Effect of Fuel Injector-type Spark Plug on Combustion Characteristics

J.K. Yeom† and S.S. Chung*

Key Words: Stratified charge, Ultra lean burn, Injector-type spark plug, Constant volume chamber, Initial ignition flame, Lean combustible limit

Abstract

This study proposes a new stratified charge system for low emission and ultra lean burn. In order to examine combustion characteristics of the new system, sparkplug with a hole at positive pole and a common CNG injector for injecting fuel were used in this study as injector-type spark plug. The new stratified charge system injects fuel of extremely small quantities and ignites mixture around sparkplug gap. Also, the system was fitted in a visualized constant volume chamber. Then, for analysis of the combustion characteristics, we examined combustion pressure, lean inflammable limit, and visualized combustion flame according to equivalence ratio by comparison with homogeneous charge (HC) method and the new stratified charge (SC) method. As results of this study, in the case of using this system, the propagation speed of initial flame was increased and total combustion period was reduced in the ultra lean burn in the same equivalence ratio. These phenomena occurred clearly under the conditions of lean equivalence ratio. Furthermore, the lean inflammable limit of mixture was extended by using the injector-type spark plug.

Nomenclatures

V_m	: volume of methanol	[cc]
ϕ	: equivalence ratio	[-]
P_T	: the final pressure	[MPa]
V_c	: volume of chamber	[m^3]
ρ	: density of methanol at atmospheric temperature	[kg/m^3]
T_i	: the initial temperature	[K]
R_m	: gas constant of methanol	[kJ/kg·K]

(2009년 11월 5일 접수 ~ 2009년 12월 16일 심사완료)

†Division of Mechanical Engineering, Dong-A University, Busan 604-714, Korea

*Division of Mechanical Engineering, Dong-A University, Busan 604-714, Korea

E-mail : laser355@donga.ac.kr

TEL : (051)200-7640 FAX : (051)200-7656

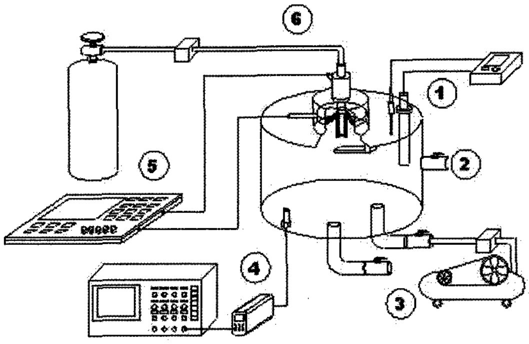
1. Introduction

In order to develop the green vehicle, many studies have been conducted for improvement of the injection system, in-cylinder flows, ignition system, and so on. In a spark ignition engine, however, a lean mixture is supplied to reduce emission such as NOx, CO, HC, and so on(1-5). The lean-burn engine and the GDI (Gasoline Direct Injection) engine belong to the engine operated under the fuel lean condition. In the GDI engine, injection timing is advanced and a method to form stratified charge near the spark plug is adapted toburn successfully in a light load. Although some methods such as an improvement of the in-cylinder flow are proposed, stratified charge needs an enhanced method to burn lean mixture in an engine with a compression ratio of about 10. For example, it is necessary to promote early flame growth by supplying rich mixture to a spark plug area. Moriyoshi et al. (1996) reported that combustion performance was improved by reduced combustion duration and ignition delay in the case of stratified charge(6-8). However, in the combustion of the lean mixture, the velocity of flame propagation and combustion pressure became lower in proportion to the lean mixture degree(9). Then stratified combustion was introduced in order to solve such problems. The stratified combustion enhanced ignitability, and formed reliable flame kernel by formation of pertinent mixture near spark plug(10). Although the stratified combustion could improve combustion efficiency with lean mixture, also, its stratified charge by in-cylinder flow would not regularly form a combustible mixture near spark plug. To form the regular combustible mixture near spark plug for stratified combustion, fuel injector-type spark plug is proposed. To burn lean mixture stably by forming strong flame kernel in early combustion period, small quantity of gas fuel is injected into spark plug gap. The influence of the ground electrode shape on combustion is examined by the changing the shapes (typical flat type, triangle type, hemisphere and hole types) of impinging the fuel against the electrode.

2. Experimental apparatus and procedure

2.1 Experimental apparatus

Figure 1 is a schematic diagram of whole experimental apparatus. A cylindrical shape constant volume chamber was used and its volume was 241 cc. Two quartz windows were installed on both sides of the chamber. Combustion process was photographed by a high-speed digital camera (maximum framing rate: 10000 FPS). A K-type thermocouple of 0.1 mmin diameter was used for measuring the internal temperature of the chamber. The internal temperature was maintained by several cartridge heaters inserted in the chamber wall. An adapter was set up for forming a mixture on the side of the chamber. Air for the mixture formation passes two filters and is restored in a surge tank. The air was provided with constant pressure by a regulator and a valve.



① Heater control part
② Fuel injection hole
③ Intake and exhaust port
④ Pressure sensor
⑤ Injection and ignition control part
⑥ Injector-spark plug system

Fig. 1 Schematic diagram of experimental apparatus.

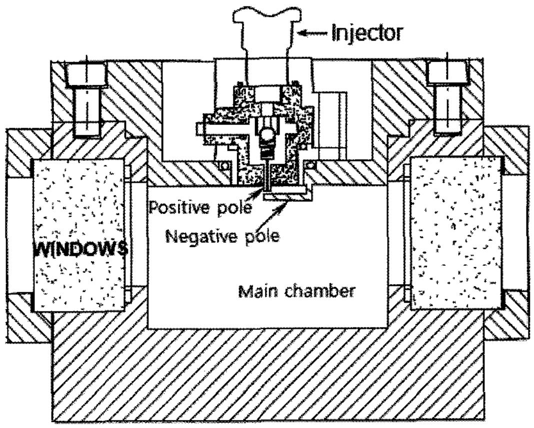


Fig. 2 Schematic diagram of the constant volume combustor.

Com-bustion pressure in the chamber was measured by a piezo-type transducer (Kistler Co, 6051B) that was installed in the chamber and recorded by an oscilloscope through an amplifier. 12 bit A/D and Micom (PIC16C74) which had 8 kB EEPROM were used to control simultaneously the ignition timing of an injector-type spark plug and the formation of stratified charge. CDI (Condenser Discharge Ignition system) was used as an ignition device; the first output voltage was 250 kV, and the second output voltage was 9000 kV.

Figure 2 shows a schematic diagram of the con-

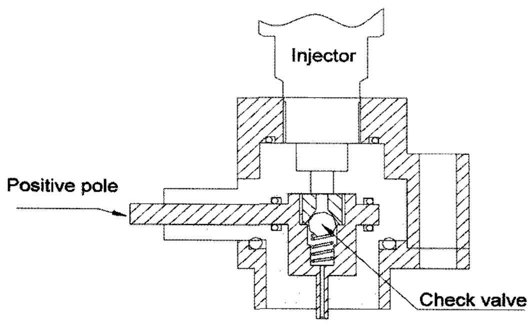


Fig. 3 Schematic diagram of the injector-type spark plug.

stant volume chamber. There is the constant volume chamber with aluminum alloy for corrosion resistance and manufacture. Also, in order to take image, the chamber consists of two quartz glass windows which were installed opposite to each other. The main chamber volume of the chamber is 241cc.

Figure 3 shows a schematic diagram of injector-type spark plug which was used in this experiment. The plug consists of an injector for CNG, housing that covers the injector, and a center electrode to provide a source of electricity. In order to form stratified cha-rge, a hollow cylinder of 0.7 mm in diameter was installed in the center electrode. A check valve was set up in the hollow cylinder to block up the leak-age of explosion pressure and to protect the inject-or. As test fuels, methanol (CH_3OH) which could be vaporized easily in set temperature of the chamber was used to make a premixture in the main chamber, and methane (CH_4) was injected used from the injector-type spark plug for stratified charge.

2.2 Experimental procedure

Experimental conditions of initial pressure, initial temperature, equivalence ratio, and ignition timing are summarized in Table 1. After injecting fuel of equivalence ratio set by a micro liter syringe through an adapter for fuel supply, a combustion experiment was performed with homogeneous mixture by supplying air of set-up pressure and temperature. Under the atmospheric pressure, methanol quantity (V_m)

Table 1. Experimental conditions

Parameter		Conditions
Initial pressure	[MPa]	0.3
Initial temperature	[K]	373
Equivalence ratio	[ϕ]	0.5~1.2
Injection duration	[ms]	7~10
Ignition timing	[ms]	0~35

injected into the chamber is expressed as follows in volume with an equivalence ratio(11).

$$V_m = \frac{12.26\phi P_T V_c}{\rho_{ma} R_m T_i}$$

In a case of using an injector-type spark plug, methane quantity for the formation of a flame kerne lin early combustion was 2.4 mg per one test. It is about 2.6% high in mass ratio as comparing with methanol for premixture. When methane was only injected to the chamber, the equivalence ratio of the mixture in the chamber became 0.06. Therefore, the injected methane from the injector-type spark plug could not form homogeneous mixture in a chamber and was located in a local area. The equivalence ratio of the mixture of methanol and air was defined as a whole equivalence ratio by disregarding the quantity of methane for the total premixture.

Figure 4 shows the operating sequence of the injector-type spark plug. Methanol is injected for 10 ms and ignited after 20 ms from reference signal.

Figure 5 shows shapes of ground electrodes used in this study. The flat type is a typical ground electr-

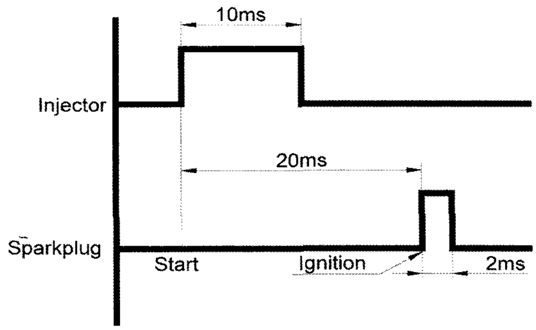


Fig. 4 Time chart for electronic control of the injector and spark plug.

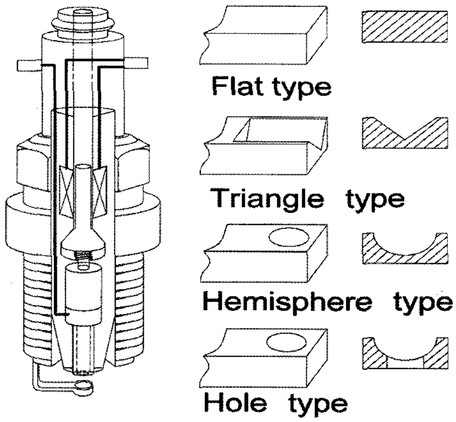


Fig. 5 Shapes of the ground electrode of the test spark plug.

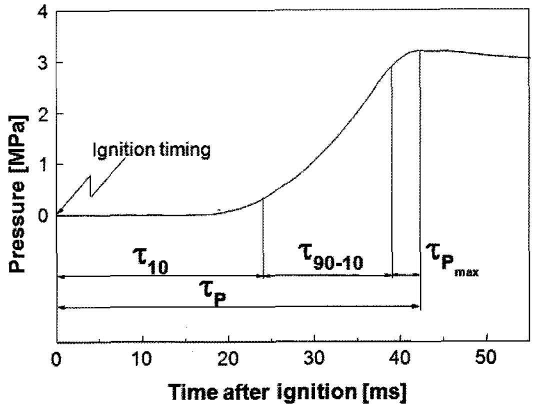


Fig. 6 Diagram for division of combustion periods with time in a constant volume.

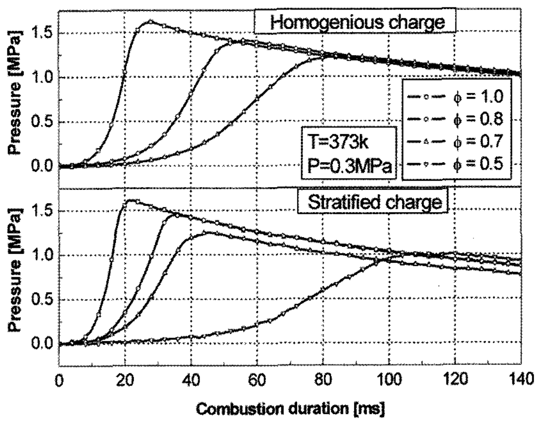


Fig. 7 Comparison of combustion pressure between the HC and the SC methods in the flat-type electrode.

rode of spark plug, and differs from those of the triangle type, hemisphere type and hole type. In lean-mixture combustion like this study, the ground electrodes of the three types were selected because of the effect expected from turbulent flame flow caused by impinging on the ground electrode. The size of the electrode is the same. Also, it is modified for a side of ground electrode. Each groove is located at the central axial of center electrode so that injected fuel would be impinged directly into the ground electrode.

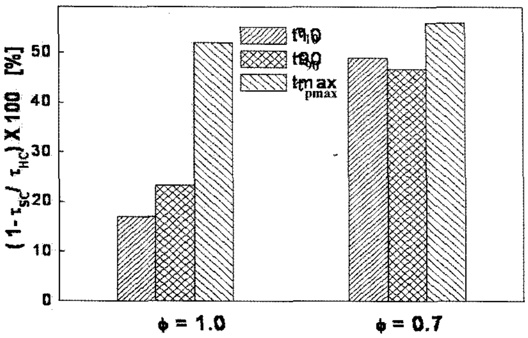
3. Results and discussion

3.1 Combustion characteristics analysis by using constant volume chamber

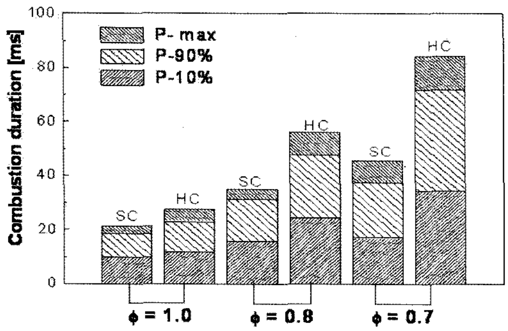
Figure 6 shows combustion pressure as a function of time. The elapsed time until 10% of maximum pressure after ignition is defined as the early combustion period (τ_{10}), the elapsed time from 10% to 90% is defined as the main combustion period ($\tau_{90\text{-}10}$), and the elapsed time from 90% to maximum pressure is defined as the late combustion period (τ_{Pmax}). The τ_P is defined as the whole combustion period.

Figure 7 shows a pressure-history plot for comparison between **HC** (**H**omogeneous **C**harge) and **SC** (**S**tratified **C**harge) method using the flat-type ground electrode. Under the equivalence ratio ϕ=1, combustion velocity of the SC method is faster than that of the HC method, about 5.6 ms in arriving to the maximum pressure point, but it is not significant. For ϕ=0.7, however, the τ_{Pmax} was shortened to 40.2 ms. From the result of the SC method, the lean combustible limit was extended from 0.7 to 0.5 and τ_{Pmax} was 105.2 ms. Therefore, the influence of the SC method is more significant in lean mixtures than in rich mixtures.

Figure 8-(a) shows accumulated time of each comb- ustion period. The τ_P of the SC method was short-er than that of the HC method and the degree of the shortenings is in proportional to lean degree of mixture. Fig. 8-(b) shows the decrease ratio of time classified by each combustion period. In the case of ϕ=1, the τ_{10} and τ_{Pmax} in the SC method



(a) Temporal change in combustion period in each equivalence ratio



(b) Decrease rate of combustion period

Fig. 8 Combustion period and decrease rate in each equivalence ratio.

were shortened by 17% and 52%, respectively. In the case of ϕ=0.7 that is the fuel-lean combustible limit, the τ_{10} and the $\tau_{90\text{-}10}$ decreased by 47% and 56%, respectively. Therefore, the shortening of the early and the main combustion periods are obtained with the decrease of the equivalence ratio.

Figure 9 shows a change of combustion pressure classified by the equivalence ratio in each shape of the ground electrode. In the case of ϕ=1, whole combustion period is similar. The whole combustion periods of the triangle-type and the hemisphere-type ground electrodes were shorter about 5 ms than that of the F and the ground electrode for ϕ=0.7, and the whole combustion periods of the F and the and the hemisphere-type ground electrodes were faster about 13 ms for ϕ=0.5. The holed the ground electrode in rich mixtures shows similar pressure history whmbuit is custioed with others. The early combustion period is proportional to lean

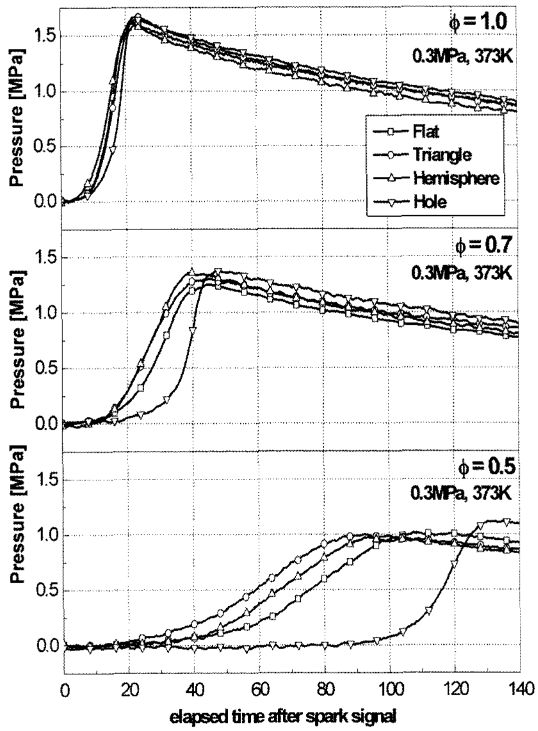


Fig. 9 Comparison of combustion pressure with time in each equivalence ratio.

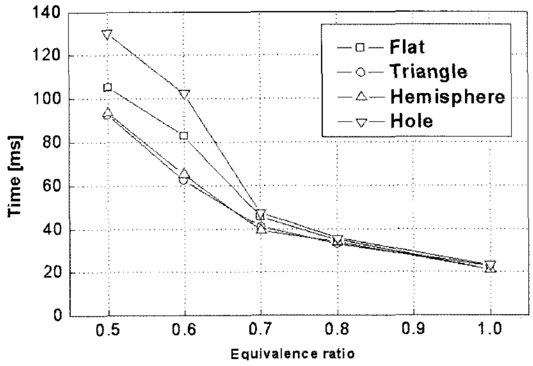


Fig. 10 Effect of ground electrodes on whole combustion period according to equivalence ratio.

degree, and the main combustion period decreases whmbuit is custioed with that of other ground electrodes. Therefore, the effect of geometric change of ground electrode on the combustion characteristics is larger in lean mixture than in rich mixture. Also, such effect can be confirmed that there is comparison of whole combustion period in Fig. 10.

Figure 10 shows a graph of whole combustion period according to the shape of the ground electrode in each equivalence ratio. As shown in Fig. 10, in the case of spark plug with the negative pole of the hemisphere or triangle type, the combustion duration decreases at the lean-mixture range, however, in the case of spark plug with the negative pole of the hole type, the combustion duration increases. Then it can be speculated that turbulent fuel injection due to impingement on the ground electrode redn erode bustion duration.

3.2 Combustion characteristics analysis by using visualization technique of flame luminosity

In order to grasp combustion characteristics of the injector-type spark plug, flame luminosity for visualization was photographed. The visualization area and location of the central and the ground electrodes are shown in Fig. 11.

Figure 12 shows photographs to visualize early flame formation with injecting only methane into the chamber using the injector-type spark plug. Because the flame intensity is very weak early in combustion period, the flame image could be captured after 18 ms of time from ignition start. Then the time in Fig. 12 is one after spark ignition. As shown in the figure, flame shape is irregular due to turbulence of mixture by the fuel injection, and the flame front grows in one side because of quenching of flame by impingement with a ground electrode.

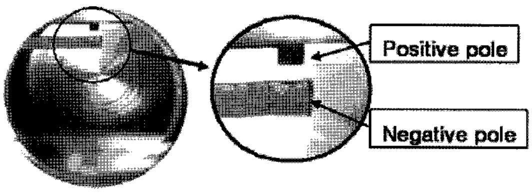


Fig. 11 Schematic of a injector-type spark plug.

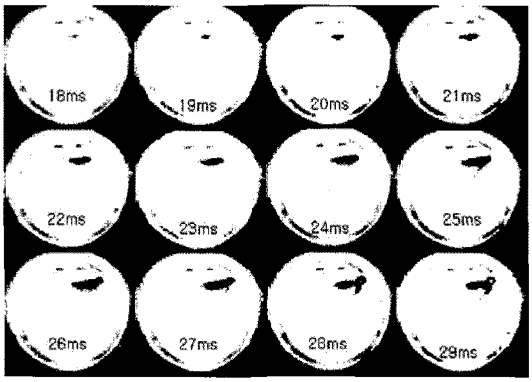
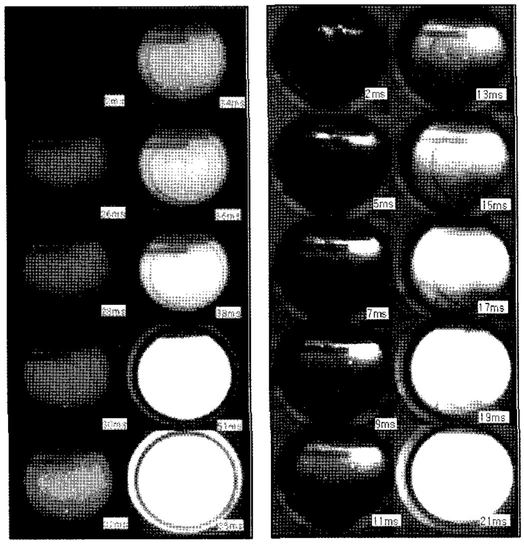


Fig. 12 Photographs to visualize early flame formation by the injector-type spark plug.



(a)**HC**(Homogeneous Charge) (b)**SC**(Stratified Charge)

Fig. 13 Photographs of flame luminosity using the HC and the SC method in the equivalence ratio ϕ=0.7.

Figure 13 shows the photographs of flame which used the HC and the SC methods in the equivalence ratio ϕ=0.7. The time in Fig. 13 is one after spark ignition. In the HC method of Fig. 13-(a), the flame front propagates with having a fixed shape and elapsing time. However, the flame front which has an irregular shape propagates within the chamber in the SC method of Fig. 13-(b). From the above result, it is considered that methane injection technique using injector-type spark plug promotes flame propagation and effect of the turbulent flow.

4. Conclusions

In this study, the combustion of stratified charge which uses the injector-type spark plug was examined in the constant volume chamber, and the results are summarized in the followings:

1. In the case of using this system, the propagation speed of initial flame is increased and total combustion period is reduced in the lean burn in the same equivalence ratio. These phenomena occurred clearly under the conditions of lean equivalence ratio. Also lean inflammable limit is extended from 0.7 to 0.5 in the equivalence ratio in this study.

2. With decreasing equivalence ratio, especially, the early combustion period and the main combustion period shorten in the SC (Stratified Charge) ignition method.

3. Effect of geometric change of ground electrode on the combustion characteristics is larger in lean mixture than in rich mixture in ranged from equivalence ratio ϕ=0.5 to 1.0.

4. In the case of spark plug with the negative pole of the hemisphere or triangle type, the combustion duration decreases at the lean-mixture range, however, in the case of spark plug with the negative pole of the hole type, the combustion duration increases.

Acknowledgement

This study was supported by research funds from Dong-A University.

References

(1) R. L. Evans, "Combustion chamber design for a lean-burn SI engine", SAE paper No. 921545, 1992.

(2) H. Okano, "Development of lean burn engines in Toyota, Symposium of Lean Burn Gasoline Engine", JSME, 16, 1992, pp. 20~25.

(3) S. Iguchi, "Combustion and current status of lean burn engine, Symposium of Lean Burn Gasoline Engine", JSME, 16, 1992, pp. 1~16.

(4) S. Iguchi, "Development of lean burn engine system in Japan", The 6th Kia Motors International Symposium, Korea, 1, 1993, pp. 25~34.

(5) B. S. Kim, C. H. Kwon and J. I. Ryu, "Combustion characteristics of stratified mixture in a constant volume combustion chamber with sub-chamber", KSAE paper No. 953773, 1995, pp. 122~134.

(6) Y. Moriyoshi, H. Morikawa, T. Kamimoto and T. Hayashi, "Combustion of very lean enhancement premixture part in stratified charge conditions", SAE Paper No. 962087, 1996.

(7) Y. Iwamptp, K. Noma, T. Yamauchi and H. Ando, "Development of gasoline direct injection engine", SAE Paper No. 970541, 1997.

(8) M. Kono, Y. Wada and Y. Ujie, "Promoting effect of liquid explosion aided by high energyid explon inhibition and combustion of mixture in a close vessel", JSAE Review, Vol. 9, No. 2, 1998, pp. 10~14.

(9) L. Lewis and G. Von Elbe, "Combustion, flames and explosions in gases", 2nd Edit, Academic press, New York, 1961, pp. 199~400.

(10) M. S. Hong and K. S. Kim, "A study on direct injection stratified charge combustion with spark ignition in constant volume bomb", trans. KSME, Vol. 2, No. 5, 1994, pp. 30~40.

(11) T. W. Lee, J. S. Lee, Y. J. Tak, S. S. Chung, and J. Y. Ha, "Fundamental study on combustion characteristics of methanol fuel in a constant volume chamber", KSME Transaction, Vol. 18, No. 2, 1994, pp. 389~397.