

The Measurement of Penetration Length of Diesel Spray by Using Background Oriented Schlieren Technique

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ABSTRACT

The measurement of spray penetration length is one of crucial tasks for understanding the characteristics of diesel spray and combustion. For this reason, many researchers have devised various measurement techniques, including Mie scattering, schlieren photography, and laser induced exciplex fluorescence (LIEF). However, the requirements of expensive lasers, complicated optics, delicate setups, and tracers that affect fuel characteristics have been disadvantages of previous techniques.

In this study, the background-oriented schlieren (BOS) technique is employed to measure the vapor penetration length of diesel spray for the first time. The BOS technique has a number of benefits over the previous techniques because of its quantitative, non-intrusive nature which does not require lasers, mirrors, optical filters, or fuel tracers. The objectives of this study are to establish the BOS technique as a viable method and then to use it to measure the vapor penetration of diesel spray as a function of ambient temperature, pressure, and orifice pressure drop by using BOS technique after verifying the possibility as a new useful method.

The experiments were performed on an optically accessible, constant-volume pre-combustion type chamber (CVPC) simulating the ambient conditions within a diesel engine. A single-hole solenoid injector and a common rail system were used for fuel injection. The structured background with randomly generated dots was taken by a high speed CCD camera, and the images were post-processed by analysis programs. The schlieren images were also taken under the same set of conditions to validate the results of the BOS

technique. The BOS results show a good agreement with the schlieren results in terms of vapor penetration. It is worthwhile to develop a more convenient and quantitative diagnostic technique applicable for investigating the penetration characteristics of diesel spray and capable of providing fundamental information to the area of CFD study.

INTRODUCTION

In diesel engines, spray penetration affects atomization, vaporization of injected fuel and air-fuel mixing. Understanding the penetration characteristic, therefore, is an essential task in diesel engine studies. For this reason, there has been a wide range of research on spray measurements employing various techniques. Siebers [1] employed Mie scattering to measure the liquid length dependence on the injection pressure, the orifice diameter and aspect ratio, the ambient gas temperature and density, and the fuel volatility and temperature. Myong et al. [2] measured the liquid and vapor phases of fuel by Mie scattering and schlieren photography simultaneously to evaluate the vaporization characteristics of single- and multi-component fuels under various conditions. Musculus et al. [3] applied Mie scattering and the planar laser-induced fluorescence (PLIF) technique for the diagnosis of liquid length and vapor edge in an optical heavy-duty engine under low temperature combustion (LTC) condition. Cárdenas et al. [4] used Mie scattering, schlieren technique, and PLIF to investigate liquid/vapor characteristics and the hot reaction zone of clustered-hole injector developed for reducing soot emission. Pickett et al. [5] reported that the shadowgraph/schlieren method can be used not only to see vaporization of fuel but also to identify a cool flame region.

schlieren photography measures the density gradient of objects and can thus give us the image of liquid and vapor phases combined [6, 7]. The method, however, has limitations; objects larger than the concave mirrors are beyond measurement, and a delicate optical setup is required. Laser-induced exciplex fluorescence (LIEF) can measure both liquid and vapor phases of spray separately; however, it not only requires fuel tracers that affect fuel characteristics but also a relatively high-power laser and complex optics [8,9,10]. Liquid penetration of fuel spray can be measured easily by means of backlight imaging, a technique similar to Mie scattering but without laser or mirrors [11]; however, vapor penetration is difficult to detect without laser or mirrors.

First presented by Meier and Richard in [12-13], the BOS technique is similar to schlieren photography in that it is sensitive to density gradients; however, it does not require any mirrors or a point light source. It was initially applied to a large scale measurement, such as the compressible vortex field around a helicopter blade, which is an object field too large to apply schlieren photography because of the size limitation of the mirrors [12-13]. On the other hand, quantitative measurements of supersonic and transonic flow fields have also been reported [14,15,16]. Because BOS senses the density gradients, as does the ordinary schlieren technique, the technique is potentially applicable to the spray measurements.

To establish the viability of BOS as a useful tool for engine research, comparisons were made between BOS and normal schlieren photography by measuring the vapor penetration length of fuel spray using both techniques. Experiments were performed under two sets of ambient conditions with varying injection pressure. BOS images taken by a high-speed CCD camera were post-processed by a 2D cross-correlation algorithm (used in PI V technique), and the contour plots generated by displacement vectors were compared with the schlieren images taken under the same condition.

THE PRINCIPLES OF BOS

The operating principle of BOS is briefly introduced in this section; detailed information can be found in [17]. If the camera lens and the image plane (film or a CCD sensor) are placed as shown and there is no object between the background and the camera lens, the light path will be as shown in Fig. 1 (a). If some volume with a dissimilar density is placed between the object plane and the lens, the optical path is altered, and a dot at the center of the background is imaged at a position away from the center of the image plane by a distance Δy , as shown in Fig. 2(b). BOS makes use of this displacement Δy .

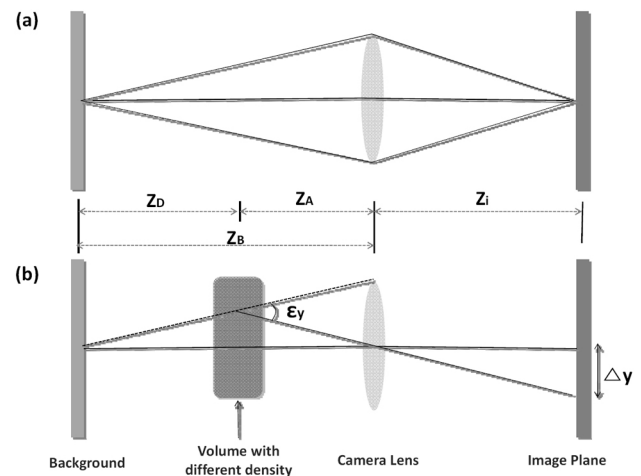


Figure 1. Ray propagation (a) with no intervening object and (b) with a volume with a dissimilar density placed between background and camera lens [12]

Within the 2D image plane, the dot moves in both x and y directions according to the density gradients in the volume in front of the camera. These movements, expressed as displacement vectors, are proportional to the integral of the refractive index gradient. Thus, the refractive index field can be calculated by solving the Poisson's equation. Using the Gladstone-Dale relation, the density field is finally obtained.

EXPERIMENTAL SETUP

THE CONSTANT VOLUME PRE-COMBUSTION TYPE CHAMBER

In this study, a constant-volume pre-combustion type chamber (CVPC), shown in Fig. 2, was used to realize appropriate temperature and pressure conditions sufficient to vaporize the diesel fuel. The CVPC has benefits over other optical research equipment because of its capability to generate a wide range of temperatures and pressures [18]. It is also easy to obtain appropriate experimental conditions by adjusting the composition of pre-combustion gases and by determining the synchronization time of fuel injection at cool down. The specification of the CVPC is listed in Table 1.

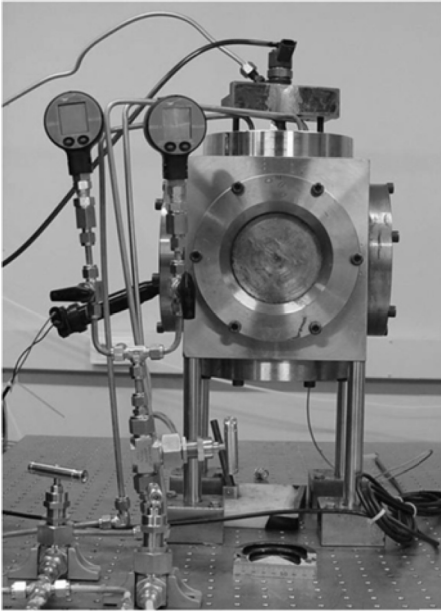
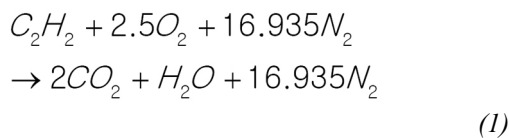


Figure 2. Constant-volume pre-combustion type chamber

Table 1. The specification of the constant-volume pre-combustion type chamber

Displaced Volume	1650 cc
Pre-combustion Gases	Acetylene, Oxygen, Nitrogen
Max Temperature	1600 K
Max Pressure	60 bar
# of Windows	4
Fuel Injection	Bosch Common Rail System

Acetylene, oxygen and nitrogen were fed to the CVPC as pre-combustion gases. The gas mixture was ignited by using a spark plug located on the side wall. In order to prevent auto ignition and to see pure vaporization effect of diesel fuel, the ratio of acetylene to oxygen was determined in such a way that no oxygen remained after pre-combustion. This process was accomplished using the following equation [17].



Kistler 6061B pressure transducer was used to measure pressure and R-type thermocouple was used to measure burnt gas temperature in the chamber. After pre-combustion, temperature and pressure in the chamber rapidly increased with propagation of premixed flame and then cool down was occurred because of heat transfer to walls. Diesel fuel was injected at the target point during the cool-down process. The injector was driven by a one-shot ECU and conventional software. The injection duration was fixed to 1 ms for all cases. Figure 3 shows the pressure-time profile used to determine the injection timing.

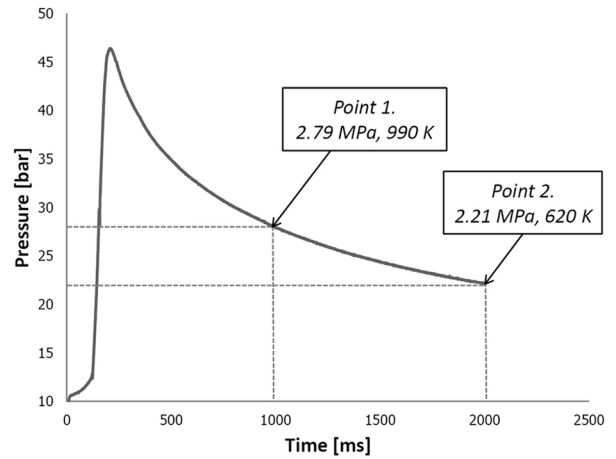


Figure 3. Pressure-Time curve for injection timing

A Bosch common rail system and a single-hole solenoid injector were used to inject the fuel. All images were taken with a high-speed CCD camera (Photron, Ultima APX Color) with a 6000 fps time resolution. Synchronization among pre-combustion, fuel injection and the high-speed CCD camera was controlled by a function generator (Stanford Research Systems, DG535). A schematic diagram of the entire system is shown in Fig. 4.

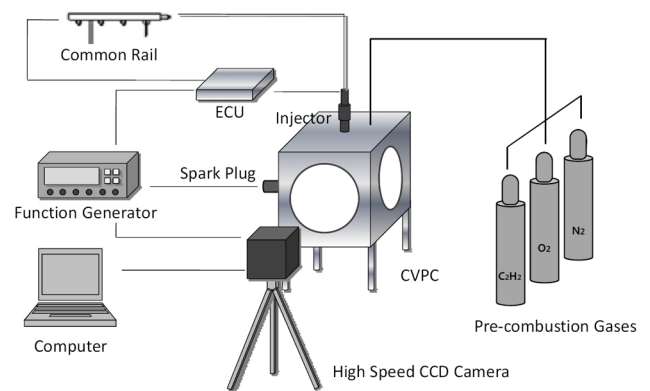


Figure 4. Schematic diagram of the experimental setup

THE OPTICAL SETUP

For a BOS measurement, penetrating windows are necessary for taking the background. An open source code (PIVMAT) which includes “random dot generator” was used to generate 100,000 random dots on A4 size (210 × 297 mm) paper and this sheet of paper is placed on the background illuminated with a light source as shown in Fig. 5. Preferably, the camera should be close to the object and the background should be far from the object to enhance Δy ; however, the distance from spray to the camera lens and that from spray to the background were both fixed to 580 mm due to the limited viewing angle of the lens and limited space for the background.