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EXPERIMENTAL STUDY ON THE STRATIFIED COMBUSTION CHARACTERISTICS ACCORDING TO COMPRESSION RATIO AND INTAKE TEMPERATURE IN A DIG ENGINE

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ABSTRACT−In the direct injected gasoline engine, atomized spray is desired to achieve efficient mixture formation needed to good engine performance because the injection process leaves little time for the evaporation of fuels. Therefore, substantial understanding of global spray structure and quantitative characteristics of spray are decisive technology to optimize combustion system of a GDI engine. The combustion and emission characteristics of gasoline-fueled stratified-charge compression ignition (SCCI) engine according to intake temperature and compression ratio was examined. The fuel was injected directly to the cylinder under the high temperature condition resulting from heating the intake port. With this injection strategy, the SCCI combustion region was expanded dramatically without any increase in NOx emissions, which were seen in the case of compression stroke injection. Injection timing during the intake temperature was found to be an important parameter that affects the SCCI region width. The mixture stratification and the fuel reformation can be utilized to reduce the required intake temperature for suitable SCCI combustion under each set of engine speed and compression ratio conditions.

KEY WORDS : Stratified-charge combustion ignition (SCCI), GDI, Mixture distribution, Stratified combustion, ROHR (rate of heat release)

1. INTRODUCTION

In order to cope with intensified global emission standards such as the ULEV (ultra-low emission vehicle), CAFE (corporate average fuel economy) and the Kyoto Protocol, there are increasing demands in the automotive industry for vehicles with better fuel efficiency and lower emissions levels. In turn, there have been substantial efforts to develop low-pollution engine technologies that can satisfy such emission regulations. SCCI (stratified-charge compression ignition) combustion uses the new gasoline combustion concept of controlled auto ignition and creates a localized dense mixture based on stratified combustion to facilitate self-ignition. Such approach enables combustion of lean mixture stratification. Strictly speaking, SCCI combustion (Koji *et al.*, 2002; Toshio and Koichiro, 2001) is a system included in the HCCI (Homogeneous Charge Compression Ignition) combustion concept. The only difference is that HCCI creates a uniform mixture for re-ignition and uses fuel with a high cetane number for compression-ignition (Sato *et al.*, 2006; Lee and Ryu, 2004). On the contrary, the SCCI combustion method involves a stratified-mixture compression-ignition and it uses fuel with a relatively low cetane number such as gasoline and creates a localized dense mixture and compression-ignition. The intake temperature and the equivalence ratio adjustment are important factors in SCCI combustion (Aoyama and Hattori, 1996; Ishibashi and Masahiko, 1998; Jacques *et al.*, 2000; Lee and Ryu, 2004). In an effort to adjust combustion in a gasoline pre-mixture compression-ignition engine, there have been studies regarding self-ignition timing adjustments through internal EGR adjustment, VVT adjustment and intake temperature adjustment (Choi *et al.*, 2004; Tomonori *et al.*, 2003). As for implementing HCCI combustion using gasoline fuel, there have been studies to assess combustion characteristics by adjusting compression ratio variation, intake temperature and negative valve overlap (Tomonori *et al.*, 2003; Koji *et al.*, 2002).

This study attempted to achieve the auto-ignition temperature get higher by increasing the intake temperature and then analyzed the combustion and emission characteristics of SCCI engine system by varying injection timing, intake temperature and compression ratio.

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2. EXPERIMENTAL APPARATUS AND METHODOLOGY

2.1. Spray Visualization System and Spray Measuring System

The experimental arrangement for visualization of spray is shown schematically in Figure 1. This apparatus is composed of laser light source (Nd:YAG), CCD camera, cylindrical lens for sheet beam and data acquisition system for image data analysis. The timing of injection and image capture is controlled by the delay generator (DG-535, STANFORD RESERCH SYSTEMS, INC.). Frozen image of spray visualization was captured onto the image grabber from the CCD camera with 50 mm lens.

2.2. Experimental Apparatus of Engine

For this experiment, a new fuel supply system was attached to a commercial single-cylinder diesel engine to realize a stratified compression-ignition engine system. Tables 1 and 2 present the engine and injector characteristics and Figure 2 displays the schematic diagram of the direct injection type SCCI engine. To implement direct injection SCCI combustion, the mechanical nozzle of the cam-plunger was removed and a low-pressure common-rail type injector was attached at the center of the engine head to construct a system for controlling the injection timing and amount. An SIDI (spark-ignition direct injection) injector was used as the low-pressure common-rail injector for this study, and injection pressure was set at 5MPa, which is lower than a diesel engine, to reduce the fuel impingement caused by collision on the wall of the fuel injected during the initial stages of compression displacement. Since gasoline has a lower cetane number than diesel for combustion through auto-ignition, a temperature controller was installed before the intake port to bring the temperature up to the auto-ignition level.

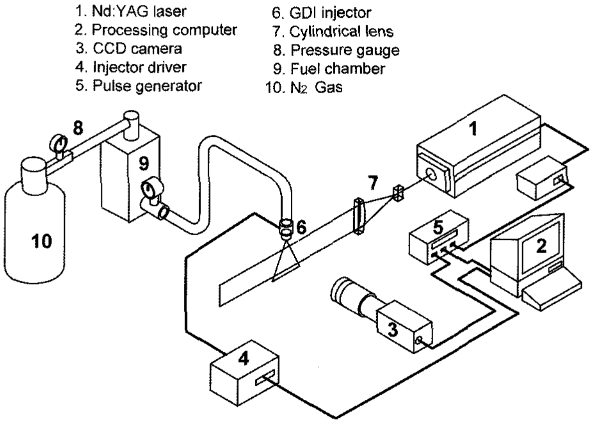


Figure 1. Schematic diagram of spray visualization system.

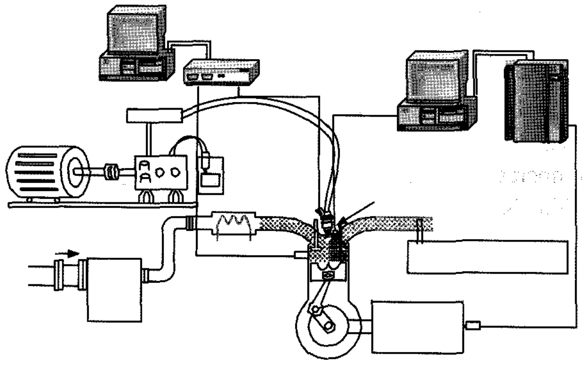


Figure 2. Schematic diagram of direct injection type SCCI engine system.

Table 1. Engine specifications.

Engine class	ND 130DI
Engine type	4Stroke, Single Cyl.
Bore×Stroke	95 mm×95 mm
Volume	673cc
CR	18
IVO/IVC	BTDC 20°/ABDC 50°
EVO/EVC	BBDC 44°/ATDC 44°
Max power (ps/rpm)	13/2400

Table 2. Specifications of fuel injection system.

Injection pressure	5MPa
Spray geometry	Hollow cone/Swirl type
Spray angle	60°

Table 3. Engine test conditions.

Engine speed	1200 rpm
Compression ratio	18, 16.2, 14.2
A/F	40, 50, 60, 70
Intake air temperature	353 K, 393 K, 433 K
Injection pressure	5 MPa
Injection timing	Late injection
Fuels	Gasoline

2.3. Experiment Conditions and Methods

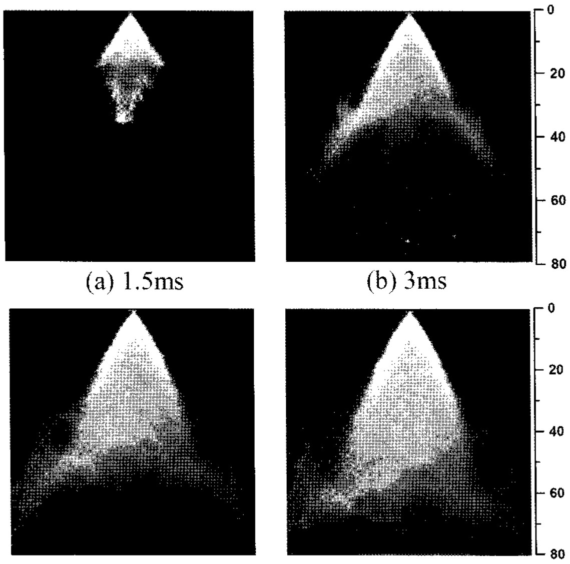
The experiment conditions for this study are outlined in Table 3. For the performance test, the coolant temperature was maintained at 80 ± 2°C, and engine performance and emission characteristics were analyzed according to variations in the intake temperature, compression ratio, injection timing and air-fuel ratio.

3. RESULTS AND DISCUSSIONS

The concept of combustion using a direct injection type engine was implemented by constructing the SCCI approach and using a fuel with a low cetane number to create a localized dense mixture and compression-ignition. The intake temperature was raised to the self-ignition level and the combustion and emission characteristics were analyzed while varying injection timing, intake temperature and compression ratio.

3.1. Evolution Processes of Global Spray

Figure 3 shows the developing processes of global spray with different elapsed time when fuel is injected at the pressure of 5 MPa with 7 ms of injection duration. As can be seen from the spray images, the spray shapes varied with the elapsed time after injection. At the early stage of injection, the spray is not developed into a swirling conical spray. Instead, a bulk of liquid consisting of large droplets and ligaments is emerging from the nozzle hole. But, the conical hollow-cone spray will be formed as the spray develops and slug of liquid lost its form by 3 msec after the start of injection. At the same time, a vortex became evident at the outer edges of the spray, which moved downstream as the spray develops. The 5 ms image showed droplets at the tip beginning to turn upwards and towards the outside, as they were entrained in the outside vortex, and this recirculation zone suppressed the spray cone angle. The vortex flow also tended to carry the small drops, and as a result, the vortex cloud was seen at the spray tip in the final spray image. This result has important implication on the air-fuel mixing process in direct-injection SI engines.



(a) 1.5ms (b) 3ms

(c) 5ms (d) 7ms

Figure 3. Spray structure of GDI injector.

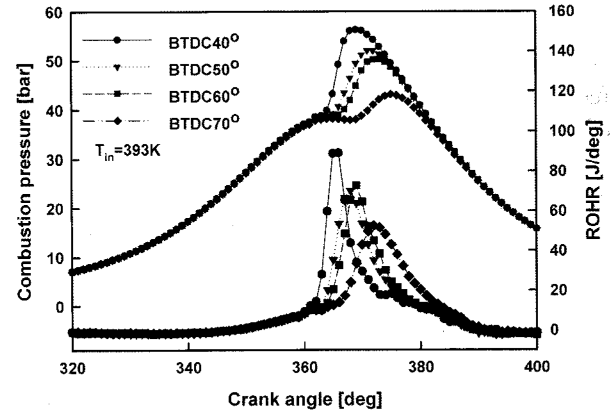


Figure 4. Effect of injection timing on the compression pressure and ROHR at compression ratio 16.2 and A/F 60.

3.2. Combustion Characteristics according to Variation in Operating Conditions

Figure 4 shows the combustion pressure and ROHR characteristics when the compression ratio and air-fuel ratio are 16.2 and 60, respectively. As injection timing is delayed, the combustion pressure increases and the ignition timing is pushed toward TDC. Considering the fact that stratified combustion drastically increases the combustion pressure, it can be concluded that the delay in injection timing is enabling the desired stratification of the mixture.

Figure 5 displays the combustion pressure and ROHR characteristics according to various intake temperatures under identical conditions as Figure 4. Although the intake temperature of 353 K and injection timing of 20° BTDC constitute conditions for stratification, the low temperature does not allow sufficient vaporization of the injected fuel, yielding poor combustion characteristics.

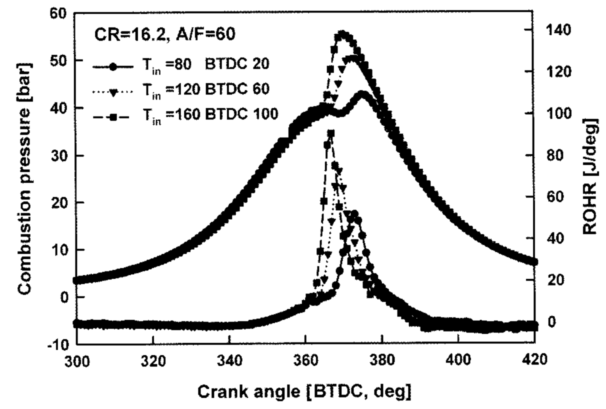
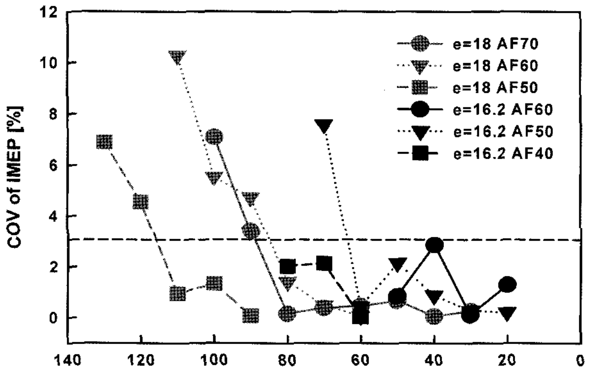


Figure 5. Effect of intake temperature on the compression pressure and ROHR at compression ratios of 16.2 and A/F 60.

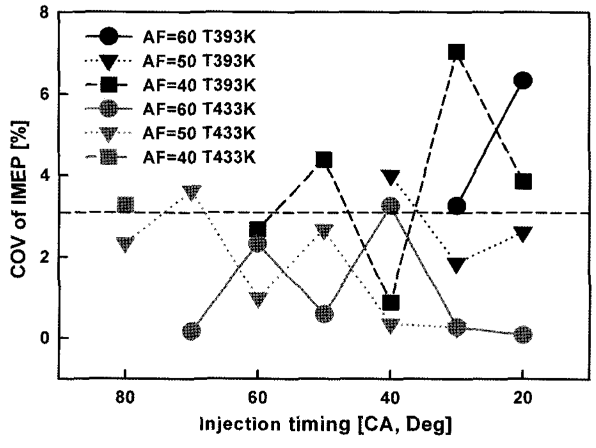
On the other hand, increasing the intake temperature creates conditions for sufficient vaporization of the injected fuel, which allows active combustion. The injection timing advances also indicates active stratified combustion.

3.3. Combustion Stability

Figure 6 indicates combustion stability according to various compression ratios, injection timings and intake temperatures. Figure 6(a) indicates combustion stability according to various air-fuel ratios at the intake temperature of 353 K. It can be noted that as injection timing is advanced, combustion stability decreases. This is thought to be caused by the fact that as injection timing is advanced, rather than the injected fuel remaining within the combustion chamber, there is an increasing amount of mixture on the cylinder wall and outside the combustion chamber. As injection timing is delayed toward the TDC, it becomes easier for the fuel to stratify at the center of the combustion chamber and it increases combustion stability. It was also shown that the lower the compression ratio, the better the combustion stability. When the air-fuel ratio becomes dense, the area of stable combustion is advanced according to the effects of injection timing. Figure 6(b) displays combustion stability according to the intake temperature with the compression ratio at 14.2. The low compression ratio decreases the temperature in the combustion chamber, increasing the probability of ignition misfire. It was confirmed that combustion was unstable at 393 K compared to 433 K. When the intake air was set at 433 K, it expedited fuel evaporation, improving combustion performance and displaying somewhat stable combustion characteristics.



(a) In the case where intake temperature Ta=353K



(b) In the case where compression ratio=14.2

Figure 6. Combustion stability according to effect of compression ratio and injection timing.

3.4. Stratification Characteristics According to IMEP and Fuel Consumption Rate

Figure 7 shows the fuel stratification characteristics

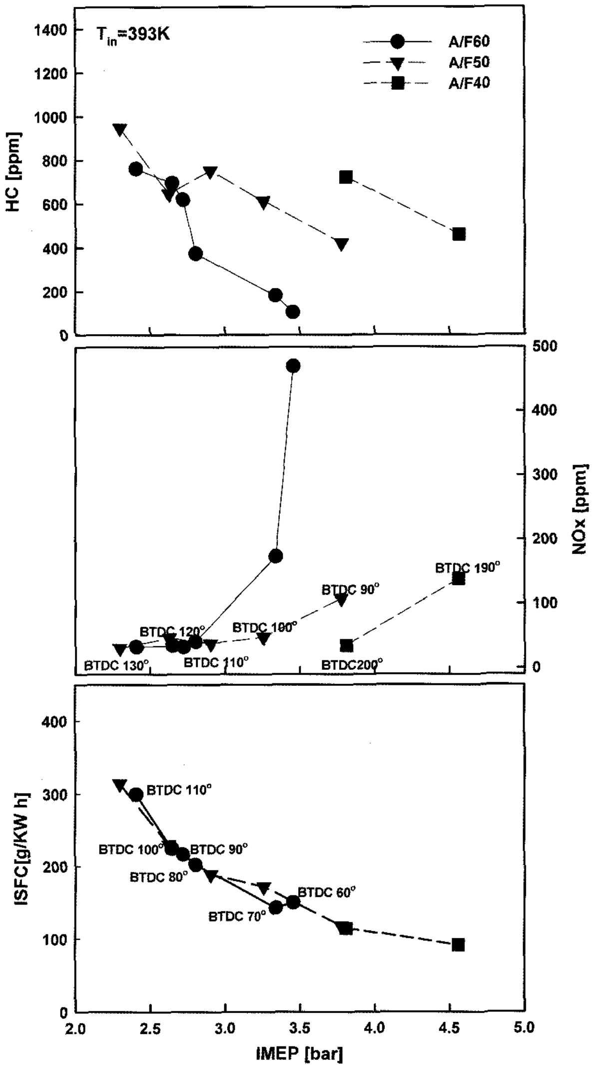
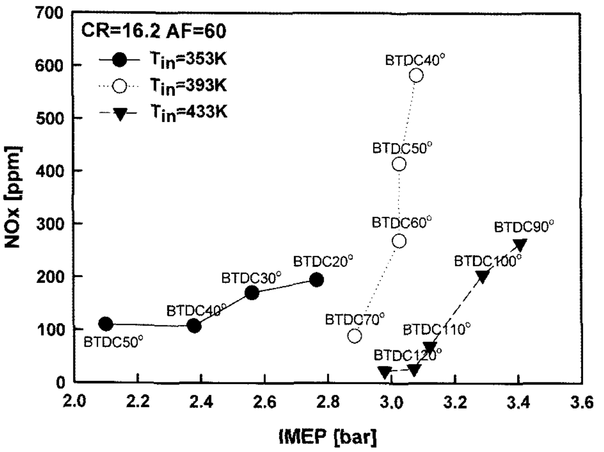
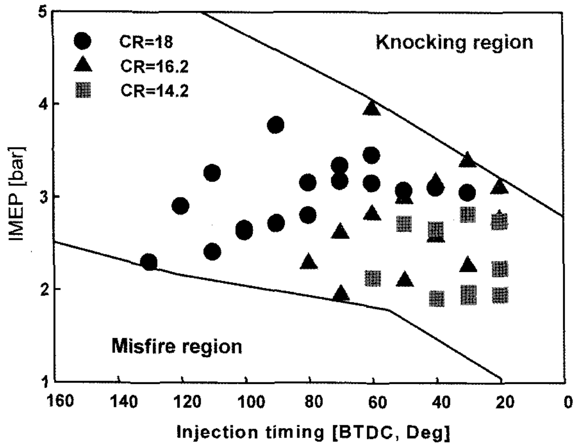


Figure 7. Effect of stratified mixture formation on combustion and emission characteristics.



(a) NOx vs. IMEP



(b) IMEP vs. injection timing

Figure 8. Effect of mixture stratification on NOx and IMEP.

according to IMEP and fuel consumption rate with the compression rate set at 18 and various air-fuel ratios. As injection timing is delayed regardless of variation in the air-fuel ratio, it was determined that the fuel consumption rate decreased. Noting the fact that the amount of NOx emission drastically increased, it was inferred that there was locally stratified mixture. Moreover as the emission of a substantial amount of HC increase, the injection timing is advanced. This result can be traced back to the fact that rather than the injected fuel creating a localized stratification, it is forming a wide and thin mixture around the piston, increasing the possibility of ignition misfire.

Figure 8 shows the stratified combustion characteristics according the IMEP and variation in the intake temperature. As injection timing is advanced, IMEP and NOx tend to increase. This is thought to be caused by the fact that the injected fuel is creating a dense mixture around the piston ball area, rapidly enhancing combustion. Furthermore, when the temperature is low (353 K), it cannot be raised to the self-ignition level, and a low level of NOx is emitted. Therefore, it can be concluded that stratified combustion is attainable by varying the intake temperature and adjusting injection timing under a designated compression ratio.

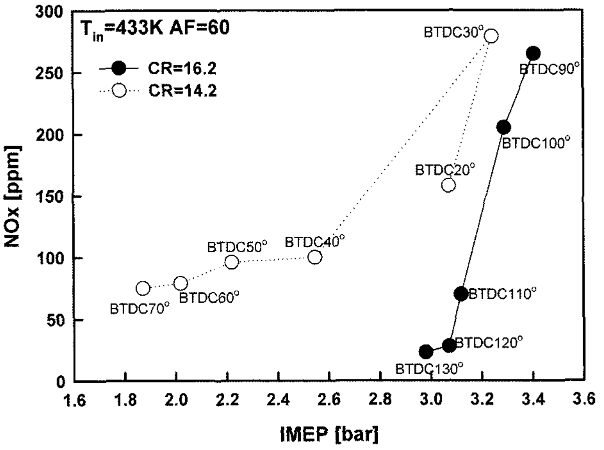


Figure 9. Effect of mixture stratification on NOx and IMEP (Tin = 433 K).

Figure 9 indicates the stratified combustion characteristics according to IMEP and variation in the compression ratio. The ambient temperature and pressure vary according to injection timing, which also varies with the compression ratio. It was found that as the compression ratio increased, injection timing advanced and combustion became active affected by the ambient temperature and pressure. Therefore, the increasing compression ratio allowed injection timing to advance and the IMEP value to increase.

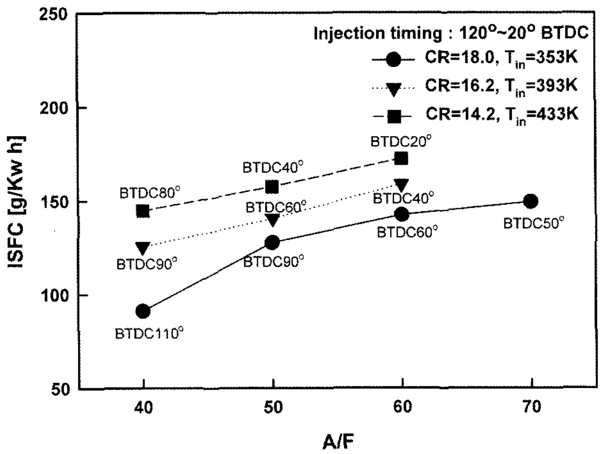


Figure 10. Operation range by mixture stratified mixture formation according to compression ratio and intake temperature.

3.5. Operation Range Characteristics of Stratified Combustion

Figure 10 shows the operation range characteristics according to the compression ratio and intake temperature acquired from results in Figure 6 and 7. Kaneko *et al.* (2001) claimed that the operation range where a uniform mixture can be created is around AF 35–40. The results of this study revealed that if the stratified mixture is formed, the air-fuel ratio yields operating characteristics in a wider range compared to a uniform mixture. Even at a thinner air-fuel ratio compared to the operation range that forms a uniform mixture, it was found that combustion became active when a stratified mixture was generated. As for the operation range according to variation in the intake temperature, although the fuel consumption rate is disadvantageous compared to cases with high compression ratios, stratified combustion characteristics are well displayed over a wide operation range.

4. CONCLUSIONS

(1) The combustion characteristics according to variation in injection timing revealed that as injection timing is advanced, ignition timing is delayed and combustion pressure is decreased. With a decreasing compression ratio, injection timing is delayed, and ignition timing is also delayed as the intake temperature increases.

(2) Combustion and emission characteristics according to variation in the compression ratio revealed that as the compression ratio increased, injection timing is delayed and the IMEP value increased. A dense air-fuel ratio also increased the IMEP value and decreased the HC level while increasing the NOx level.

(3) In cases where a stratified mixture was formed according to variations in the intake temperature, compression ratio and injection timing, the air-fuel ratio (AF40–70) displays stratified combustion characteristics in a wider operation range compared to that of a uniform mixture.

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