Effects of Piston Shapes and Intake Flow on the Behavior of Fuel Mixtures in a GDI Engine

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The purpose of this study is to investigate the stratification of fuel vapor with different in-cylinder flow, piston cavity and injection timings in an optically accessible engine. Three different piston shapes that are F(Flat), B(Bowl) and R(Re-entrance) types were used. The images of liquid and vapor fuel were captured under the motoring condition using Laser Induced Exciplex Fluorescence technique. As a result, at early injection timing of 270° BTDC, liquid fuel was evaporated faster by tumble flow than swirl flow, where most of fuel vapor were transported by tumble flow to the lower region and both sides of cylinder for the F-type piston. At late injection timing of 90° BTDC, tumble flow appears to be moving the fuel vapor to the intake side of the cylinder, while swirl flow convects the fuel vapor to the exhaust side. The concentration of mixture in the center region was highest in the B-type piston, while fuel vapor was transported to the exhaust side by swirl flow in F and R-type pistons. At the injection timing of 60° BTDC, the R-type piston was better for stratification due to a relatively smaller bowl diameter than the others.

Key Words : GDI Engine, Stratification, LIEF, Piston Shape, Injection Timing, Swirl Flow, Tumble Flow

1. Introduction

Gasoline direct injection (GDI) engines continue to receive attention due to their potential for improved fuel efficiency and reduced emissions. In GDI engines, gasoline is injected directly into the engine cylinder, which eliminates the fueling delay inherently associated with port fuel injection engine and makes it possible to precisely control cycle-to-cycle fuel-air ratio. In addition, unthrottled stratified charge operation at part load significantly reduces pumping losses, increases volumetric efficiency and helps gasoline direct injection engines achieve fuel efficiencies (Zhao et al., 1997 ; Lee et al., 1999).

Understanding the combined effect of fuel intake flow and piston shape on stratification is an essential step in the development of GDI engines. So, more work should be done on the effects of intake flow, piston shapes, and injection timings in GDI engines under warm conditions (Kume et al., 1996 ; Iwamoto et al., 1997 ; Ohsuga et al., 1997 ; Kanda et al., 2000).

The fate of the liquid fuel injected in the operation of a GDI engine is one of the most important parameters in optimizing the behavior of direct-injected engine. The vaporization of the spray controls the stratification of the fuel mixture, and also ensures the quality of combustion.

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The behavior of fuel vapor has also been investigated by Wagner (1999) using LIEF technique.

The transient in-cylinder flow field that is present during the intake and compression strokes of a GDI engine is one of the key factors in determining the operational feasibility of the system. Since a moderately strong swirl prevents fuel diffusion in the radial direction, the fuel is conserved in the cavity or near the swirl-center. Thereafter, in the latter half of the compression stroke, a secondary flow generated by an interaction between the swirl and squish flows carries rich mixture inside the cavity toward the spark gap to attain the charge stratification (Moriyoshi et al., 1998 ; Kakuhou et al., 1999 ; Tabata et al., 2000).

In this work, visualization and measurement on the spray motion were performed to clarify the combined effects of in-cylinder air motion, injection timings and piston shapes employed by the modified GDI engine to prepare the stratified charge around the center of upper cylinder.

2. Experimental Apparatus

This study was conducted in a single-cylinder optical engine which was specially modified for gasoline direct injection operation and the application of laser based diagnostics. Optical access was enabled through a fused silica cylinder.

The high fuel pressures required for direct fuel injection were generated using a compressed nitrogen cylinder and a hydraulic accumulator in order to avoid pressure fluctuations in the fuel rail. The injector was a high-pressure swirl injector with 70° of cone angle.

A high-pressure direct injector operating at 5.1 MPa was installed at the center of the combustion chamber for direct injection in cylinder and injection duration was 2 ms and temperature of intake flow gas was 80°C The engine specifications are listed in Table 1.

Figure 1 shows a schematic of the experimental apparatus. Visualization region and configurations of piston shapes are shown in Fig. 2. The spray images were digitally recorded with an

Table 1 Engine specifications

Specification	Resource	
Engine type	4-stroke, 4-valves/cylinder, S.I. Engine	
Displacement (cc)	1998	
Bore × stroke (mm)	86 × 86	
Combustion chamber	Pentroof	
Compression ratio	F-type	10 : 1
	B-type	9 : 1
	R-type	9 : 1

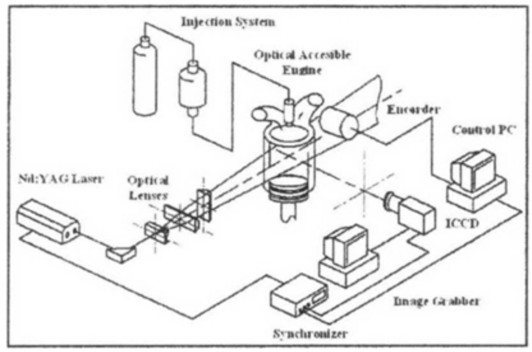


Fig. 1 Schematic diagram of experimental setup

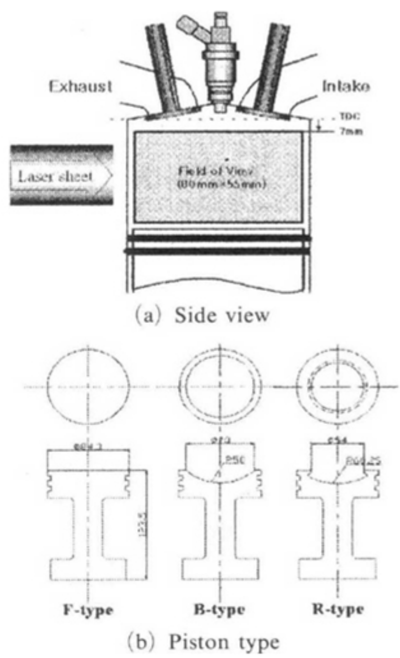


Fig. 2 Visualization region and configurations of piston shape

intensified-CCD camera that provided 640 by 480 pixel images at a resolution of 8bit and mounted perpendicular to the laser sheet. The camera system consists of a personal computer with an image grabber, a shutter controller, and a pulse generator.

The exciplex system of fluorobenzene and DEMA in a non-fluorescing base fuel of hexane was employed. The boiling points for each component were 358K, 338K, and 342K, respectively, and the solution composition was 2%/9%/89% by volume, respectively. The fourth harmonic of the Nd : YAG at 266 nm with duration of 7 ns and a laser power of 50 mJ/pulse was used to excite dopants from the fuel sprays. The laser beam was formed to a thin light sheet of 60 mm high and less than 400 um thick. The used filters were 300±25 nm for fuel vapor and 400±25 nm for liquid fuel. An additional WG280 sharp cut filter was used to eliminate the light at 266 nm.

A laser sheet passes through the mid-plane of the cylinder from the exhaust side to the intake side to allow visualization of the in-cylinder fuel distribution. Due to the pent-roof head geometry, however, the portion of the combustion chamber within the head is not accessible optically. Experimental conditions are shown in Table 2. The swirl motion is induced by closing one of the two inlet ports and the swirl intensity was increased by installing mask in the other inlet port. Swirl and tumble ratios were measured in a steady flow rig for valve lifts. A paddle wheel anemometer was used to quantify the charge motion speed.

The experiment was carried out under the no-firing condition with nitrogen gas to prevent quenching of fluorescence by oxygen. Engine performance data are acquired once the engine speed reaches 450 rpm.

Table 2 Experimental conditions

Swirl ratio	3.6
Injection pressure (MPa)	5.1
Injection duration (ms)	2
Engine speed (rpm)	450
Start of injection timings, SOI (BTDC)	270°, 180°, 90°, 80°, 70°, 60°, 50°

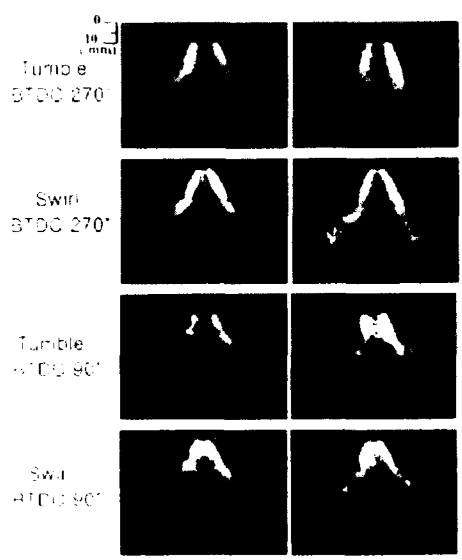
Four injection timings were set at 270°, 180°, 90° and 60° BTDC in F-type piston and 90°, 80°, 70° and 60° BTDC in B-type and R-type.

3. Results and Discussions

3.1 Effect of intake flow on the behavior of liquid fuel

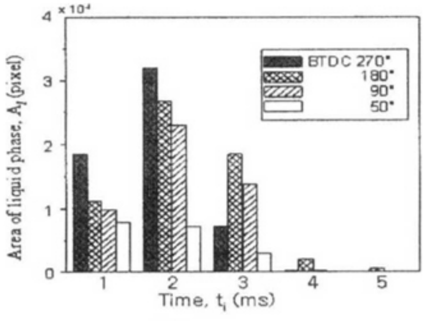
Figure 3 shows the spray fluorescence images of liquid fuel formation process in the case of F-type piston. Liquid fuel area was defined as the fluorescence area of liquid fuel induced by the laser sheet passing through the spray axis. In the case of tumble flow type, by intake flow which cross the spray axis, liquid fuel area was smaller than that of swirl flow. Spray penetration and width were larger at early injection than at late injection. Change in area occupied by liquid fuel with time after injection start is shown in Fig. 4. Liquid fuel was evaporated faster by tumble flow than by swirl flow.

Figure 5 shows the spray penetration and width in cylinder under operating condition. The later injection timing is, the smaller spray penetration and dispersion is. But spray penetration and

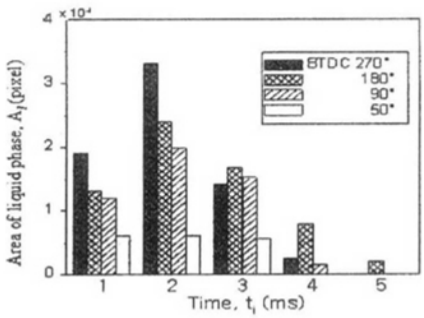


(a) t_i=1 ms (b) t_i=2 ms

Fig. 3 Spray fluorescence images of liquid fuel formation process

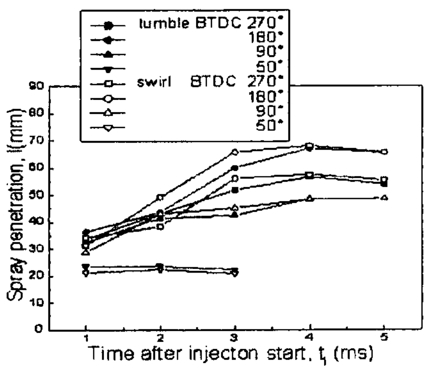


(a) Tumble

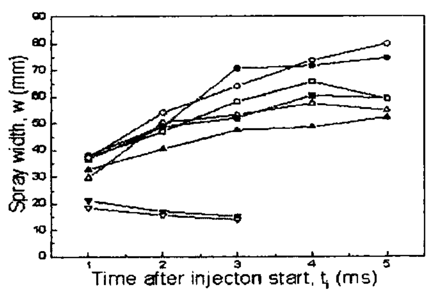


(b) Swirl

Fig. 4 Area occupied by liquid fuel



(a) Spray penetration



(b) Spray width

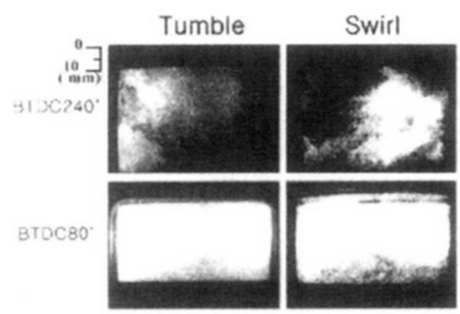
Fig. 5 Spray penetration and width with different air motion and injection timing

dispersion at injection timing of 270° BTDC were smaller than 180° BTDC. It is considered that evaporation of liquid fuel is influenced by intake flow.

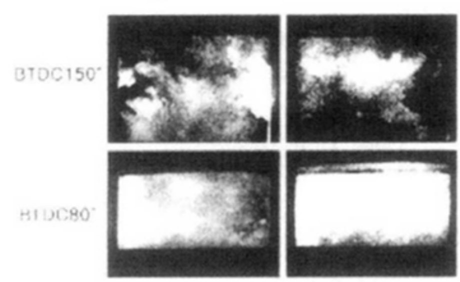
3.2 Effect of crank angle and intake flow on the behavior of fuel vapor

Figure 6 shows the distribution of fuel vapor in cylinder at early injection timing(270° and 180° BTDC). Tumble flow transported most of fuel vapor to the lower region and both sides of cylinder at early injection timing(270° and 180° BTDC). Thus, the distribution of fuel vapor did not become uniform up to the half of the compression stroke. Swirl flow confined fuel mixture into the swirl origin in upper region of the cylinder.

Figure 7 shows the distribution of fuel vapor in cylinder at late injection timing(90° and 50° BTDC). At late injection timing(90° BTDC), tumble flow transported fuel vapor to the intake side of cylinder, while swirl flow moved fuel vapor to the exhaust side. In the case of injection



(a) Injection at BTDC 270°

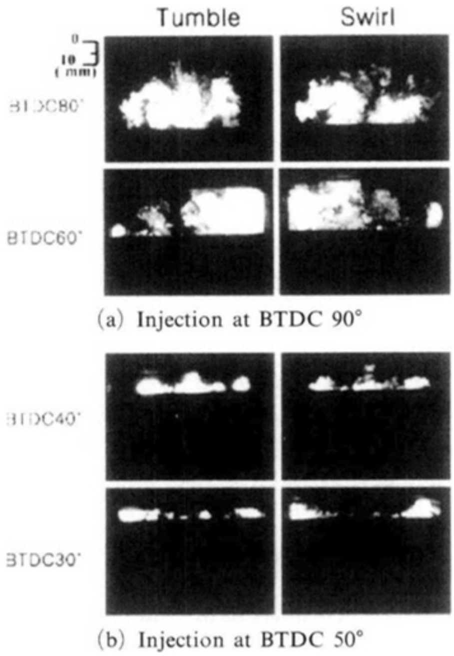


(b) Injection at BTDC 180°

Fig. 6 Spray fluorescence images according to crank angle at early injection timing of 50° BTDC, fuel spray impinged on piston top and spread to radial direction. It is considered that little air flow influences behavior of fuel vapor after the half of the compression stroke.

3.3 Effect of piston shapes and crank angle on the behavior of fuel vapor

Figures 8 and 9 show the spray fluorescence images and the fluorescence intensity ratio profiles for three piston types(F, B and R-type) according to crank angle at injection timing of 90° BTDC. In the case of F-type piston without swirl, tumble flow transported most of fuel vapor to intake side of cylinder according to crank angle, while with swirl flow to the exhaust side. In the case of B-type piston, most of fuel vapor remained inside the piston bowl. But parts of fuel vapor appeared above the center of piston bowl at 320°CA. In the case of R-type piston, most of fuel vapor remained widely above piston bowl and was moved to exhaust side by swirl flow.



(a) Injection at BTDC 90°

(b) Injection at BTDC 50°

Fig. 7 Spray fluorescence images according to crank angle at late injection

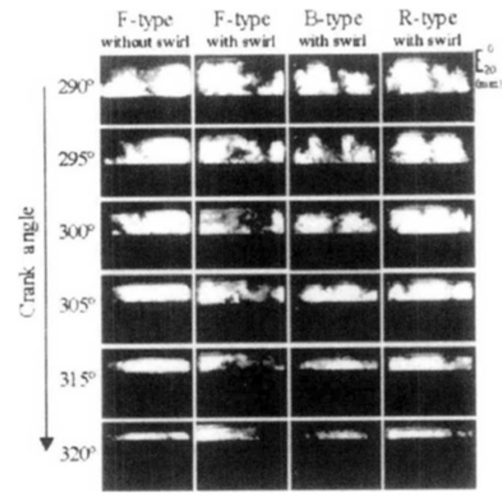


Fig. 8 Spray fluorescence images according to crank angle at injection timing of 90° BTDC

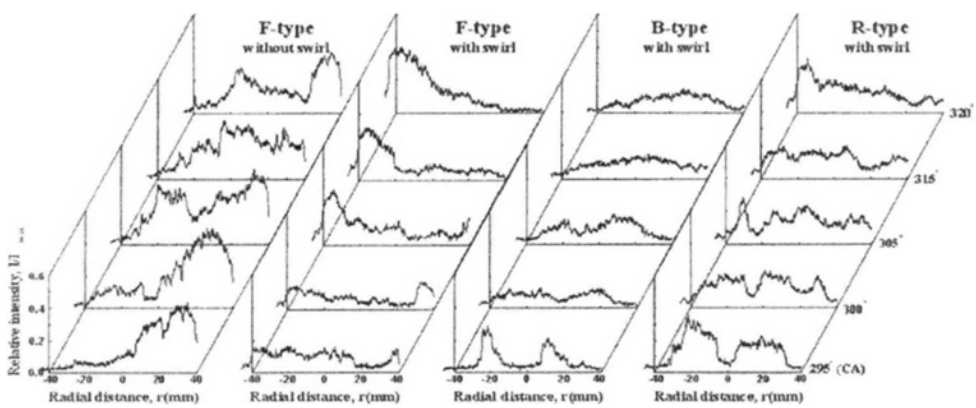


Fig. 9 Fluorescence intensity ratio profiles according to crank angle (z=15 mm, SOI : 90° BTDC)

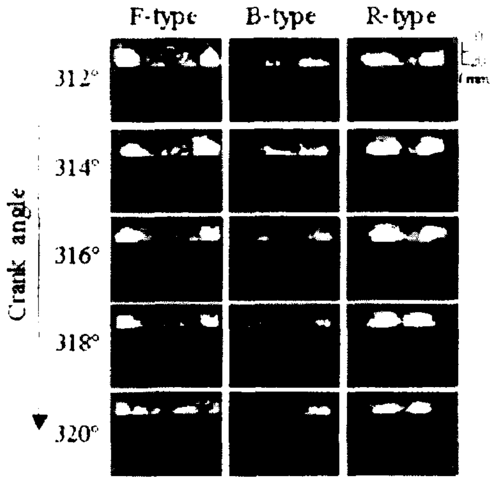


Fig. 10 Spray fluorescence images according to crank angle at injection timing of 60° BTDC

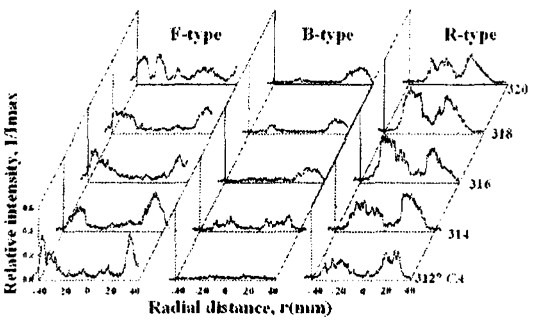


Fig. 11 Fluorescence intensity ratio profiles according to crank angle(z=15 mm, SOI : 60°)

Figures 10 and 11 show the spray fluorescence images and the fluorescence intensity ratio profiles for three types(F, B and R-type), respectively, according to crank angle at injection timing of 60° BTDC. In the case of F-type piston, fuel spray impinged on the top of the piston head and spread to radial direction. In the case of B-type piston, most of fuel vapor was transported to the piston bowl, and little appeared above the piston bowl. In the case of R-type piston, most of fuel vapor remained above the center of the piston bowl. It is considered that spray width is narrowed by high pressure in cylinder at the half of the compression stroke and the fuel vapor in the center of the piston bowl was moved to the upper side of in-cylinder by the squish motion.

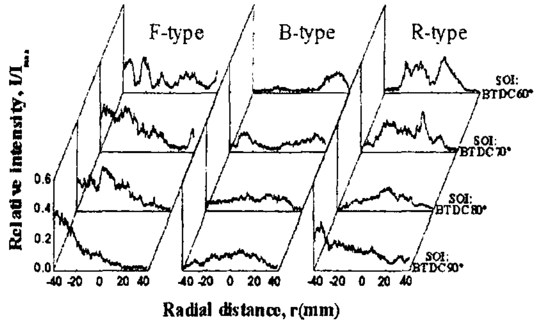


Fig. 12 Fluorescence intensity ratio profiles with different injection timings at crank angle, 320°BTDC (z=15 mm)

Figure 12 shows the fluorescence intensity ratio profiles with different injection timings at crank angle of 40° BTDC. In the case of F-type piston, most of fuel vapor concentrated at the exhaust side for the four injection timings.

In the case of B-type piston, fuel vapor appeared above the center of the piston bowl at early injection timing(90° BTDC), while rich fuel vapor appeared above the center of the piston bowl at late injection timing(80°, 70° and 60° BTDC) in the case of R-type piston.

7. Conclusions

The combined effect of injection timings, piston shapes and intake flow on stratification of fuel mixture has been investigated in GDI engine using LIEF technique. The main conclusions are summarized as follows :

(1) At early injection, liquid fuel was evaporated faster by tumble flow than swirl flow

(2) Tumble flow plays a role to transport the most of fuel vapor to the lower region and both sides of cylinder at early injection timings, while swirl flow shows the fuel mixture confined the swirl origin in upper region of the cylinder.

(3) At the injection timing of 90° BTDC, tumble flow plays a role to transport the fuel vapor to the intake side while swirl flow to move the fuel vapor to the exhaust side.

(4) At the injection timing of 60° BTDC, the R-type piston was better for stratification due to a relatively smaller bowl diameter than the others

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