Microscopic Visualization of Transient Spray from Multi-hole Injector of DISI Engine

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Abstract

The main objective of this experimental study is to observe the atomization process very close to an injection hole nozzle exit of multi-hole injector of DISI engine and to examine the effect of injection pressure on characteristics of spray behavior. In order to investigate the atomization process, visualization of spray structure was performed using an ultra high-speed video camera (Max. camera speed 1Mfps), coupled with a long distance microscope and a Barlow lens. In order to clarify the effect of injection pressure, the experiments were carried out in a closed chamber at the atmospheric pressure. Backlighting from a strong metal halide lamp was used. Quantitative exit flow velocity and droplet diameter of atomization process were obtained by using time-series images with high temporal resolution. In this study, the experimental results of average exit flow velocity of atomization process were compared with the predicted exit flow velocity from NOZZLE FLOW MODEL. And experimental results of mean droplet diameter from microscopic visualization were compared with the results obtained from both predicted KH-RT model and phase Doppler anemometry (PDA) experimental results. It has been shown that experimental results for exit flow velocity of multi-hole injector due to the variation of injection pressure show good agreement with predicted results from NOZZLE FLOW MODEL. It is observed that the mean droplets diameter is constant after certain time from injection at the location 60mm down stream from the nozzle tip at the same pressure. The success of the visualization technique has demonstrated that the visualization technique is well suited for studying spray behavior from multi-hole injector of DISI engine

Introduction

The improvement of fuel economy and emission reduction is now the main driving force in automotive engine research. The design of more powerful, fuel-efficient and environmentally friendly gasoline engine is currently one of the main goals of engine researchers and manufacturers worldwide. Gasoline direct injection (GDI) engine technology has been proved to be a good potential for future automobile engine. The development of direct Injection spark Ignition (DISI) engines has been shown to be a very promising approach for minimizing the environmental impact and maximizing fuel economy, without compromising performance and driving comfort [1]. The design of the fuel injector plays a key role in the performance of DISI engines. Currently most DISI engines emerged in the international market use a wall-guided direct injection system [2-4]. This system has several problems including excessive unburned hydrocarbon emissions, high soot production due to the fuel attachment on the piston bowl. But recently spray- guided design has received more attention. The spray guided system generates a stratified fuel concentration near a spark plug due to the direct fuel injection toward that point. Multi- hole injector has a potential to use spray guided system. The multi-hole injectors are more promising because they offer the long sought spray pattern tailoring flexibility and reduced penetration [5-7]. Several researchers have applied the multi-hole injector to the DISI engines as a spray guided concept [8-10]

There are several measurement techniques are used in order to understand the spray characteristics formed by multi-hole injector. Laser sheet method with laser-induced fluorescence (LIF) [8], phase Doppler anemometer PDA[9], Particle image velocimetry [9] have been carried to provide the detailed information about spray tip penetration, spay cone angle, distribution of the liquid/vapor phase, or droplet velocity and diameter.

The main objective of this experimental study is to observe and investigate the atomization process very close to an injection hole nozzle exit of multi-hole injector of DISI engine and to examine the effect of injection pressure on characteristics of spray behavior. In order to investigate the atomization process, microscopic visualization of

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spray structure was performed using an ultra high-speed video camera (Max. camera speed 1Mfps), coupled with a long distance microscope and a Barlow lens [11-12]. In order to clarify the effect of injection pressure, the visualized experiments were carried out using DISI injector in a closed chamber at the atmospheric pressure. Backlighting from a strong metal halide lamp was used. Quantitative exit flow velocity and droplet diameter of atomization process were obtained by using time-series images with high temporal resolution. In this study, the experimental results of average exit flow velocity of atomization process were compared with the predicted exit flow velocity from NOZZLE FLOW MODEL [13]. And experimental results of mean droplet diameter were compared with the results obtained from both predicted KH-RT model [14] and PDA experimental results.

Experimental Set-Up and Conditions

The objective of this study is to investigate, by using microscopic image system, the influence of injection pressure on the atomization mainly exit velocity and spray droplet size diameter of the flow emerging from the nozzle. The DISI injector investigated in this study is prototype that was fabricated specifically for research use. It has two hole nozzle in order to focus on the spray structure of one spray plume. The diameter of nozzle exit is ϕ 0.21 mm. The two-hole nozzle has a spray angle at 90 degree.

Figure 1 shows schematic diagram of the experimental setup for microscopic visualizations of this study. The system consists of a constant volume chamber, DISI injector, fuel supplying system, an electronic controlling circuit, and high-speed video camera. The inside size of the constant volume chamber is diameter Φ 180 and 350mm in height. The chamber allows optical accesses through four sides windows. The DISI is mounted on the upper end plate of the constant volume chamber. To achieve fuel supply with a constant pressure for injector, pressure fuel supply system is prepared; an accumulator containing fuel inside is pressurized by nitrogen that was pressure regulated to 10 MPa from a high pressure gas cylinder. The injection signal is controlled by a pulse generator, which generates pulses with certain time duration, and the signal is synchronistically to the injector and the high speed video camera. A strong metal-halide lamp was used as a source of back light.

The injection pressure was changed at 3, 5, 7, 10MPa. Injection duration under each injection pressure condition was determined to obtain the same total mass of fuel. The liquid fuel used throughout the study is the Dry-Solvent. The important physical properties of this liquid are: density ρ: 765 kg/m^3, surface tension σ: 25 mN/m and kinematic viscosity ν: 1.032 mm^2/s. The volatility of the Dry-Solvent is less than that of gasoline and Dry-Solvent is often used in experimental investigations where the evaporation is wanted to be limited. The experiments were performed at room temperature and atmospheric ambient pressure.

A high- speed video camera (maximum speed: 1Mfps, minimum exposure time: 0.125 μs, Shimadzu Hyper Vision HEX-108) was used. The photographic image is black and white bits setup. This high-speed video camera has a resolution of 260x312 pixels. In this study Barlow lens was used with long distance microscope to get high magnification which allowed to take image in the area 2x2.4mm (magnified image) and equivalent one pixel length about 7.69μm. Figure 2 shows typical example for microscopic unprocessed magnified image of well dispersed region at 60mm downstream from the nozzle exit in the spray. These images have been analyzed and the calculations have been conducted by using GIMP program and Matlab program. The images were threshold, on the well focused plane, to pick out the atomization outline from background. For each testing condition, several sequence images (over than 400 images) were used to determine the droplet size diameter of the spray. In order to evaluate the accuracy of the microscopic images system used in this study, a detailed comparison of the spray sizing results using the microscopic images and PDA instrument was performed.

Numerical Computation Tool

In the present study, the microscopic visualization of experimental results of average exit flow velocity of atomization process was compared with the predicted exit flow velocity from NOZZLE FLOW MODEL [13]. The model provides the velocity and diameter at the nozzle exit as a function of the nozzle diameter, nozzle length, L, and nozzle angle. And experimental results from microscopic visualization of average droplet diameter were compared with the results obtained from predicted KH-RT model [14] and PDA experimental results. This is first attempt to using KH-RT model for low pressure DISI compared with Diesel engine.

NOZZLE FLOW MODEL

Several possible regimes occur in the injector nozzle including laminar, turbulent, cavitating and hydraulic flip regimes [13]. Due to the injection pressure in modern injectors, cavitating flows are very likely to occur within nozzle length. Cavitation is produced due to the low static pressure occurring in the flow under speed conditions near the nozzle inlet. If the nozzle inlet has a small enough rounding, the flow tends to detach from boundary layer, thus forming what is known as a "vena contracta" within the nozzle. This flow contraction at the nozzle inlet reduces the effective cross-section of the stream, and consequently flow velocity must increase if mass flow rate has to be constant. Furthermore, this flow acceleration across the vena contracta produces a decrease in the static pressure in that zone. This reduced pressure can drop to the value of the vapor pressure for the exiting temperature, causing a partial vaporization of the liquid, generating small bobbles or vapor cavities, which give the name of cavitation [15].The instantaneous flow condition inside the nozzle can be calculated from the input parameters including the injection pressure, ambient pressure, and nozzle diameter [13-19]. The output parameters are the instantaneous effective injection velocity and effective flow exit area.

$$V_{eff} = \frac{2C_c p_1 - p_2 + (1-2C_c)p_v}{C_c\sqrt{2\rho(p_1 - p_v)}} \quad (1)$$

$$A_{eff} = \frac{2C_c^2(p_1 - p_v)}{2C_c p_1 - p_2 + (1-2Cc)p_v} A \quad (2)$$

KH-RT BREAKUP MODEL

The Kelvin Helmholtz wave (KH) model and the Rayleigh-Taylor (RT) model are introduced together to estimate the stability and droplet size diameter [14, 20-26]. It is assumed that primary breakup mainly occurs by KH instability, and RT instability causes secondary breakup as shown in Fig. 3. In region A, the droplet is detached from the intact liquid core by KH instability. Once the droplet detached from liquid column, the secondary breakup is occurred by the competition of KH and RT instability in region B. Initial jet velocity and nozzle diameter are obtained from the NOZZLE FLOW model.

Results and Discussion

EFFECT OF INJECTION PRESSURE ON EXIT FLOW VELOCITY

In this research, average exit flow velocity is defined and determined using time-series of magnified image (camera speed: 500Kfps, exposure time: 1µs) very close to the nozzle exit. Exit flow velocity was calculated detecting the motion of any certain points at different radial points at nozzle exit from sequence images. Figure 4 shows the effect of injection pressure at 3, 5, 7, and 10 MPa on exit flow velocity. This figure shows how the injection pressure has strong impact on the exit flow velocity. Exit flow velocity is increasing as a function of injection pressure. From 3MPa injection pressure to 10MPa injection pressure the maximal difference of velocity is about 75%. The variation of the exit velocity is not proportional directly to just injection pressure change but the effect of cavitation increasing the value than that predicted. Under non-cavitating conditions the exit velocity from different injection pressure is proportional to root square of pressure. Once cavitation appears the mass collapses and the cross section area will be smaller than the real one and the exit velocity is no longer a function of the injection pressure. The value of velocity will be larger than that calculated from root square of injection pressure. Figure 4 also presents the estimated exit flow velocity for the same injection pressure. As for the measurement, the calculation reports that the exit flow velocity is influenced by injection pressure. As far as the influence of the injection pressure is concerned, the calculations (NOZZLE FLOW MODEL) of exit flow velocity indicated that almost no difference with experimental results at low injection pressure. With increasing the pressure, exit flow velocity is different from calculation. Increasing pressure led to rapid lost in momentum by breakup, so that the exit flow velocity from microscopic visualization is naturally different from NOZZLE FLOW MODEL. Globally speaking, there is disagreement between the measurements and calculation (NOZZLE FLOW MODEL) with increasing in injection pressure.

DROLET SIZE DISTRBUTION

The behavior of the droplet is important for estimating spray characteristic and spray formation inside cylinder. In this research a detailed comparison of the temporal droplet size distributions measured by microscopic method and PDA method was conducted at 60 mm location downstream of the nozzle exit at 3, 5, 7, and 10MPa fuel injection pressure. Figure 5 (a) shows the droplet size distribution at injection pressure 3, at time 2.2, 2.8, and 3.2 ms after start of injection. Figure 5 (b) shows the results under injection pressure 5MPa, at time 1.8, 2.2, 2.8ms after start of injection. The left side of figure 5 (a) and (b) shows the results of microscopic visualization measurements, and the right side shows the results of PDA measurements results. At times 2.2 and 1.8ms after start of injection for 3 and 5 MPa respectively, most of the droplet sizes show values around 22 to 45µm for both the microscopic visualization results and PDA results. With increasing the time for 3 and 5 MPa, both visualization and PDA results, show that the number density for the smaller droplet sizes increase. However, there is some unacceptable droplet sizes less than 16 μm were removed from visualization experimental results due to noise from unfocused area, which may be one source of variation of microscopic visualization results from PDA measurement results. In addition, microscopic method might lose some information in recording very small droplets due to resolution limits. Different measurement techniques give qualitatively similar trend as the measurement timing is changed. The quantitative difference may also originate from the different measurement volume used.

TEMPORAL VARIATION OF SAUTER MEAN DAIMETER

Figures 6 shows a comparison of time-series of Sauter mean diameter (SMD) behavior, measured by microscopic visualization method and PDA method. The corresponding measurement position is 60mm downstream from the nozzle exit under injection pressure 5, 7, 10MPa. In the results both techniques show that at the same value of injection pressure, the SMD value decreases during initial injection duration at each measurement point in dispersed region. At the initial stage, the spray shape of the end point is beginning to collapse due to the drag. In addition, as can be seen, after initial injection time in quasi steady state SMD is regular, because the rate of disintegration and coalescence are smaller. The SMD results from microscopic visualization show similar tendency of those of PDA results. Higher injection pressure produces smaller value, confirming the effect of injection pressure on the atomization performance.

VALIDATION OF THE DROPLET SIZE

Figure 7 shows a comparison between the results of droplet sizes using microscopic visualization method with those from PDA and estimated using the KH-RT model. Microscopic visualization method and calculation method report that droplet diameter is influenced by injection pressure. Droplet size decrease with increasing injection pressure due to momentum exchange with ambient gas is more vigorous for the spray higher injection pressure and led to rapid breakup to smaller droplet diameter. As far as the influence of the injection pressure is concerned. Good qualitative agreement is seen at low injection pressure. On the other hand, for high injection pressure there is difference between microscopic visualization method results and both PDA results and KH-RT model results due to resolution limits for small droplets in microscopic visualization techniques.

Conclusions

Exit flow velocity and droplet size diameter from DISI injector with various injection pressures were investigated by microscopic visualization using an ultra high-speed video camera, coupled with a long distance microscopic and a Barlow lens. The results led to conclusions as follows:

1. The exit flow velocity increases with increasing injection pressure. Microscopic visualization results agreed with NOZZLE FLOW MOEDEL results.
2. Two different measurement techniques, microscopic visualization method and PDA method, give qualitatively similar trends for droplet size distribution and the value of SMD as injection pressure and the injection time of the measurement region was changed.
3. As the first attempt to using numerical computation tool for DISI, microscopic visualization of average droplet sizes results due to variation of injection pressure show agreement with droplet sizes predicted by KH-RT model and average droplet sizes of PDA results in the low injection pressure.
4. The success of the microscopic visualization technique has demonstrated that the visualization technique is well suited for study spray behavior from multi-hole injector of DISI engine.

Acknowledgment

The authors would like to acknowledge Fatma Ahmed and Yuuichi Shibata, the students at Okayama University, for their helps in the experimental work.

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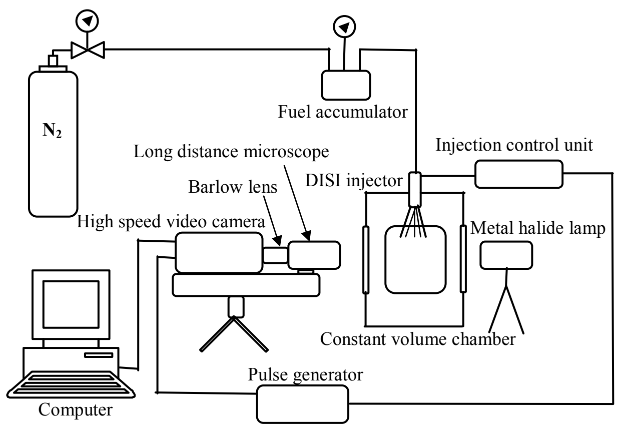


Figure 1. Schematic diagram of the experimental setup

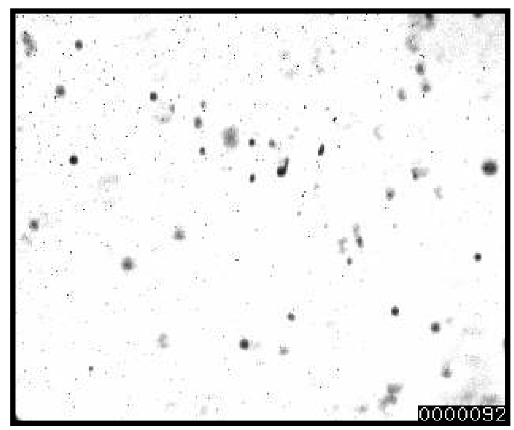


Figure 2. Unprocessed magnified image

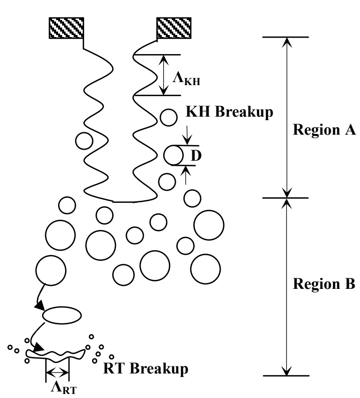


Figure 3. Schematic showing the concept of KH-RT breakup model

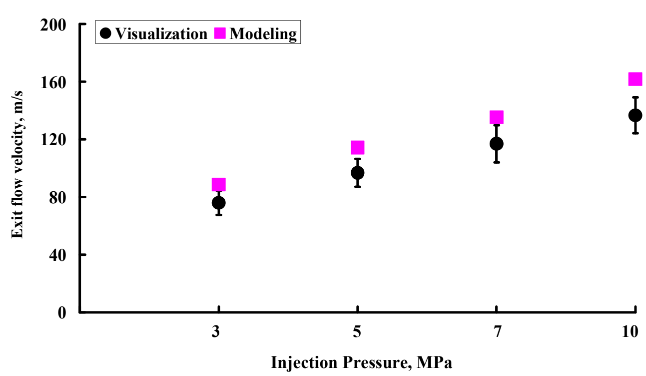
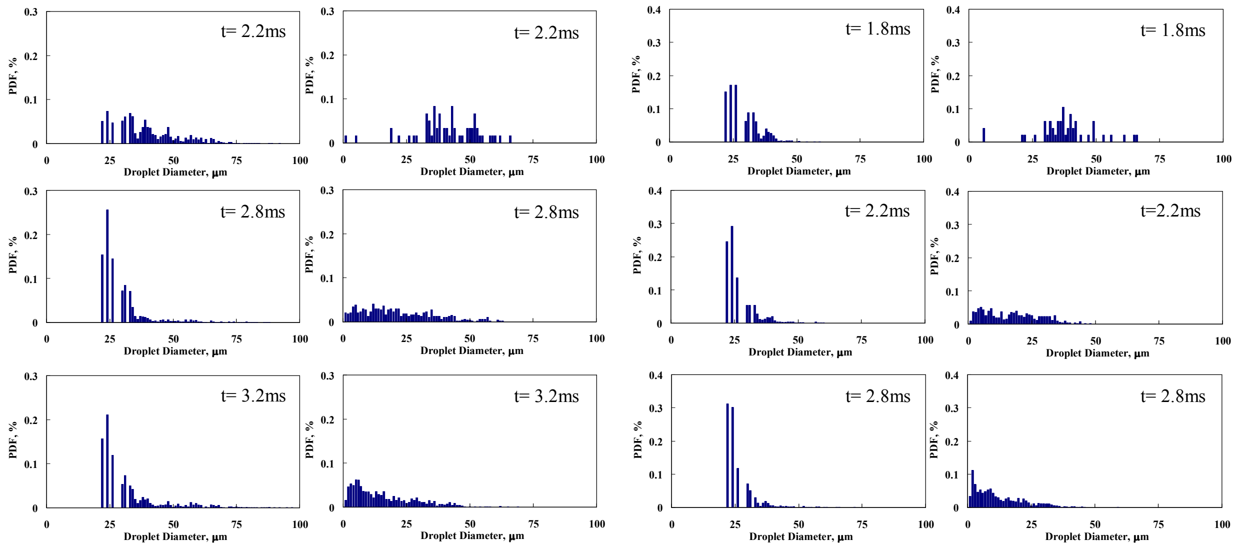


Figure 4. Influence of injection pressure on exit flow velocity



Visualization PDA Visualization PDA

(a) Injection Pressure 3MPa (b) Injection Pressure 5MPa

Figure 5. Droplet size distribution

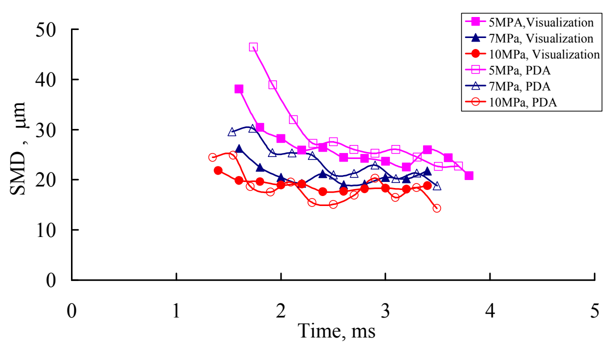


Figure 6. Effect of injection pressure and time on SMD of the spray from DISI

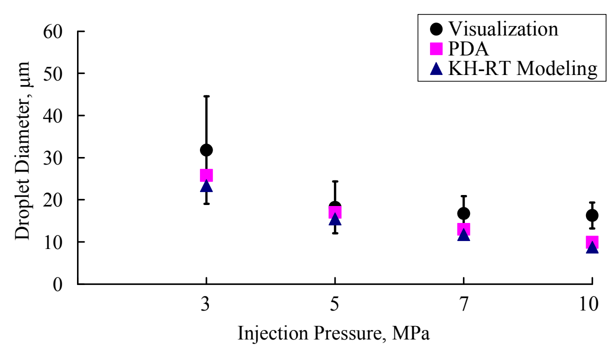


Figure 7. Comparison of average droplet diameter from visualization with PDA and KH-RT Modeling