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COMBUSTION CHARACTERISTICS OF INHOMOGENEOUS METHANE-AIR MIXTURE IN A CONSTANT VOLUME COMBUSTION CHAMBER

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ABSTRACT−A cylindrical constant-volume combustion chamber was used to investigate the flow characteristics at the spark electrode gap and the combustion characteristics of an inhomogeneous charge methane-air mixture under several parameters such as stratified pattern, initial charge pressure, ignition time and the excess air ratio of the initial charge mixture. Flow characteristics including mean velocity and turbulence intensity were analyzed by a hot-wire anemometer. The combustion pressure development, measured by a piezo-electric pressure transducer, was used to investigate the effect of initial charge pressure, excess air ratio and ignition times on combustion pressure and combustion duration. It was found that the mean velocity and turbulence intensity had the maximum value around 200–300 ms and then decreased gradually to near-zero value at 3000 ms. For the stratified patterns, the combustion rate under the rich injection (RI) condition was the fastest. Under the initial charge conditions, the second mixture was accompanied by an increase in the combustion rate, and that the higher the mass which is added in the second stage injection, the faster the combustion rate.

KEY WORDS : CVCC (Constant-Volume Combustion Chamber), Inhomogeneous methane-air mixture, Stratified pattern, Initial charge pressure, Initial excess air ratio

1. INTRODUCTION

With the increasing concerns of energy security and the environment, much effort has been focused on stratified combustion and the development of alternatives for crude oil-based fuel. From the viewpoint of alternative fuels, among the most promising are gaseous fuels such as CNG, LPG or hydrogen. CNG fuel is especially coming into the spotlight and CNG buses or trucks have been in service in several countries (Kato *et al.*, 2001; Ursu and Perry, 1996).

CNG has several benefits such as higher thermal efficiency due to the higher octane value and lower exhaust emissions including CO_2, as a result of small NMOG formation and the lower C/H ratio (Maji *et al.*, 2000).

A lean-burn spark ignition engine is an attractive concept in engine design as it provides improvement in engine efficiency, which is key factor in reducing CO_2 output, one of the major factors in global warming. With the wide extension of the lean limit for higher engine efficiency in modern 4-valve spark ignition engines, studies have shown that the mixture can be stratified around the spark plug by the optimization of mixture introduction and injection into the combustion chamber. But there are some problems in lean combustion such as bad ignition characteristics, decrement of the combustion rate and combustion instability. Especially a significant increase in HC emissions occur under light-load conditions, 10-times higher than that of gasoline fuel (Frank and Heywood, 1991).

The ignition and combustion processes of premixed air-fuel mixtures are governed by the complex interaction of several parameters physically and chemically. However, for the improvement of engine performance and exhaust emission characteristics, it is necessary to understand in-cylinder phenomena. The combustion process of an S.I. engine is strongly controlled by several parameters such as excess air ratio, in-cylinder flow, chamber geometry and so on. In a real engine system, the measurements of combustion phenomena and the verification of the effects of each parameter on combustion are very difficult because each parameter is related complicatedly with the others. Thus, to understand combustion phenomena, it is necessary to investigate the combustion characteristics of premixed flames in a CVCC, which can show the effects of each parameter on combustion separately.

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Hong and Kim (1994) investigated the effects of the direction of injection and the ignition location on inhomogeneous combustion using in-cylinder flow in a CVCC. Furuno *et al.* (1995) studied locally stratified charge combustion by the soap bubble method under the quiescent flow condition in a CVCC. Lee *et al.* (1996) studied the turbulence characteristics, flame speed and flame shape and the effect of turbulence on flame propagation. Besides the above papers, there are many reports which have studied homogeneous charge mixtures in a CVCC (Strauss and Edse, 1959; Ryan and Lestz, 1980; Hjima and Takeno, 1986; Kim and Kwon, 1995; Kim and Lee, 1996; Lee *et al.*, 1996). But a few studies on stratified charge mixtures in a CVCC are found in the literature.

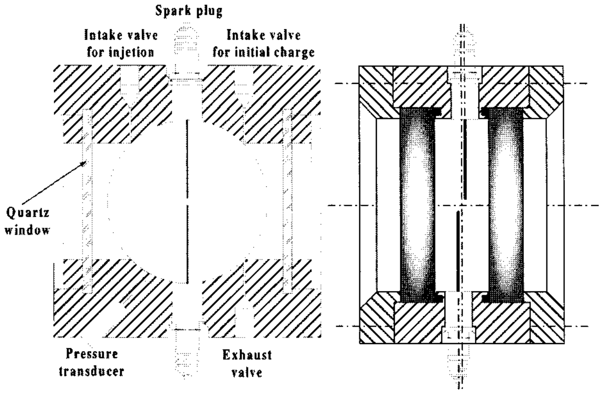
Therefore the present study deals with stratified combustion through the two-stage injection of a methane-air mixture. To determine the ignition time, the flow characteristics at the spark electrode gap are investigated by hot wire anemometer, and also investigated the effects of the initial charge pressure and initial excess air ratio on the stratified combustion of a methane-air mixture in a CVCC.

2. EXPERIMENTAL APPARATURS

2.1. Combustion Bomb and Measurement System

A schematic diagram of the CVCC is shown in Figure 1. The combustion chamber is disc-shaped with a diameter of 86 mm and a thickness of 25 mm. The combustion vessel consists of two fused silica glass windows, so that the flame kernel and its propagation can be observed. There are two intake ports to supply the initial charge mixture and the injection mixture for two-stage injection at opposite sides of the combustion chamber. A pair of spark electrodes with a 2 mm gap is oppositely located on the walls of the chamber. The ignition is initiated in the geometric center of the vessel. The diameter of the tungsten electrodes is 1 mm. Under the conditions of 2 mm spark gap and a mean velocity below 5 m/s, the minimum ignition energy is below 10 mJ (Lewis and von Elbe, 1987; Heywood, 1988). So, in this study, the effect of ignition energy on combustion is not considered. The temporal evolution of the pressure inside the vessel is monitored and measured with a piezo-electric pressure transducer (Kistler 6160 B).

A schematic diagram of the experimental apparatus is shown in Figure 2. It consists of a methane-air supply system with two mixing chambers, the CVCC, a data acquisition system and a combustion gas purging system. Mixing chamber A is filled with methane and air for the initial charge (excess air ratio; λ_{ini}) and mixing chamber B for the injection (λ_{inj}). Each mixing chamber has a homogeneous mixture with a different excess air ratio.



(a) Front view (b) Side view

Figure 1. Schematic diagram of CVCC.

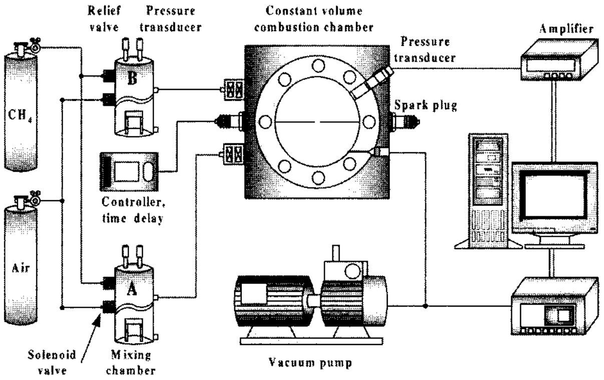


Figure 2. Schematic diagram of experimental apparatus.

Excess air ratio is determined by the partial pressure of methane and air with an uncertainty in the excess air ratio of the mixtures estimated to be less than 1%. The partial pressures of the gases are monitored with a diaphragm-type pressure sensor and can be adjusted to an accuracy of approximately 0.1 kPa. Both mixing chambers feed the combustion chamber through solenoid valves.

A CCA (constant temperature hot wire anemometer, IFA-300) is used to investigate flow characteristics including mean velocity and turbulence intensity at the spark elecrode gap. A micro-manometer and a TSI model 1125 calibrator are used to calibrate the CCA and the standard deviation of calibration is 0.45.

2.2. Description of the Expreiment

Following a standardized purging procedure using a vacuum pump, the vessel is filled with an initial charge mixture (λ_{ini}) which is leaner or richer than that of the injection mixture. After 10 seconds, the CVCC contents are allowed to reach a quiescent state, and then the CVCC is charged to a final precombustion pressure of 0.30 MPa with the injection mixture (λ_{inj}). For following ignition, combustion begins. After the combustion is terminated, the exhaust gas is purged through the exhaust port with a vacuum pump.

The combustion experiment consists of two parts. In part 1, the effect of the stratified pattern is investigated. Stratified patterns consists of rich injection (type RI, $\lambda_{ini} > \lambda_{inj}$), homogeneous injection (type HI, $\lambda_{ini} = \lambda_{inj}$) and lean injection (type LI, $\lambda_{ini} < \lambda_{inj}$). In the case of RI, the air ($\lambda_{ini} = \infty$), of which the pressure is 50% of the final precombustion pressure ($P_{overall}$ = 0.30 MPa), is filled into the vessel. After 10 seconds, the rich mixture (λ_{inj} = 0.497) is injected into the vessel and the precombustion pressure of the combustion chamber is 0.3 MPa and the overall excess air ratio is 1.1. In the case of HI, the initial charge mixture and the injection mixture have the same excess air ratio ($\lambda_{ini} = \lambda_{inj}$ = 1.1). LI is the reverse of the RI conditions. The combinations of excess air ratio between the initial charge mixture and the injection mixture and other conditions are shown in Table 1.

In part 2, to investigate the effects of the initial charge pressure (P_{ini}) and the excess air ratio of the initial charge mixture (λ_{ini}) on combustion, the initial charge pressure is set at 25% (0.075 MPa), 50% (0.15 MPa) and 75% (0.225 MPa) of final precombustion pressure ($P_{ovreall}$ = 0.3 MPa) and the excess air ratio of the initial charge mixture is set at 2.0, 3.0, 5.0 and ∞ under only the RI condition. The overall excess air ratio ($\lambda_{overall}$) is 1.1 and 1.4, the

Table 1. Experimental condition for stratified pattern.

	HI	RI	LI
λ_{ini}	1.1	∞	0.497
λ_{inj}	1.1	0.497	∞

$P_{ini} = P_{inj}$ = 0.15 MPa (50% of $P_{ovreall}$)
$\lambda_{overall}$ = 1.1, τ_{ig} = 300, 500, 1000 ms

Table 2. Experimental condition for initial charge pressure.

P_{ini} (%)	λ_{ini}	$\lambda_{overall}$ = 1.1	$\lambda_{overall}$ = 1.4
		λ_{inj}	λ_{inj}
25	2	0.950	1.269
	3	0.896	1.179
	5	0.855	1.114
	∞	0.799	1.024
50	2	0.739	1.066
	3	0.642	0.888
	5	0.578	0.778
	∞	0.497	0.647
75	2	0.423	0.706
	3	0.320	0.486
	5	0.261	0.378
	∞	0.196	0.271

RI condition, $P_{overall}$ = 0.3 MPa,
τ_{ig} = 300, 500, 1000 ms

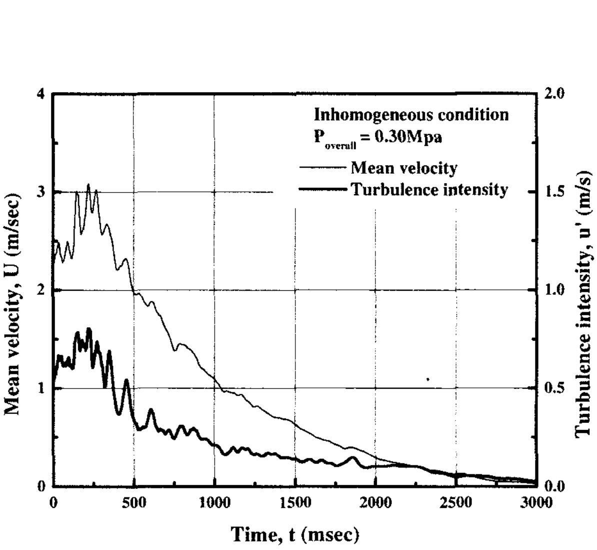


Figure 3. Flow characteristics at spark electrode gap.

ignition time (τ_{ig}) is 300, 500 and 1000 ms. By adjusting the intermediate pressure (P_{ini}) accordingly, the overall excess air ratio ($\lambda_{overall}$) can be held constant for different values of λ_{ini} and λ_{inj}. The combinations of excess air ratio are shown in Table 2. In all cases the run-to-run repeatability is excellent with a coefficient of variation of peak pressure of only 1.2% in the worst case, and typically less than 0.7%.

3. RESULTS AND DISCUSSION

3.1. Flow Characteristics

The results of the mean velocity and turbulence intensity at the spark electrode gap by using CCA are shown in Figure 3. The mean velocity and turbulence intensity are increased to maximum values between 200 and 300 ms and then decreased to beneath 0.05 m/s gradually at 3000 ms. For the results of the flow characteristics, the ignition time is set at 300 ms (mean velocity ≈ 3 m/s), 500 ms (≈2 m/s) and 1000 ms (≈1 m/s).

3.2. Combustion Characteristics for Stratified Pattern

To investigate the effect of the stratified pattern on combustion, an experiment under the HI, RI and LI conditions is conducted and the schematic diagram of the stratified pattern is shown in Figure 4. The initial charge pressure is 50% of the final precombustion pressure (0.3 MPa) and the ignition times are 300, 500, and 1000 ms.

The representative combustion results such as pressure development, mass fraction burned and rate of pressure rise under the stratified pattern for ignition time of 300 ms are shown in Figure 5. The calculation of the mass fraction burned is as follows:

$$\mathrm{Mb(t)} = \frac{P(t) - P_{overall}}{P_{\max} - P_{overall}} \quad (1)$$

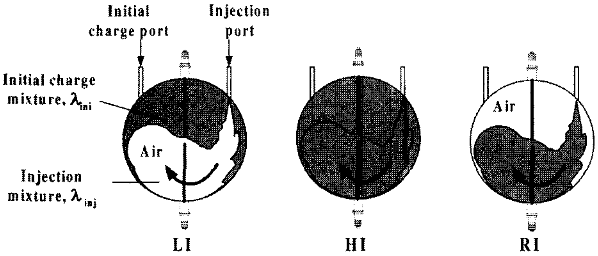


Figure 4. Schematic diagram of stratified pattern.

where, $P(t)$ is the combustion pressure, $P_{overall}$ is the precombustion pressure in the CVCC and P_{max} is the maximum combustion pressure. Eq. (1) means that the fraction of gas burned is equal to the fraction of the total pressure rise (Lewis and von Elbe, 1987). And the rate of pressure rise is used for the relative standard of rapid combustion. It is observed that the combustion rate of the RI pattern is the fastest.

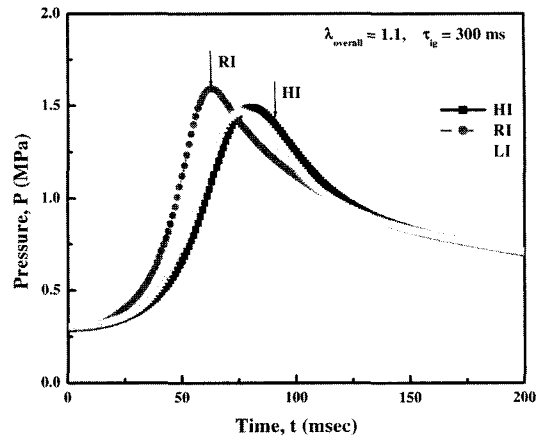
In all cases, the results of the maximum pressure and the combustion duration are shown in Figure 6. The maximum combustion pressure has a higher value for the RI pattern. The HI pattern shows a 1.5–3.4% higher value than that of the LI pattern and the RI pattern shows a 8.4–14.1% higher value than that of the LI pattern. In Figure 6(b), τ_{10}, the flame development duration, is the time interval between the spark discharge and the time when 10% of mass has burned or of the fuel chemical energy has been released. $\tau_{10\text{-}90}$ is the rapid combustion duration, τ_{90} is the flame propagation duration and τ_{100} is the overall burning duration. For all cases, the combustion duration of the RI pattern has the minimum value. Especially note worthy is the fact that from the result of $\tau_{10\text{-}90}$, rapid combustion is also achieved in the case of the RI pattern.

It is very interesting that all combustion durations under the LI condition at 300 ms are shorter than those under the HI condition and vice versa at 1000 ms. It seems that, as the ignition time is increased, the concentration distribution of the stratified mixture, that is to say the pattern of the stratified mixture, is changed at the ignition position.

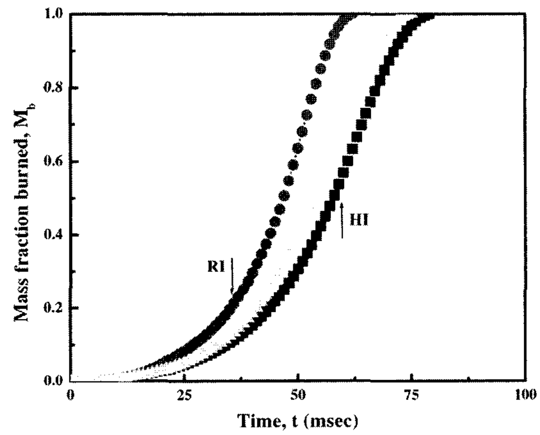
From the results of the stratified pattern, it is confirmed that the RI condition has better combustion characteristics than those of the other conditions. So the study on the effects of the initial charge pressure and the initial excess air ratio on combustion is conducted only under the RI condition.

3.3. Combustion Characteristics under Initial Charge Condition

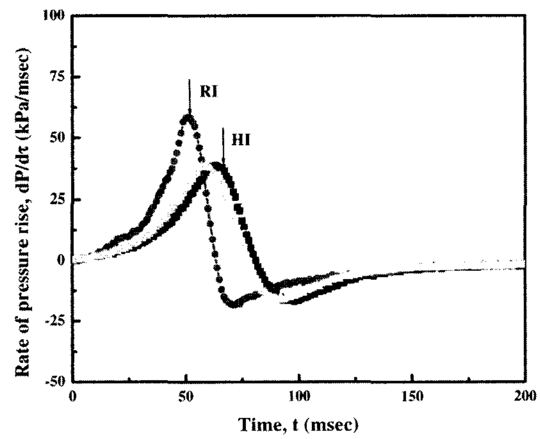
The effects of the initial charge pressure and the initial excess air ratio on stratified combustion are investigated under the RI condition. The combustion result at the initial charge pressure of 75% and the initial excess air ratio of ∞ is not presented in this paper due to the high instability of the combustion.



(a) Pressure



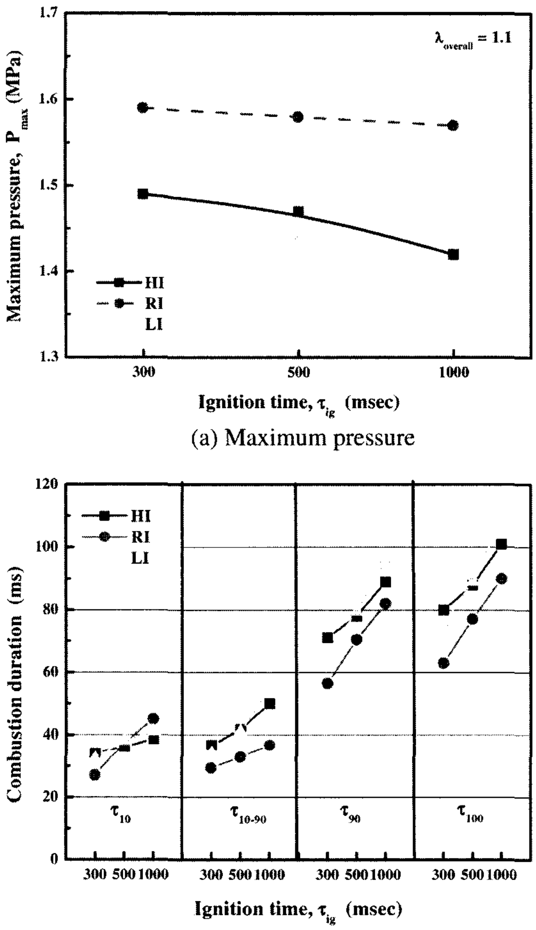
(b) Mass fraction burned



(c) Rate of pressure rate

Figure 5. Result of pressure data for stratified pattern.

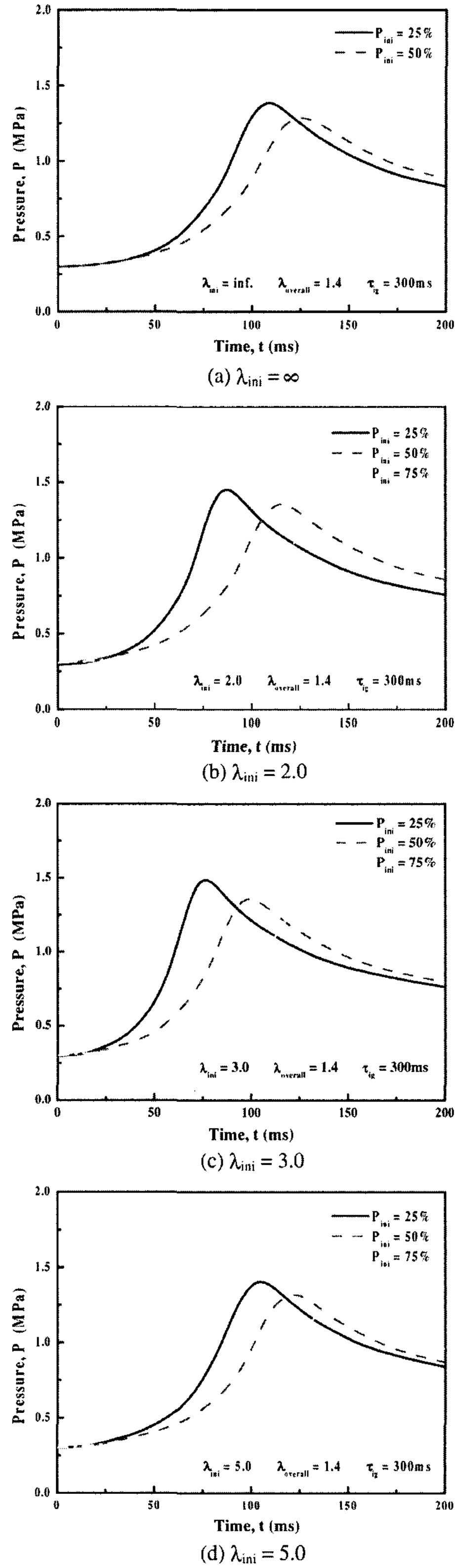
Figure 7 is the representative result of the pressure data with the initial charge pressure for the constant initial excess air ratio at the overall excess air ratio of 1.4 and



(a) Maximum pressure

(b) Combustion duration

Figure 6. Effects of stratified pattern and ignition time on maximum pressure and combustion.



(a) $\lambda_{ini} = \infty$

(b) $\lambda_{ini} = 2.0$

(c) $\lambda_{ini} = 3.0$

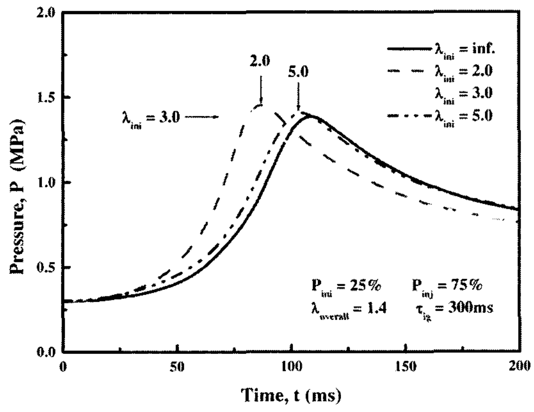
(d) $\lambda_{ini} = 5.0$

Figure 7. Effect of initial charge pressure on combustion pressure.

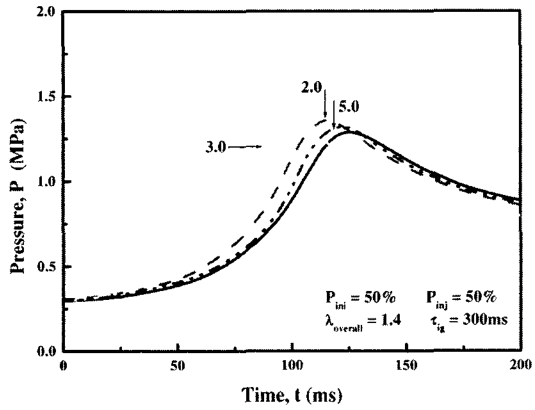
the ignition time of 300 ms. For all cases, the maximum combustion pressure is the highest at P_{ini} = 25%, because the higher the mass which is added in the second stage injection, the faster is the combustion rate due to the better flow characteristics.

The effects of the initial excess air ratio for the constant initial charge pressure are shown in Figure 8, which is replotted from Figure 7. Under the condition of λ_{ini} = 3.0, the combustion characteristics including maximum pressure and combustion duration are shorter than those under other conditions.

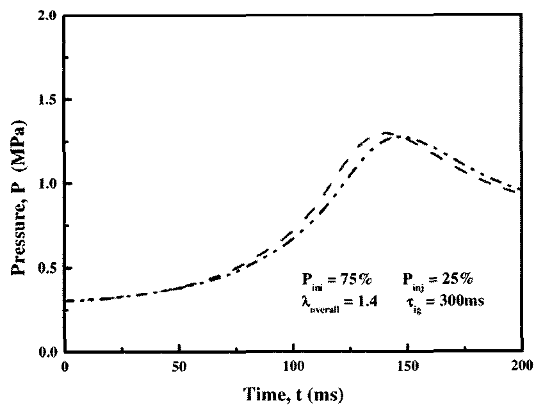
Figure 9 shows the maximum pressure under all conditions. For the overall excess air ratio of 1.1, the highest value of maximum pressure is observed in the initial excess air ratio of 3.0 condition, but it is not observed clearly as shown in Figure 9(a). However, under the leaner condition of $\lambda_{overall}$ = 1.4, this tendency is observed clearly in the order of λ_{ini} = 3.0, 2.0, 5.0 and as shown in Figure 9(b). Figure 10 shows the combustion



(a) 25%



(b) 50%

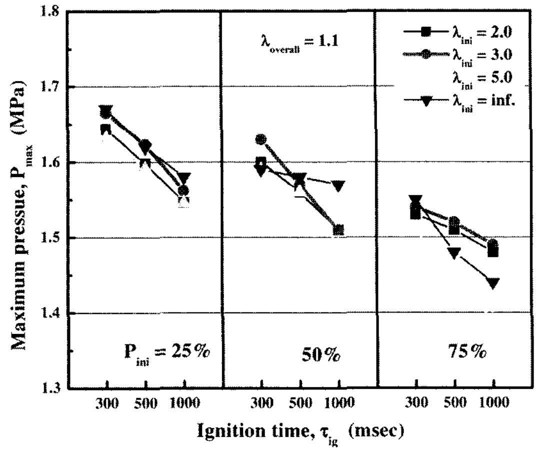


(c) 75%

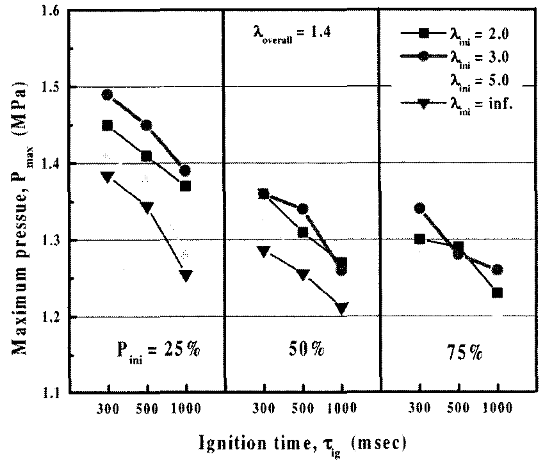
Figure 8. Effect of initial excess air ratio on combustion pressure.

duration under all conditions. In all cases, the initial excess air ratio of 3.0 has the shortest combustion duration.

Generally the highest combustion rate is obtained when all of the fuel is contained in a stoichiometric mixture in the vicinity of the ignition source due to the high burning velocity of this mixture and the complete



(a) $\lambda_{overall} = 1.1$



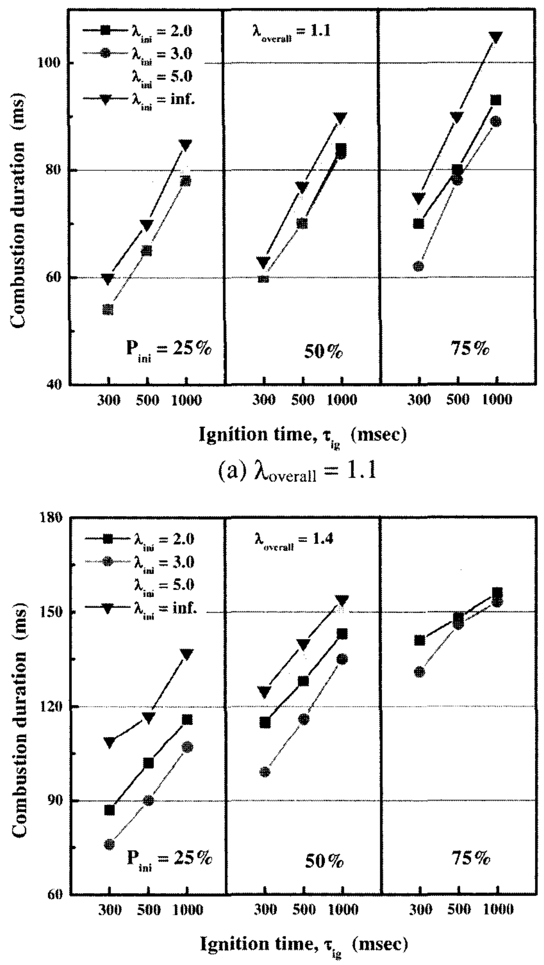
(b) $\lambda_{overall} = 1.4$

Figure 9. Effect of initial charge pressure and initial excess air ratio on maximum pressure.

oxidation.

Under the constant initial excess air ratio condition, as the initial charge pressure is increased, that is to say as the injection mixture becomes richer, the maximum combustion pressure is decreased because of the lack of mixing in the combustion chamber. The products of rich combustion still retain a significant chemical enthalpy which can only be realized by oxidation. But the lack of mixing in the combustion chamber prevents this, and thus the rich mixtures in the center region do not realize complete oxidation, resulting in a lower maximum pressure.

The improvement of the combustion rate, that is to say, the elivation of the maximum pressure and the shortening of the combustion duration, may be realized by using the two-stage injection, which injects an initial excess air ratio of 3.0 during the intake stroke and injects a richer mixture during the compression stroke, under gaseous



(a) $\lambda_{overall} = 1.1$

(b) $\lambda_{overall} = 1.4$

Figure 10. Effect of initial charge pressure and initial excess air ratio on combustion duration.

fuel direct injection and lean burn engine.

4. CONCLUSION

The results of the present study can be summarized as follows.

(1) Mean velocity and turbulence intensity which are measured by CCA at the spark electrode gap, have the maximum value at 200–300 ms and then decrease to beneath 0.05 m/s at 3000 ms.

(2) In the results of the stratified patterns, the combustion rate under the type RI condition is the fastest. The maximum pressure under the type HI condition shows a 1.5–3.4% higher value than that under the type LI condition, and the maximum pressure under the type RI condition shows an 8.4–14.1% higher value than that under the type LI condition.

(3) Under the RI condition, as the initial charge pressure is decreased, the combustion rate is increased. The initial excess air ratio of 3.0 shows a better combustion rate those that of the other initial excess air ratios.

(4) It is expected that the combustion rate will be increased through two-stage injection, which injects an initial excess air ratio of 3.0 during the intake stroke and injects a richer mixture during the compression stroke, under gaseous fuel direct injection and lean burn engine.

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