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Light intensity and image visualization of GDI injector sprays according to nozzle hole arrangements

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ABSTRACT

The light intensity measurement and image visualization of multi-hole injection spray due to different hole arrangements and hole numbers were investigated. The light intensities and behavior characteristics of the GDI spray were analyzed through the axial and diagonal spray penetration, cone angle, and spray area from the spray images by using the image visualization system and image analysis system. The atomization performance of GDI injectors was analyzed by the local and overall Sauter mean diameter (SMD) measurement.

It is revealed that the higher injection pressure shows higher light intensity levels due to the strong vortices and collision by a high injection pressure. The light intensity level at the outer and end region of the spray shows lower value compared to that at the center spray region. In all of test injectors, the increased injection pressure leads to the decrease of the droplet size distribution in the initial spray. But, there is little difference of the droplet size at low and high injection pressure in middle and latter period after the injection. The overall SMD of GDI injectors showed from 14 to 23.14 μm.

1. Introduction

The main factors of image measurements for the spray can be divided into four elements such as brightness, location, droplet size, and its shape. In general, the optical density is influenced on the fraction of the incident light that penetrates through the spray volume without being scattered or absorbed [1]. In a gasoline direct injection (GDI) system, the spray and atomization characteristics of injected fuel play an important role in the fuel–air mixture formation and performance characteristics of the engine. In a GDI engine, the fuel is directly injected into the combustion chamber, and the fuel stratification is realized so that air–fuel mixture is well prepared at the vicinity of a spark plug at the time of spark event [2,3]. The air–fuel mixture in a GDI engine is usually much leaner than stoichiometric condition. In this point of lean mixture operation, GDI engines have less fuel consumption characteristics [4,5]. Therefore, many studies on the improvement of atomization and mixture formation characteristics are actively progressing, experimentally, and numerically [6–9]. In the spray processes, fuel atomization factors such as a spray shape, the location of fuel injector, the number of injector hole, and an arrangement of nozzle hole, an injection angle are important parameters in the GDI engine system. Recently, the high pressure multi-hole injector is used to form better homogeneous air–fuel mixture. In order to improve the GDI engine performance, the combustion and atomization characteristics of the fuel injector have been conducted by many investigators [10–14]. Romunde et al., [15] conducted the investigation on the developing process of injection spray from the multi-hole injector for a direct injection spark ignition engine according to the ambient conditions. In their work, the results showed that the spray tip penetration increased as the ambient pressure decreased, and it decreased with the decreasing ambient temperature. In order to improve the spray formation from spray-guided multi-hole GDI injectors, Skogsberg et al., [16] conducted numerical analysis and experimental study by using laser diagnostic approach. They showed that the injectors with 6-hole nozzles and 50° umbrella angles were unsuitable for stratified combustion in a single cylinder optical engine. In spite of various studies on the spray characteristics for the combustion systems, the experimental studies on the light intensity and image visualization of gasoline direct injection spray for the multi-hole injector are little and limited compared to the investigation of macroscopic spray behaviors. In this point of view, the purpose of this work is to investigate the light intensity, image visualization of gasoline spray, macroscopic characteristics, and fuel atomization of multi-hole GDI injector sprays using four test injectors with

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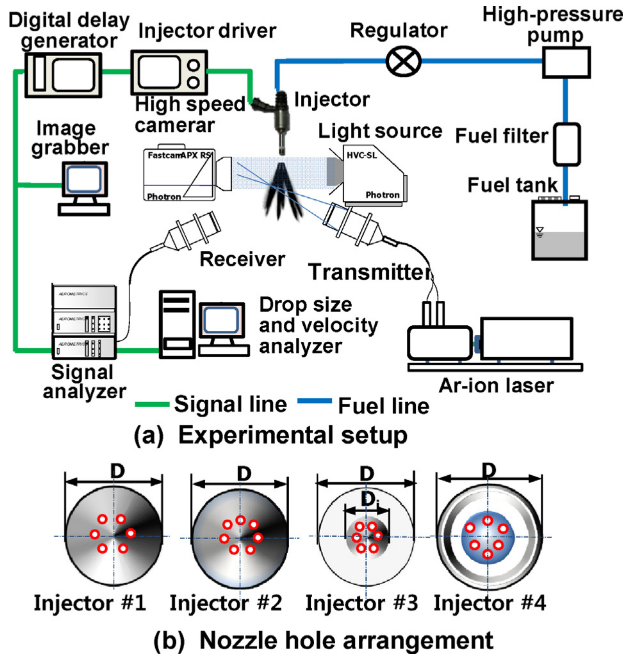

Fig. 1. Spray visualization and droplet measuring system and nozzle hole arrangement [D = 4.5 mm, injector 1: hexagonal hole arrangement (d = 0.2 mm, z = 6), injector 2: hexagonal hole arrangement (d = 0.2 mm, z = 7), injector 3: concentrated hexagonal hole arrangement (d = 0.2 mm, D_i = 1.5 mm, z = 6), injector 4: triangular hole arrangement (d = 0.2 mm, z = 6)].

different hole arrangement and hole number. In addition, the atomization performance were analyzed the spray droplet size and their distribution according to the time after start of injection.

2. Experimental setup and procedure

2.1. Spray visualization and atomization system

Fig. 1 shows a schematic diagram of experimental setup for the light intensity analysis, fuel spray visualization system and nozzle hole configuration of GDI injectors. The multi-hole injector spray was visualized by the high speed camera (Photron, Fastcam-APX RS) with metal-halide lamp. In addition, the injection signal from the injector driver and the shutter signal of the high speed camera were synchronized by using digital delay/pulse generator (Berkeley Nucleonics Corp., Model 555). On the other hand, spray droplets which injected from the test injector were analyzed by the droplet measuring system (phase Doppler particle analyzer, PDPA). The light source of PDPA system is an Ar-ion laser (INNOVA 70 C, Coherent) with 5 W output (maximum). PDPA system consists of a transmitter, receiver, and signal analyzer. Fig. 1(b) shows test GDI injectors with different arrangement and number of nozzle hole. Test injectors 1 and 3 have six injection holes and fully symmetric hole arrangement with adjacent angles between two holes of 60°. In the case of injector 1, the six nozzle holes were arranged as hexagonal and symmetric types. The injector 2 is similar to injector 1 and with seven holes. Both injectors have a sac volume as a rounded tip conical type. On the other hand, the hole of test injectors 1 and 2 are positioned on a larger imaginary circle than those of injector 3. Injector 3 has a concentrated hole arrangement at the end of conical tip. In case of injector 4, the arrangement of the six nozzle holes were formed almost triangular type. Unlike previous three injectors, it has a sac volume of flat type.

2.2. Experimental procedure

Sprays of GDI injectors were visualized at 180° direction from the electrical plug of injector. The high speed camera used for the frozen spray images set up a 10,000 fps of frame rate with a resolution of 512 × 512 pixels and a 0.1 ms of shutter speed. In order to analyze the spray behaviors according to the angle view, high speed camera is located in an angle of 90 and 180° based on the electrical plug of injector. The injection pressure was fixed to 4 and 10 MPa, and the ambient gas pressure is 0.1 MPa and 290 K of ambient conditions.

For investigating the atomization performance of four injectors, the measurement points were selected at 30, 50, and 75 mm from the nozzle tip towards the axial direction. To move the measuring point, the transmitter and receiver shifted by using 3-dimensional traverse system which is possible to shift as 0.1 mm unit. Approximately 15,000 droplets were collected and averaged at three measurement points.

2.3. Image processing for analysis of light intensity

In the light intensity level, all pixels in the spray images obtained by the high speed camera with light source have the brightness level of 256 grayscale. In addition, the light intensity values are determined from 0 (black) to 255 (white) of brightness levels. Therefore, the contour plot on the light intensity levels can be shown the knowledge on the spatial distribution of fuel droplets according to the density of droplets. Also, each pixel from the original image has the brightness level of 256 grayscale for calculating the spray area. These pixels over the threshold level of 50 in this study were selected. The spray area was calculated from total area of all selected pixels.

3. Results and discussions

3.1. Light intensity and spray development processes

Fig. 2 shows the spray images of gasoline fuel and light intensity images of spray development of each injector at 4 MPa of injection pressures and 2 ms of time after the start of injection. In the light intensity, the injectors 1 and 4 at the injection pressure of 4 MPa represents the lower and higher fluctuation level of light intensity in the spatial distribution compared to the injectors 2 and 3. On the other hand, the spray flow of injectors 2 and 3 showed the interference between the injected plumes of spray at early injection stage by the increased number of holes (injector 2) and the closed location among the holes (injector 3).

The spray shape of injector 1 showed the higher fluctuation of light intensity at 40 and 60 mm of axial distance, but injector 2 indicated homogeneous and higher light intensity at both measuring points than those of injector 1 because of the increase of the number of nozzle hole. In the case of injector 3, the spray image illustrated the narrow spray angle and higher intensity at the radial range between −20 and +20 mm. In the measuring point 60 mm, spray image is split in three images. Injector 4 shows the spray shape as the five fingers and their intensity are high fluctuation at two observed points. It is believed that the injected sprays were progressed with small influence on the disturbance by neighbor's sprays.

As shown in Fig. 3, the spray images of test injectors at the injection pressure of 10 MPa were clearer and brighter than those at the injection pressure of 4 MPa because the injected fuel mass was increased as the injection pressure increased.

In the light intensity images, the spray droplets distribution at the center region is significantly denser than those of 4 MPa. This is