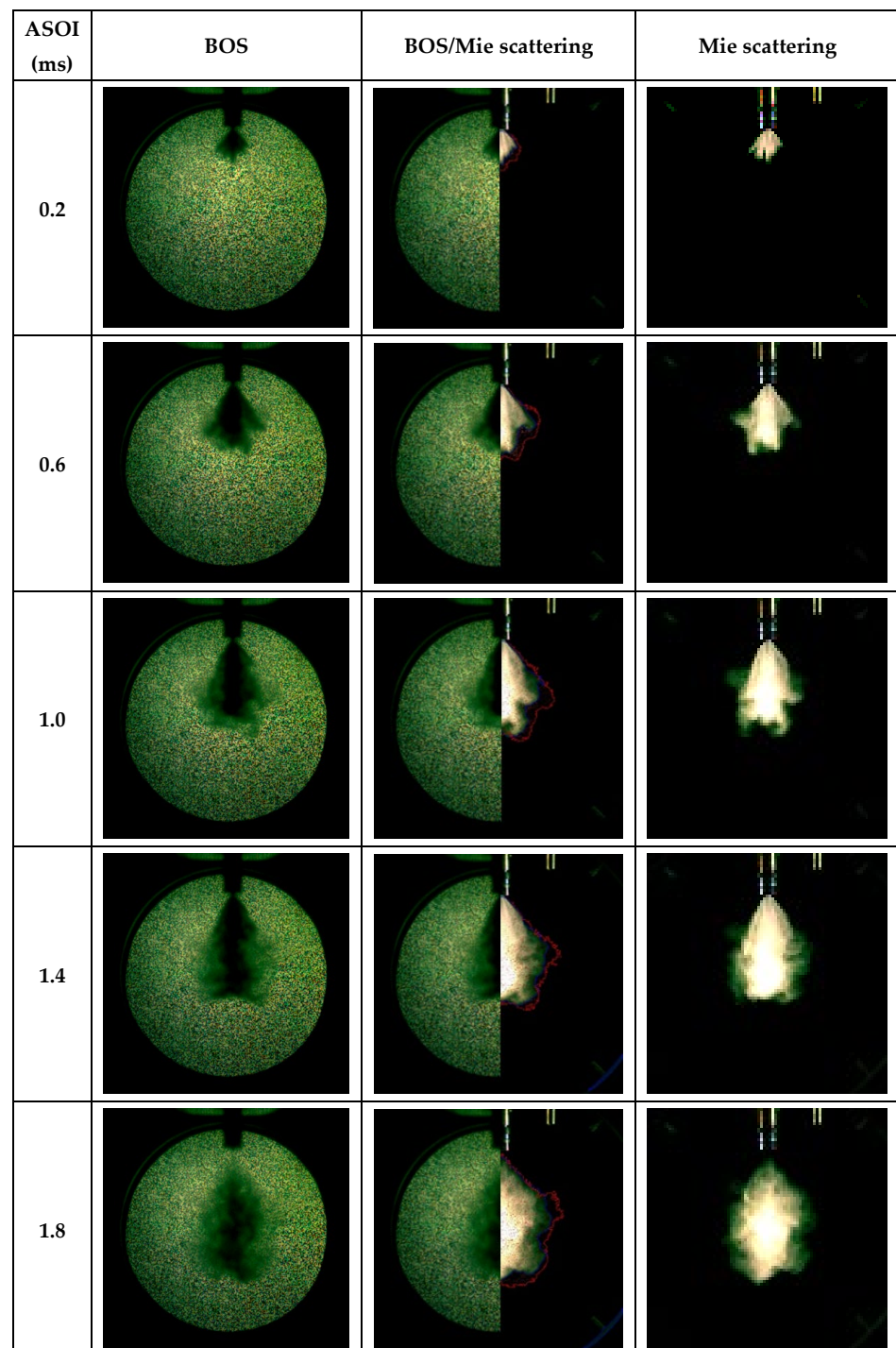


Figure 8. Comparison of BOS and Mie scattering images (P_{inj} : 250 bar, P_{amb} : 5 bar, and T_{amb} : 120 °C, E100).

The differences between the Mie scattering and BOS results were more obvious at low ambient pressures but became smaller at higher ambient pressures, as shown in Figure 10. At an ambient pressure of 1 bar, the difference in the spray penetrations obtained using the two measurement methods was approximately 7 mm and the difference in the spray angles was approximately 25°. However, at the ambient pressure of 10 bar, the spray penetration difference became smaller at approximately 1 mm, and the spray angle difference shrank to approximately 15° because the vaporization rate of the fuel decreased as the ambient pressure increased.

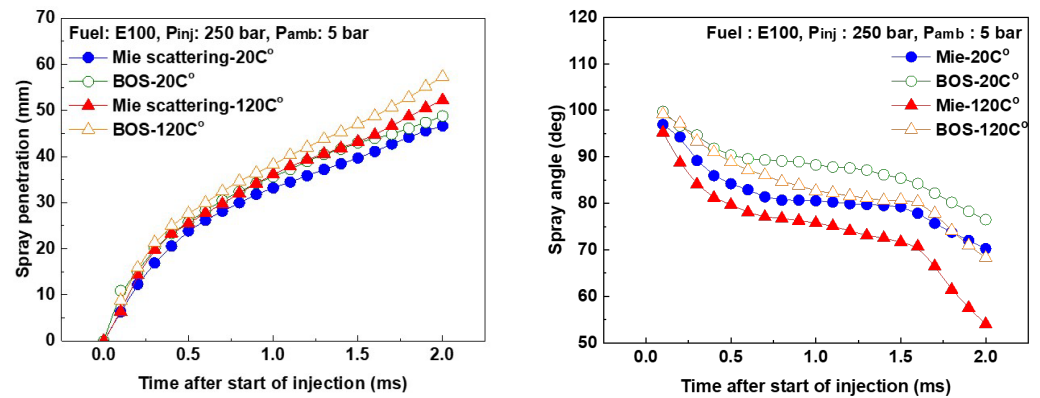


Figure 9. A comparison of the spray characteristics between the BOS and Mie scattering methods.

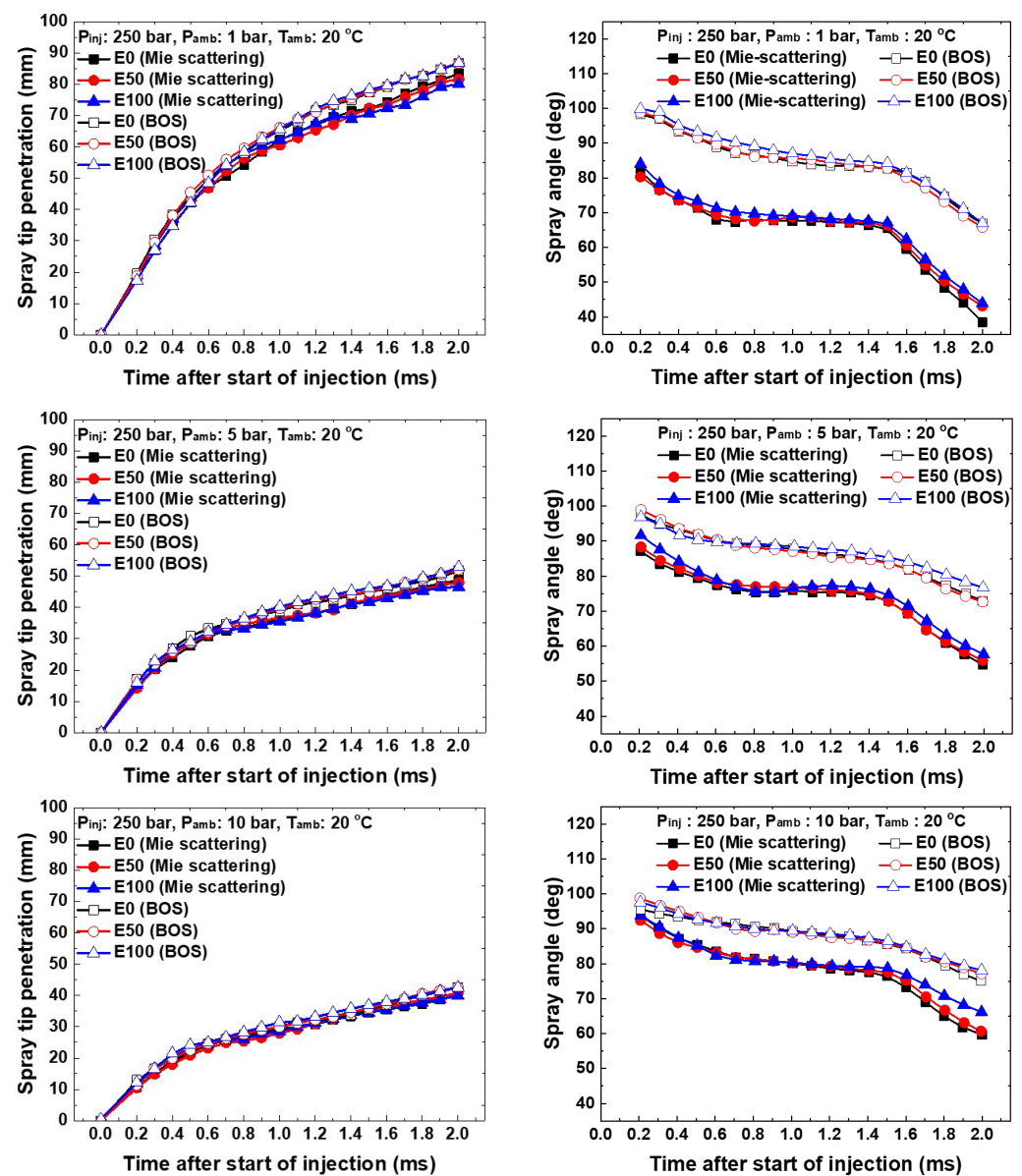


Figure 10. The results for the spray characteristics of the blends according to the ambient pressure.

As shown in Figure 11, the vaporization ratio can be compared by comparing the areas of the spray images acquired using the BOS and Mie scattering methods. The vaporization characteristics were evaluated based on the differences between the measurement results

of the two methods for each fuel. Figures 12 and 13 show the results of the spray areas measured according to the ambient temperature and pressure, respectively. For all the fuels, the differences in the results tend to be larger at higher ambient temperatures. In addition, the differences decrease at higher ambient pressures. The differences between the results for E100 fuel tend to be larger than those for E0. These results indicate that the excess fuel resulting from the increased spray penetration and the widened fuel spray angle, due to vaporization, can cause wall wetting.

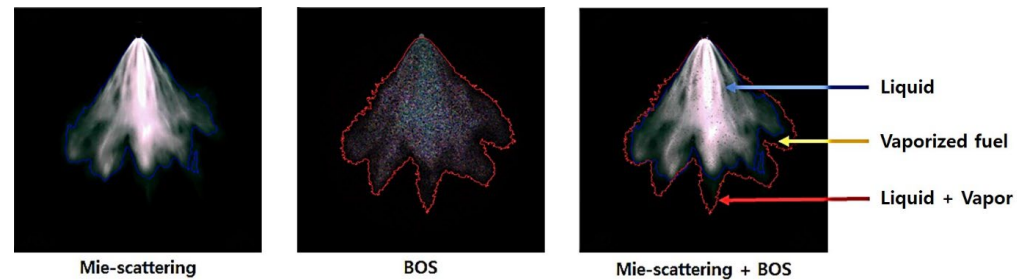


Figure 11. Differences between Mie scattering and BOS images.

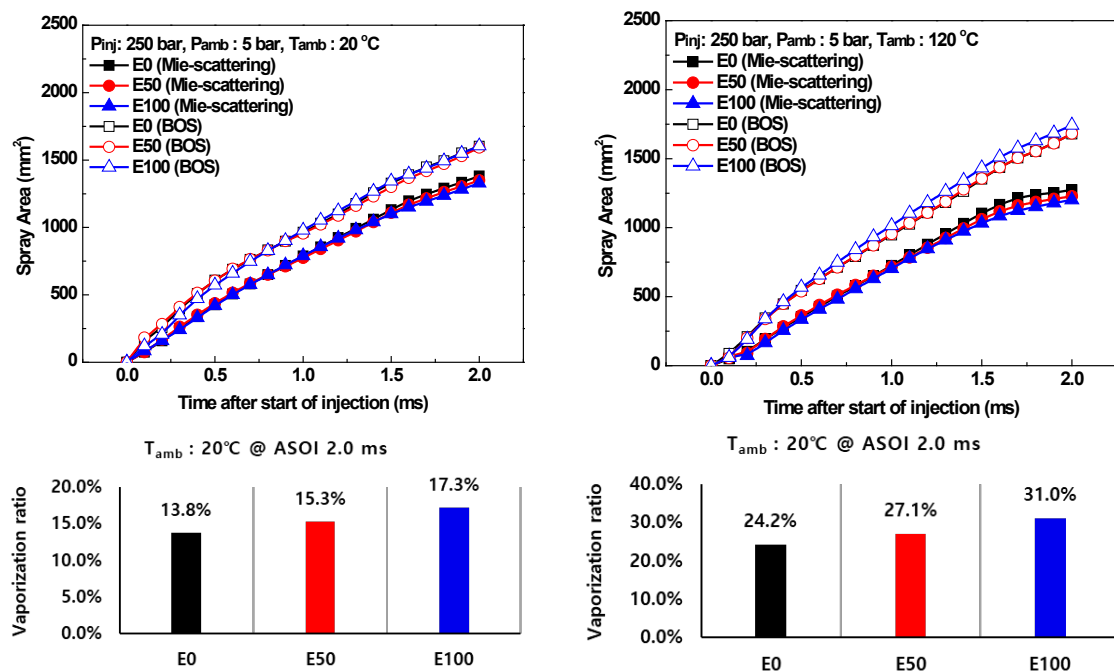


Figure 12. The spray areas and vaporization ratio for the blends, according to the ambient temperature.

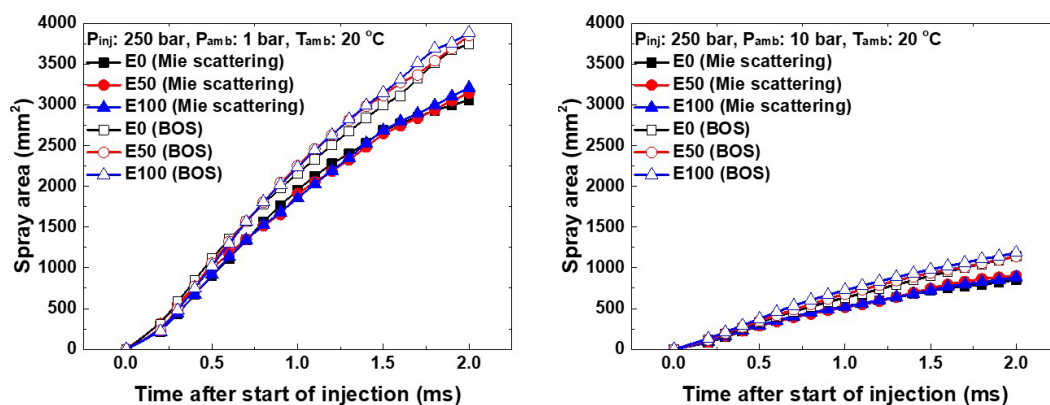


Figure 13. The spray areas for the blends according to the ambient pressure.

3.3. Spray Collision with Piston

Figure 14 shows spray impingement images of the piston according to the time after injection. The distance between the injector and the piston was 50 mm. The time required for the fuel to collide with the piston is shorter in the BOS images. The fuel spray penetration for E100 is generally longer than that for E0, and the time to collision with the piston is shorter because the high density of ethanol led to the increased momentum of the atomized fuel.

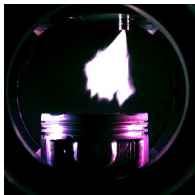
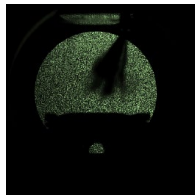
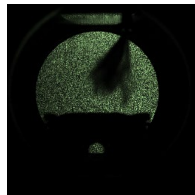
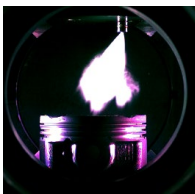
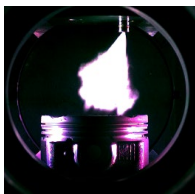
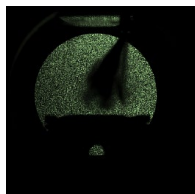
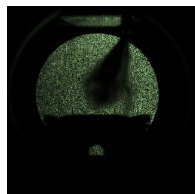
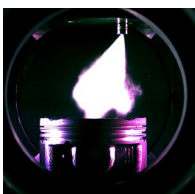
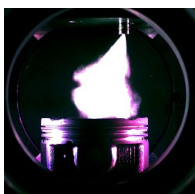
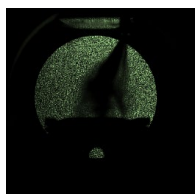
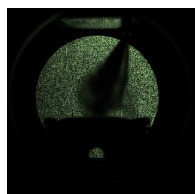
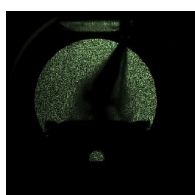
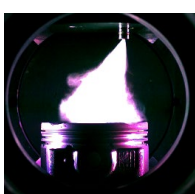
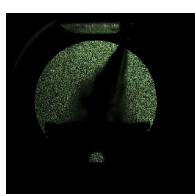
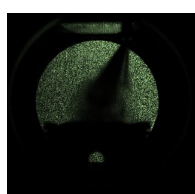
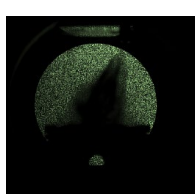
P_{inj} : 250bar	Mie scattering		BOS	
ASOI (ms)	E0	E100	E0	E100
0.6				
0.8				
1.0				
1.2				
1.4				
1.6				

Figure 14. Cont.



Figure 14. The images of the spray impingement by the piston.

Based on these images, the spray width is defined as the maximum width of the spray shape, as shown in Figure 15. Figure 16 shows the spray width after injection. The spray penetration was 50 mm at approximately 0.8 ms after injection, and it can be seen from Figure 10 that the fuel collided with the piston after approximately 0.8 ms. The slope of the increase in the spray width of the injected fuel increased as it collided with the piston. The injected fuel moved horizontally with respect to the piston after colliding with it. Assuming that the piston bore is 70 mm, liquid fuel will reach the cylinder wall at approximately 1.9 ms while vaporized fuel will reach the wall at approximately 1.7 ms. This shows that it is possible to predict not only the liquid fuel spray behavior but also wall wetting by vaporized fuel under various conditions using high-speed cameras in visualization experiments.

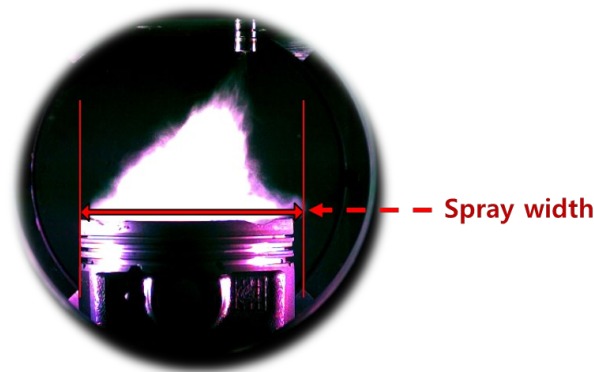


Figure 15. The definition of the spray width.

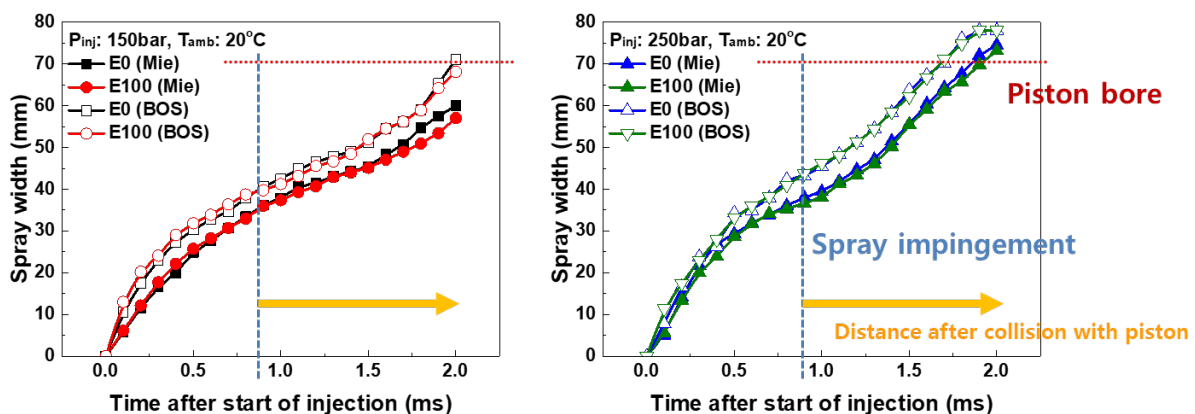


Figure 16. Prediction of wall wetting.

4. Conclusions

The differences in the spray shape and the spray behavior were observed between different fuels in spray visualization experiments for optimizing ethanol–gasoline-blended fuel combustion. The following conclusions can be drawn from a comparative analysis between the Mie scattering and the BOS methods results:

- (1) Because the spray penetration and spray angle obtained from the BOS method—which can be used to obtain images of the spray, including the vapor—are larger than those obtained from the Mie scattering, it was concluded that vaporization could occur as the spray progressed.
- (2) The accelerated fuel vaporization at high ambient temperatures resulted in larger differences in the results at different ambient temperatures.
- (3) As the ambient pressure increased, the differences between the results of the Mie scattering and the BOS methods, and those for different fuel blending ratios, became insignificant. It was concluded that the rate of vaporization decreased as the ambient pressure increased.
- (4) In general, the differences between the spray penetrations and spray angles for E100 are larger than those for E0. This suggests that the vaporization rate of E100 during injection was higher than that of E0.
- (5) The collision image between the fuel and piston could be used to predict the collision of vaporized fuel, including liquid fuel.
- (6) The wall-wetting phenomenon, which may adversely affect combustion, occurred because of vaporized fuel that was not visualized.

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