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A study on the macroscopic spray behavior and atomization characteristics of biodiesel and dimethyl ether sprays under increased ambient pressure

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ABSTRACT

The aim of this work is to investigate the spray behaviors of biodiesel and dimethyl ether (DME) fuels using image processing and atomization performance analysis of the two fuel sprays injected through a common-rail injection system under various ambient pressure conditions in a high pressure chamber. In order to observe the biodiesel and DME fuel spray behaviors under various ambient pressures, the spray images were analyzed at various times after the start of energization using a visualization system consisting of a high speed camera and two metal halide light sources. In addition, a high pressure chamber that can withstand a pressure of 4 MPa was used for adjusting the ambient pressure. From the spray images, spray characteristics such as the spray tip penetration, cone angle, area, and contour plot at various light intensity levels were analyzed using image conversion processing. Also, the local Sauter mean diameters (SMD) were measured at various axial/radial distances from the nozzle tip by a droplet measuring system to compare the atomization performances of the biodiesel and DME sprays.

The results showed that the ambient pressure had a significant effect on the spray characteristics of the fuels at the various experimental conditions. The spray tip penetration and spray area decreased as the ambient pressure increased. The contour plot of the biodiesel and DME sprays showed a high light intensity level in the center regions of the sprays. In addition, it was revealed that the atomization performance of the biodiesel spray was inferior to that of the DME spray at the same injection and ambient conditions.

1. Introduction

In a high speed direct injection (HSDI) diesel engine, the fuel spray development and atomization characteristics play an important role in the improvement of combustion and engine performance, because they influence the fuel–air mixing in the cylinder. Therefore, it is necessary to analyze the spray development and atomization characteristics of various fuels in order to reduce exhaust emissions and improve thermal efficiency of the diesel engine. Among the various alternative fuels, biodiesel and dimethyl ether (DME) fuels are the most popular. This is because biodiesel fuel can be used in a conventional diesel engine without modification of the engine and a diesel engine fueled with DME can be operated with only a partial modification of the fuel supply system. In addition, these alternative fuels contain large amounts of atomic oxygen in comparison with diesel fuel and their exhaust emissions, such as hydrocarbon (HC), soot, and particulate matter (PM), are remarkably decreased. However, biodiesel and DME fuels differ from conventional diesel fuel in some characteristics such as a nozzle cavitating flow, spray behavior, atomization, the combustion process, and formation of emissions [1–7]. Therefore, there have been many investigations into the spray development, combustion and emission characteristics of these two alternative fuels in diesel engines.

Teng et al. [8–12] conducted numerical studies on the thermodynamic properties of liquefied DME fuel such as density, viscosity, latent heat, enthalpy, surface tension and vapor pressure. Based on the existing molecular and chemical structure theories, they developed various equations for the fuel properties according to temperature for the analysis of fuel-system design and modeling. An experimental investigation into the effects of temperature on the properties of biodiesel fuel was conducted by Yoon et al. [13] and Yuan et al. [14]. In addition, Park et al. [15] carried out research into biodiesel and biodiesel–ethanol blend fuel properties such as the specific gravity, density, dynamic and kinetic viscosity and developed empirical equations describing them. To compare the spray characteristics of DME and diesel fuel, Suh et al. [16] investigated DME and diesel spray characteristics in the combustion chamber. They reported that the spray tip penetration of DME fuel is shorter than that of diesel fuel and that the DME spray has a smaller Sauter mean diameter (SMD) than diesel spray under the same injection conditions. Experimental investigations into the spray structure of diesel fuel and various oxygenated fuels, including dimethyl ether, using a PIV measuring

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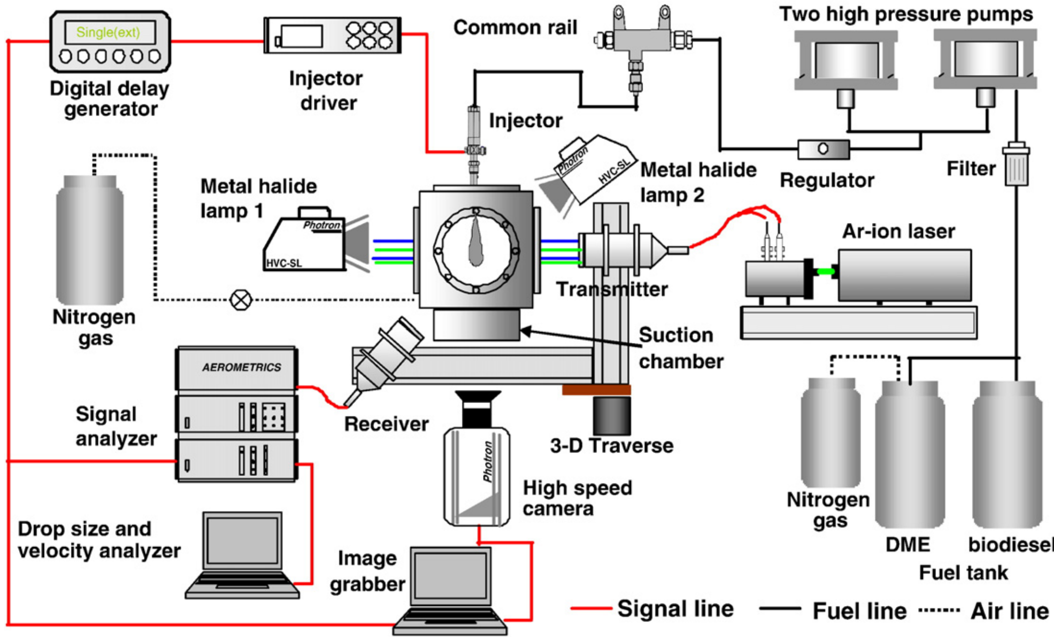

Fig. 1. Schematics of spray visualization and droplet measuring systems.

method were carried out by Wu et al. [17]. The spray and combustion characteristics of biodiesel-blended fuel at various mixing ratios were investigated by Lee et al. [18]. They reported that the spray tip penetrations of biodiesel and biodiesel-blended fuels showed a similar pattern, regardless of the mixing ratio of the biodiesel and the atomization performance of the biodiesel-blended fuel was inferior to that of the conventional diesel fuel due to the high surface tension of the biodiesel fuel. Kim et al. [19,20] conducted experimental and numerical investigations of the atomization characteristics of diesel, biodiesel, DME and biodiesel–ethanol blended fuels. In their work, the calculated atomization results show good agreement with experimental results. Kim et al. [21] also carried out experimental and numerical studies to compare diesel and DME sprays for two chamber shapes under high ambient pressure conditions.

In spite of the research into biodiesel and DME fuels, detailed information about their spray behaviors and atomization characteristics under various ambient pressures is not available. The aim of this work is to investigate the spray behavior and atomization characteristics of biodiesel and DME fuels under various ambient pressure conditions in a high pressure chamber using spray image visualization and spray droplet measuring results. Using the spray images obtained from visualization system, the spray tip penetration, spray cone angle, spray area, and contour plot according to light intensity were measured and analyzed to compare the biodiesel and DME sprays. The local SMD at various axial and radial distances and under various ambient pressure conditions were measured and compared to evaluate the atomization performance of biodiesel and DME sprays.

2. Experimental apparatus and procedures

2.1. Experimental apparatus

As illustrated in Fig. 1, spray visualization and droplet measuring systems were used to investigate the spray characteristics under ambient pressure, such as the increasing rate of spray penetration, spray cone angle, spray area, and the mean droplet size distribution. The spray visualization system consisted of a high speed camera (Photron, Fastcam-APX RS) with two metal halide lamps as a light source. The frame rate and shutter speed of the high speed camera were set to 10,000 fps (frames per second) and 1/20,000 s, respectively. The resolution of the spray images was set to 512 × 512. The input signals to the high speed camera and a test injector with a single hole were synchronized by a digital delay/pulse generator (Berkeley Nucleonics Corp, Model 555). The test injector had a 0.8 mm nozzle depth and a 0.3 mm nozzle diameter, and was operated by an injector driver (TEMS, TDA-3200H). The droplet measuring system was a phase Doppler particle analyzer (PDPA) system composed of a receiver, a transmitter, and a signal analyzer, with an Ar-ion laser for a light source. The Ar-ion laser had a maximum power of 5 W, a laser beam diameter of 1.4 mm and two wave lengths of 514.4 nm and 488 nm. To measure the droplet size (SMD), the transmitter and receiver were moved by a 3-D traverse at periods of 10 mm in the axial direction, and 2 mm in the radial

Table 1
Specifications of experimental apparatus.

Visualization system with high speed camera	
Light source	Two metal halide lamps
Frame rate	10,000 fps
Shutter speed	1/20,000 s
Resolution	512 × 512
Droplet measuring system	
Light source	Ar-ion laser
Wave length	514.5 nm, 488 nm
Laser beam diameter	1.4 mm
Focal length	Transmitter : 500 mm
	Receiver : 250 mm
Collection angle	30 degrees
Filter frequency	40 MHz
PMT voltage	500 V

Table 2
Properties of biodiesel and DME fuels.

Fuel property	Biodiesel (soybean oil)	Dimethyl ether (DME)
Density (kg/m^3)	884	660
Viscosity (mm^2/s)	4.0–6.0	0.12–0.15
Surface tension (kg/s^2)	0.028	0.012
Boiling point temperature (°C)	315–350	−23
Flash point temperature (°C)	100–170	−42
Cetane number	48–65	68