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COMBUSTION CHARACTERISTICS OF HOMOGENEOUS CHARGED 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 a homogeneous charged methane-air mixture under various overall charge pressures, excess air ratios and ignition times. The flow characteristics, including the mean velocity and turbulence intensity, were analyzed with a hot wire anemometer. Combustion pressure development measured by piezoelectric pressure transducer, a flame propagation image acquired by ICCD camera and exhaust emissions measured by 2-valve gas chromatography were used to investigate effects of initial pressures, excess air ratios and ignition times on the combustion characteristics. It was found that the mean velocity and turbulence intensity had the maximum value around 200–300 ms and then decreased gradually to a near-zero value after 3000 ms and that the combustion duration was shorten and the flame speed and laminar burning velocity had the highest value under the condition of an excess air ratio of 1.1, an overall charge pressure of 0.15 MPa and an ignition time of 300 ms in the present study. The CO_2 concentration was proportional to the ignition time and overall charge pressure, the O_2 concentration was proportional to the excess air ratio, and the UHC concentration was inversely proportional to the ignition time and overall charge pressure.

KEY WORDS : CVCC (Constant Volume Combustion Chamber), Homogeneous charged methane-air mixture, GC (Gas Chromatography)

1. INTRODUCTION

With the growing concern of energy security and environmental problems, much effort has been focused on stratified combustion and the development of alternative fuels to replace crude oil-based fuel. From the viewpoint of alternative fuels, one of the promising fuels is gaseous fuel such as CNG, LPG or hydrogen. Especially CNG fuel is coming into the spotlight and CNG buses or trucks have been in service in the 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 the low NMOG formation and the lower C/H ratio (Maji *et al.*, 2000).

A lean-burn spark ignition (S.I.) engine is an attractive concept in engine design as it provides improvement in engine efficiency, which is a key factor in reducing CO_2 emission, 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, research has shown that the mixture can be stratified around the spark plug by the optimization of mixture introduction and injection into the combustion chamber. However there are some problems in lean combustion such as bad ignition characteristics, decrease of the combustion rate and combustion instability. Especially, there is a significant increase in HC emissions: 10-times higher than that of using conventional S.I. engine under the light load condition (Frank and Heywood, 1991).

The ignition and combustion processes of a premixed air-fuel mixture are physically and chemically very complicated. However, for improvement of engine performance and exhaust emission characteristics, it is necessary to understand the 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

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parameter interferes complexly with others. Thus, to understand the combustion phenomena, it is necessary to investigate the combustion characteristics of a premixed flame in a constant volume combustion chamber (CVCC), which can show the effects of each parameter on combustion separately.

Many researchers have studied the effects of temperature and pressure on the burning velocity as well as the pressure development in a CVCC (Ryan and Lestz, 1980; Hjima and Takeno, 1986). The effects of the equivalence ratio, hydrogen supplement rate and initial pressure on combustion characteristics were investigated in a CVCC under the quiescence condition (Lee *et al.*, 1996). Strauss and Edse (1959) determined the burning velocities of various mixtures from 0.1 MPa upward to 10 MPa. They found a decrease of burning velocity with increasing pressure of mixtures whose burning velocities were below approximately 50 cm/s at atmospheric pressure, and an increase of mixtures whose burning velocity were higher than those of 50 cm/s. Lefebvre (1999) defined the burning velocity and investigated the effects of the equivalence ratio, temperature and pressure, which are the most important factors governing the laminar burning velocity. There are many reports which are concerned with the analysis of pressure development, the image of flame propagation and burning velocity in a CVCC (Furuno *et al.*, 1995). But few studies of exhaust emission characteristics in a CVCC are found in the literature (Kim *et al.*, 2000). The present paper deals with the experiment results for the homogeneous methane-air mixture at CVCC, which can investigate the characteristics of lean-stratified combustion phenomena before to investigate the stratified combustion characteristics (Choi *et al.*, 2003, 2004). First, the flow characteristics, including the mean velocity and turbulence intensity, are studied by using a hot wire anemometer at the spark electrodes gap to investigate the relationshop between flow characteristics and the ignition timing. Second, the combustion experiments are conducted to investigate the effects of fuel concentrations and initial charge pressures on combustion characteristics such as pressure development, flame speed and laminar burning velocity through the pressure history and flame image which are acquired by piezoelectric pressure transducer and ICCD camera. Finally, the emission characteristics are analyzed by using a gas chromatography to find the effects of initial charge pressures, excess air ratios and ignition times on exhaust emissions.

2. EXPERIMENTAL APPARATUS

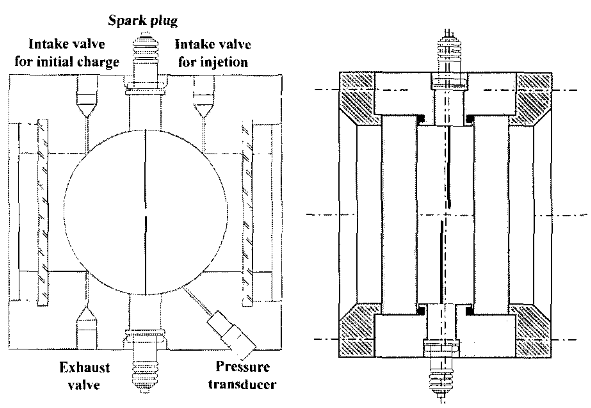
2.1. Combustion Bomb and Measurement System

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 images of flame kernel and flame propagation can be obtained. There are two-intake ports at opposite sides of the combustion chamber to simulate the stratified mixture formation, but in the present study, only one-intake port (right side) controlled by a solenoid valve is used because this paper deals with homogeneous mixture. A pair of ignition electrodes with a 2 mm gap is located at the opposite wall 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 electrode gap and a mean velocity below 5 m/s, the minimum ignition energy is below 10 mJ (Lewis and von Elbe, 1987). Therefore in the present study, the effect of ignition energy on combustion is not considered. The temporal evolution of the pressure inside the vessel is acquired by 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 (in the present study only one mixing chamber [upper side] is used), the CVCC, a data acquisition system, a combustion gas purging system and a gas chromatography.

Methane and air are introduced into the mixing chamber to make a homogeneous mixture and the excess air ratio in the mixing chamber is determined by the partial pressure of the methane and air. The partial pressures of the gases are monitored with a diaphragm-type pressure sensor and can be adjusted to an accuracy of 0.1 kPa. The uncertainty of excess air ratio is below 1.0%.

A HWA (hot wire anemometer, IFA-300) is used to investigate flow characteristics including the mean velocity and turbulence intensity at the spark electrodes gap. A micro-manometer and a TSI model 1125



(a) Front view (b) Side view

Figure 1. Schematic diagram of CVCC.

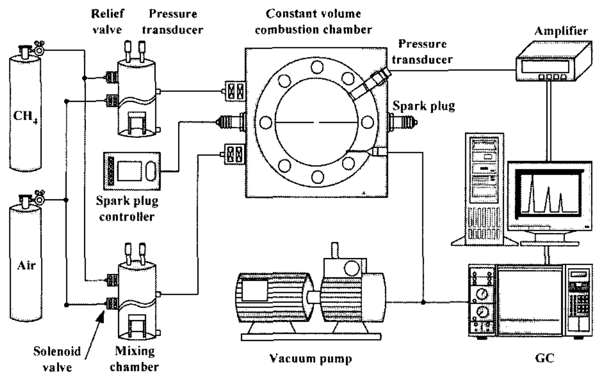


Figure 2. Schematic diagram of experimental apparatus.

calibrator are used to calibrate the CCA, and the standard deviation of calibration is 0.45.

To acquire the flame images, a 512×512, 16-bit ICCD camera (PI Max 512) is used and the exposure time is fixed at 1 μs. To synchronize each signal, two-time delay and pulse generator (DG 535) are used.

The measurement of exhaust gases such as CH_4, CO_2, O_2, N_2 and CO is performed on an gas chromatography (HP 5890 Series II) equipped with a TCD (thermal conductivity detector) and an FID (flame ionization detector). A 1.8 m Porapak Q column and a 3 m molecular sieve 13X column are used and the carrier gas is helium at a flow rate of 30 ml/min. The detector is set at a temperature of 200°C, and a temperature program is used for the oven. The typical gas chromatography data is shown in Figure 3. The retention times of each species are shown in Figure 3(a) for the TCD and in Figure 3(b) for the FID. Najm *et al.* (1998) show that many kinds of non-fuel species of hydrocarbon are produced through combustion by analyzing the detailed chemical reaction mechanism of premixed methane-air mixture. Although, there exist many kinds of non- fuel species, which has relatively lower value than that of CH_4 as shown in Figure 3(b), only CH_4 (UHC) concentration is considered.

2.2. Description of the Expreiment

To minimize the EGR (exhaust gas recirculation) effect in the CVCC, the vacuum pump is used. And then the CVCC is filled with a charge mixture and then combustion is started. After the combustion is terminated, the exhaust gas is sampled by syringe and then purged through the exhaust port with a vacuum pump. To understand the flow characteristics, such as the mean velocity and turbulence intensity, the end of the probe of the HWA is positioned at the spark electrodes gap by removing one spark plug.

The initial charge pressure in the CVCC are 0.15, 0.30 and 0.60 MPa, the overall excess air ratios are 1.1, 1.2, 1.3 and 1.4, and the ignition times are 300 and 10000 ms respectively. The detailed experimental conditions are summarized in Table 1.

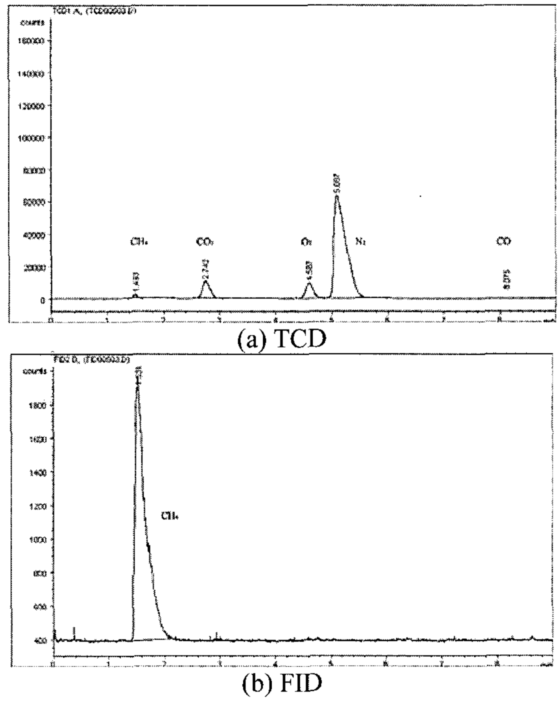


Figure 3. Typical chromatogram for each detector.

3. RESULTS AND DISCUSSION

3.1. Flow Characteristics

The experimental results of the mean velocity and turbulence intensity at the spark electrodes gap by HWA for the overall pressures of 0.15 and 0.30 MPa are shown in Figure 4. In both cases, the mean velocity and

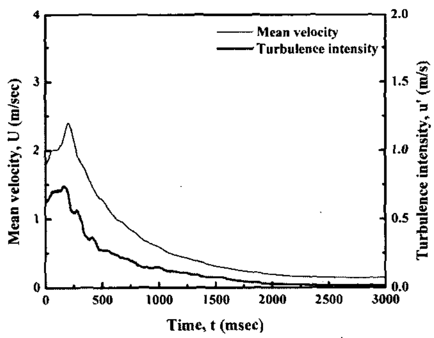
Table 1. Experimental conditions.

	Overall pressure ($P_{overall}$, MPa)	Excess air ratio (λ)	Ignition time (τ_{ig}, ms)
Flow	0.15, 0.30		-
Combustion	0.15, 0.30, 0.60	1.1, 1.2, 1.3, 1.4	300, 10000
Exhaust emission	0.15, 0.30, 0.60	1.1, 1.2, 1.3, 1.4	300, 500, 1000, 10000

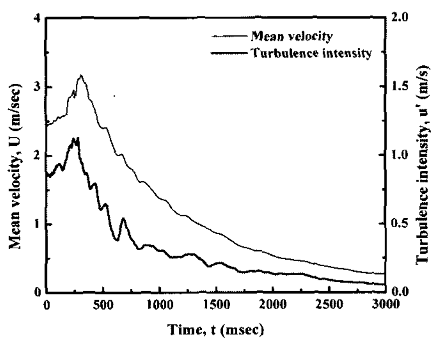
turbulence intensity are increasing to a maximum value and then are gradually decreasing to below 0.3 m/s and 0.05 m/s at 3000 ms respectively. In the case of the 0.15 MPa condition, the time which has the maximum mean velocity and turbulence intensity values is about 200 ms, and in the 0.30 MPa condition the time is about 300 ms. The time difference of about 100 ms between 0.15 MPa and 0.30 MPa of injection pressure owes to the fact that overall pressure of 0.15 MPa has a relatively lower flow momentum than that of 0.30 MPa.

3.2. Combustion Characteristics

To investigate the relationship between the flow characteristics and the ignition times the maximum combustion pressures are acquired with the change of ignition times (τ_{ig} = 200, 300, 500, 1000, 10000 ms), excess air ratios (λ = 1.1, 1.2, 1.3, 1.4) and overall pressure ($P_{overall}$ = 0.15, 0.30 MPa). Figure 5(a) and (b) show the effect of the ignition time and excess air ratio on the maximum combustion pressure. In both cases, the maximum combustion pressure has the highest value at the excess air ratio of 1.1 and decreases with an increasing in excess air ratio under the condition of a constant ignition time. Generally the ignition time of 200 or 300 ms has the maximum pressure value under the condition of a constant excess air ratio and the ignition

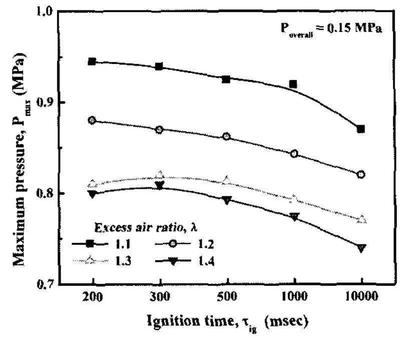


(a) $P_{overall}$ = 0.15 MPa

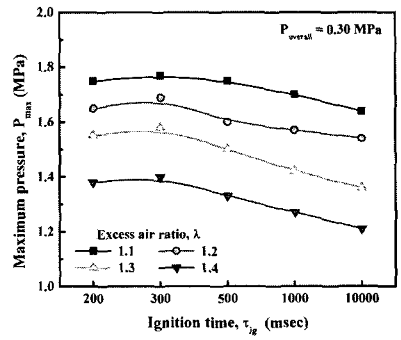


(b) $P_{overall}$ = 0.30 MPa

Figure 4. Flow characteristics at a spark electrode gap.



(a) $P_{overall}$ = 0.15 MPa



(b) $P_{overall}$ = 0.30 MPa

Figure 5. Effect of the ignition time and the excess air ratio on the maximum combustion pressure.

time of 10000 ms, which is the quiescent flow condition, has the minimum value. It seems that the thermal loss to the electrode is reduced because the initial flame kernel is moved from the spark electrode due to the higher initial mean velocity at the earlier ignition time of 200 or 300 ms. From these results, it appears that the effect of heat and mass transfer on combustion is enlarged because of the higher turbulence intensity. Because of these factors, it is understood that the flow characteristics and the ignition time have a close relationship. Thus the ignition time, which is defined by the time from solenoid valve is closed, is decided to 300 ms, which has high mean velocity and turbulence intensity, and 10000ms, which is the quiescent condition, respectively.

The typical results of the mass fraction burned and rate of pressure rise calculated from the pressure data for the ignition times of 300 and 10000 ms at the overall pressure of 0.15 MPa are shown in Figure 6. The mass fraction burned is calculated by equation (a).

$$M_b(t) = \frac{P(t) - P_{overall}}{P_{\max} - P_{overall}} \qquad (1)$$

where, $P(t)$ is the combustion pressure, $P_{overall}$ is the overall charge pressure in the CVCC and $P_{\max}$ is the maximum combustion pressure. Equation (1) means that the fraction of gas burned is equal to the fraction of the total pressure rise (Lewis and von Elbe, 1987). The rate of pressure rise is used to the relative reference of rapid combustion.

Figure 7 shows the effect of the ignition time, the overall pressure and the excess air ratio on the maximum combustion pressure. For effect of ignition time, the 300 ms condition has the higher maximum pressure than that of the 10000 ms, which is the quiescent condition. The pressure difference is larger as the overall pressure increases. The increasing rates of the maximum combustion pressure are 5.7–8.8% in the case of the overall pressure of 0.15 MPa, 8.3–16% for 0.30 MPa and 14.4–32.2% for 0.60 MPa. As the mixture becomes leaner, the maximum combustion pressure differences tend to increase. From these results, it is confirmed that an appropriate flow condition is the positive factor compared to the quiescent flow condition.

Figure 8 shows the effect of each parameter on the combustion duration which is calculated from the mass fraction burned. τ_{10}, the flame development duration, is the time interval between the spark discharge and the time when 10% of the mass has burned or fuel chemical energy has been released. τ_{90}, the flame propagation duration, is the time interval required to burn the bulk (in this study, 90% of the mass has burned) of the charge and τ_{max} is the overall burning duration. In the ignition time of 300 ms, the average flame development duration is reduced 4 ms (in 0.15 MPa), 4.8 ms (in 0.30 MPa) and 6

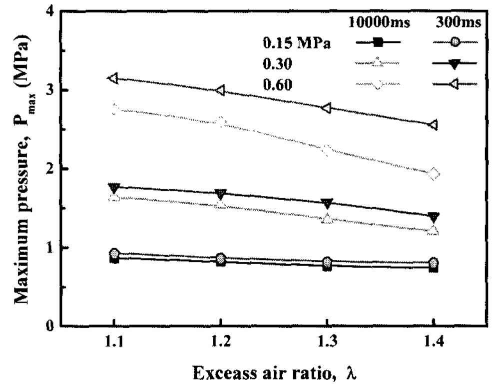
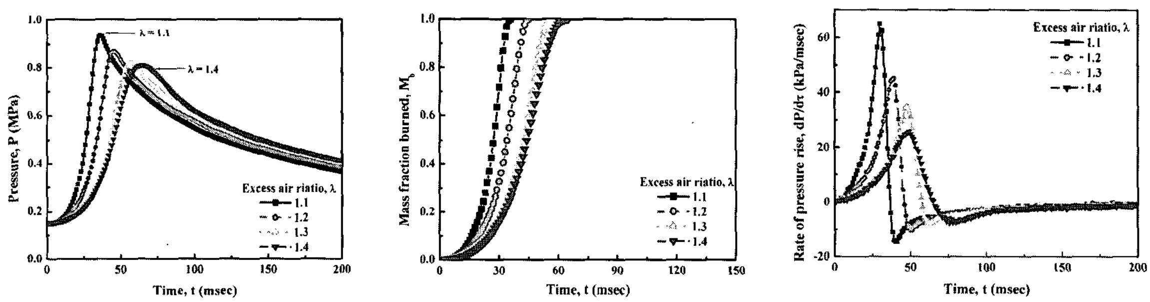


Figure 7. Effect of the ignition time, the excess air ratio and the overall pressure on the maximum pressure.

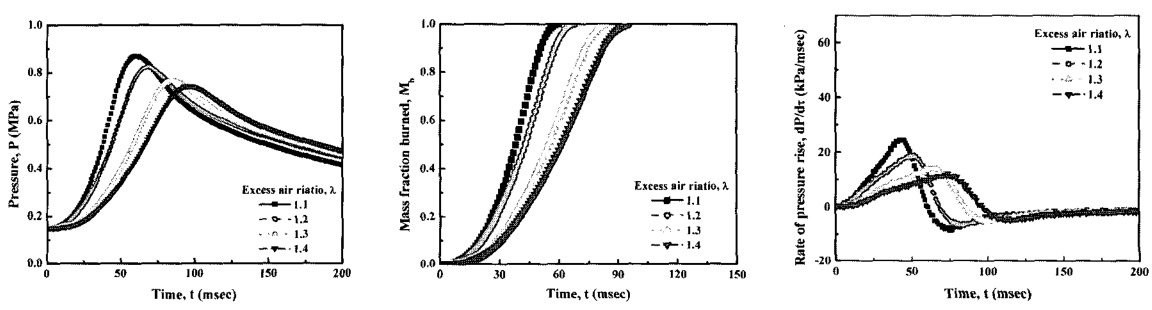
ms (in 0.60 MPa) compared to the quiescent condition respectively. The average flame propagation duration is reduced to 21.2, 26.6 and 45 ms and the average overall burning duration is reduced to 26.3, 38.8 and 56.3 ms respectively. The time differences are larger as the mixture becomes leaner. In Figure 8(c), the combustion duration for the excess air ratio of 1.4 and ignition time of 10000 ms are not represented because of too-long combustion duration (about 339 ms).

3.3. Flame Speed and Laminar Burning Velocity

Figures 9 and 10 are the typical flame propagation

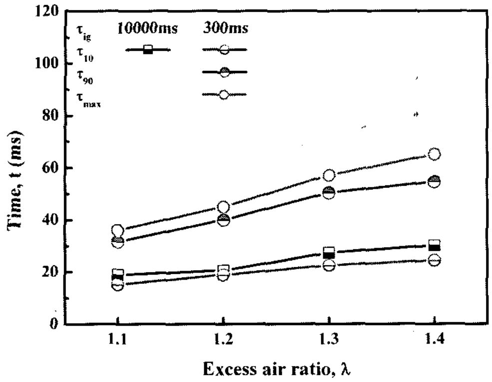


(a) τ_{ig} = 300ms

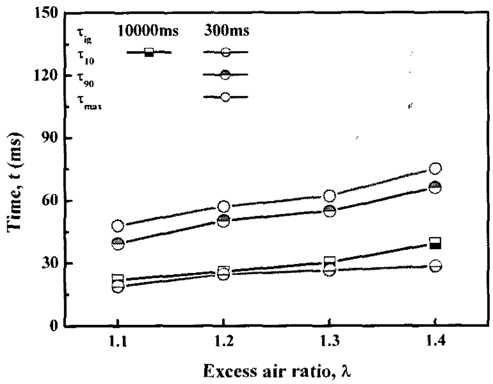


(b) τ_{ig} = 10000ms

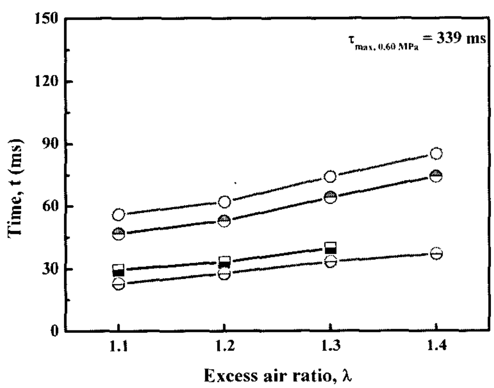
Figure 6. Typical pressure data at $P_{overall}$ = 0.15 MPa.



(a) $P_{overall}$ = 0.15 MPa



(b) $P_{overall}$ = 0.30 MPa



(c) $P_{overall}$ = 0.60 MPa

Figure 8. Effects of the excess air ratio and the ignition time on the combustion duration.

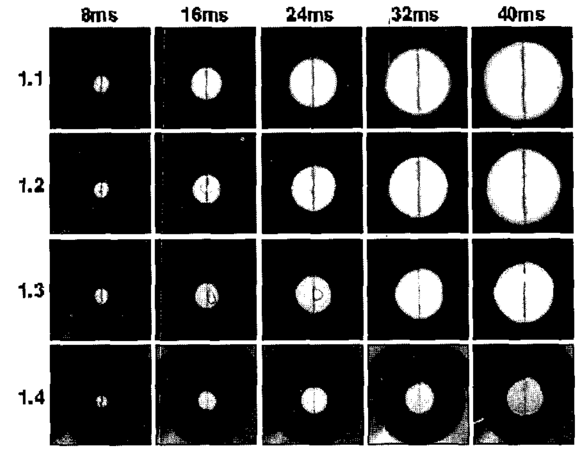


Figure 9. Effect of the excess air ratio on the flame propagation ($P_{overall}$ = 0.60 MPa, τ_{ig} = 10000 ms).

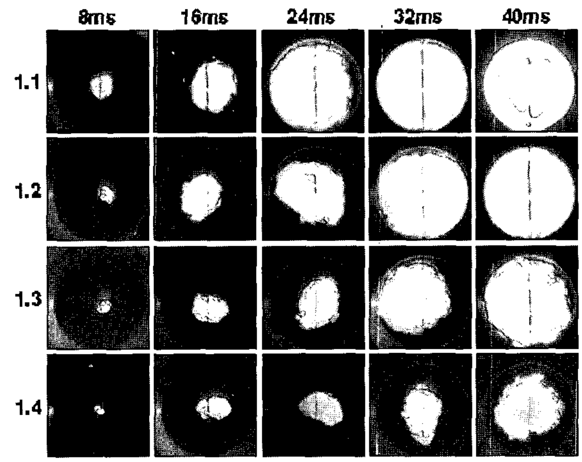
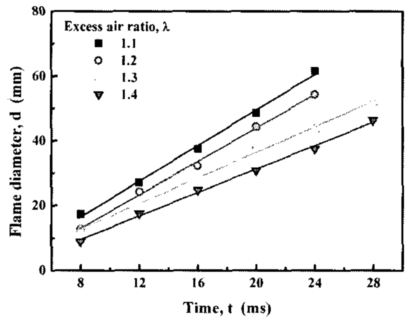


Figure 10. Effect of the excess air ratio on the flame propagation ($P_{overall}$ = 0.60 MPa, τ_{ig} = 300 ms).

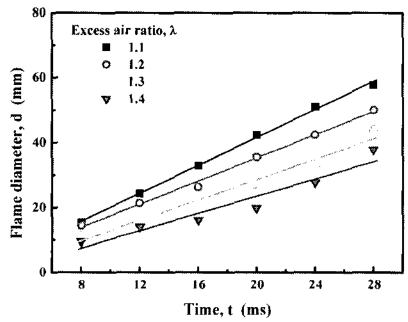
images acquired by ICCD camera for the overall pressure of 0.60 MPa. In the ignition time of 10000 ms, as time elapses, the spherical-shaped flame propagation procedure is well observed, as shown in Figure 9. The flame diameter is smaller and the intensity of the image is weaker with increase in excess air ratio. The vertical line in the flame center region is the spark electrodes. In the 300 ms condition, which has a higher mean velocity and turbulence intensity at the spark electrodes gap and is predicted to produce a strong swirl bulk flow in the CVCC, the flame grows quickly compared to 10000 ms, as shown in Figure 10.

Figure 11 shows the flame diameter acquired from the flame propagation image. The flame diameter is decreased to the increment of the excess air ratio and the overall pressure. As the overall pressure is increasing, the flame speed is reduced due to the density of the mixture in the combustion chamber. The flame diameter is presented to linear fitting and the standard deviation is below 3.1%.

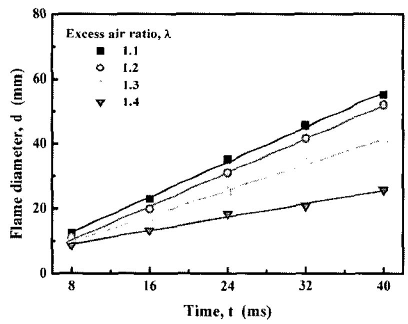
The inclination of the linear fitting indicates the average flame speed, and the results are shown in Figure 12. The average flame speeds are in the range from 80 to 235.7 cm/s for the overall pressures and excess air ratios.



(a) $P_{overall}$ = 0.15 MPa



(b) $P_{overall}$ = 0.30 MPa



(c) $P_{overall}$ = 0.60 MPa

Figure 11. Effects of the excess air ratio and the overall pressure on the flame diameter.

In the present study, the maximum average flame speed is 235.7 cm/s at the excess air ratio of 1.1 and the overall pressure of 0.15 MPa.

The values of combustion pressure are almost same during about 10–20 ms after ignition as shown in Figure 6. As shown in Figure 13, the burning velocity, therfore, is determined using the flame speed within the maximum 20 ms in order to remove the effect of the pressure rise in the combustion chamber on the burning velocity. The assumptions and the procedure for the calculation of the burning velocity are as follows. First, it is assumed that the pressure difference before and after flame front is negligible and that the flame propagation process is in the

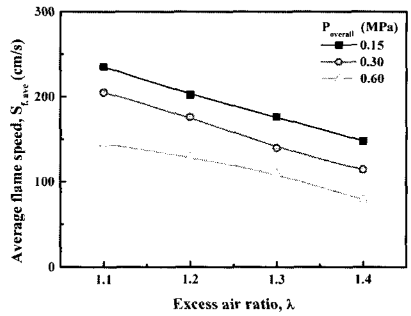


Figure 12. Effect of excess air ratio and overall pressure on average flame speed.

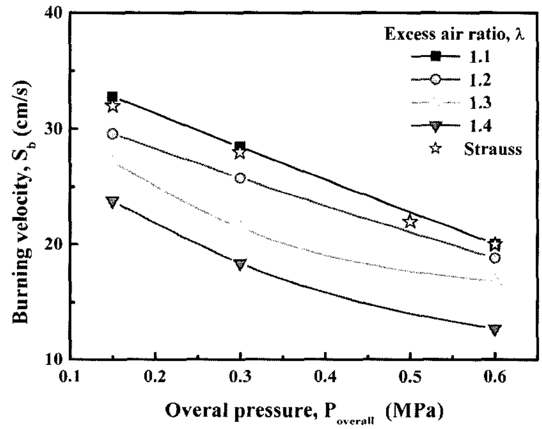


Figure 13. Effect of the excess air ratio and the overall pressure on the burning velocity.

steady state. The flame temperature is the adiabatic temperature, the combustion chamber and the environment are isothermal and the process is a constant pressure process.

From the continuity equation of the steady state

$$\rho_o S_b = \rho_f S_f \tag{2}$$

and from a constant pressure process

$$\frac{V_f}{V_0} = \frac{T_f}{T_0} \tag{3}$$

$$\rho_0 V_0 = M_0,\ \rho_f V_f = M_f \tag{4}$$

From equations (2)–(4), the burning velocity, S_b, is

$$S_b = S_f \frac{T_0 M_f}{T_f M_0} \tag{5}$$

where S_f is the flame speed, V, T and ρ are the volume, temperature and density, and the subscripts of o and f are the unburned gas and burned gas respectively. The calculation results of the molecular weight of the reactants and products and of the adiabatic temperature are shown in Table 2.

Although there are effects of the isothermal condition, flame temperature and flame thickness on the burning velocity, the general error is below 9% (Jeung, 1982).

The maximum burning velocity is 32.8 cm/s at the excess air ratio of 1.1 and the overall pressure of 0.15 MPa. As the overall pressure increases, the burning velocity of the premixed methane-air mixture, which is below 50 cm/s under atmospheric conditions, is decreasing and it is well in accordance with the results of Strauss and Edse (1959). In Figure 13, the burning velocity of Strauss and Edse (denoted by ☆) (1959) is the result of the excess air ratio of 1.0 and it is a lower value than that of the excess air ratio of 1.1 of the present study. It is caused by the error from one of several assumptions such as the adiabatic flame temperature or the constant pressure process in the present study.

An explanation of the effect of pressure on burning velocity has been given by Strehlow (1984). A change of pressure affects the dissociation equilibrium in the burned gas and also the rate of destruction of free radicals in three-body collisions. Furthermore, an increase of pressure promotes the chain-breaking reaction $H + O_2 + M \rightarrow HO_2 + M$ over the chain-branching reaction $H + O_2 \rightarrow OH + O$. Mixtures having burning velocities above the order of 50 cm/s have high flame temperatures that are responsive to repression of dissociation by pressure increase. Therefore, as the pressure is increased the temperature of the burned gas increases resulting in a heightened temperature profile of the combustion wave, increased reaction rate and consequent increase of the burning velocity. Mixtures having burning velocities below the order of 50 cm/s have low flame temperatures that are much less affected by dissociation. Such mixtures, however, are sensitive to the effect of pressure on the rates of ternary free radical reactions. Thus, an increase of pressure decreases the concentration of free radicals in the reaction zone, resulting in a decrease of burning velocity.

Table 2. Thermodynamic property and adiabatic flame temperature of methane-air mixture.

Poverall	λ	MW_R	MW_P	T_{adia}
0.15 MPa	1.1	27.74	27.67	2150.6
	1.2	27.82	27.79	2048.2
	1.3	27.89	27.88	1951.2
	1.4	27.96	27.95	1862.8
0.30 MPa	1.1	27.74	27.68	2157.8
	1.2	27.82	27.8	2051.5
	1.3	27.89	27.88	1952.8
	1.4	27.96	27.95	1863.6
0.60 MPa	1.1	27.74	27.70	2163.4
	1.2	27.82	27.80	2054.0
	1.3	27.89	27.89	1954.0
	1.4	27.96	27.95	1864.3

MW_R : Molecular weight of reactants
MW_P : Molecular weight of products
T_{adia} : Adiabatic flame temperature (K)

3.4. Exhaust Emission Characteristics

CO concentration is not detected under the experimental conditions for excess air ratio of 1.1–1.4. Figure 14 shows the exhaust emission results measured by gas chromatography. In the exhaust emission experiment, the ignition times of 500 and 1000 ms are added.

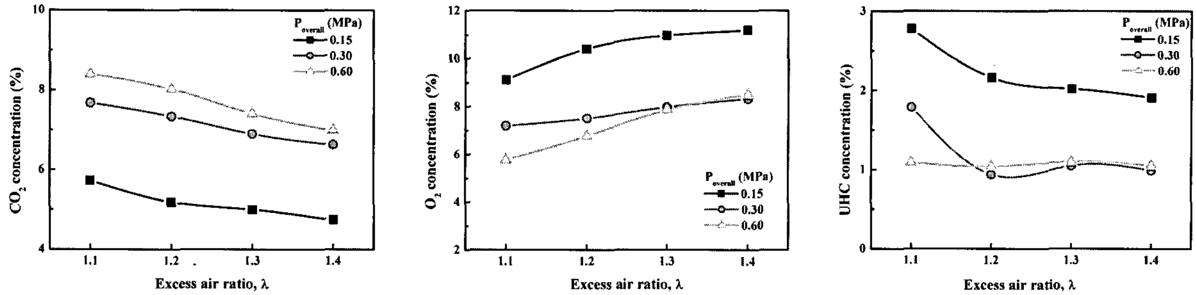
As the excess air ratio increases, CO_2 is decreased and O_2 is increased at a constant overall pressure and ignition time. But it is observed that UHC is almost the same value except under the excess air ratio of 1.1. As the overall pressure increases, CO_2 is increased and O_2 and UHC are decreased at a constant ignition time and excess air ratio. As the ignition time increases, CO_2 is increased and O_2 is decreased at a constant excess air ratio and overall pressure. UHC is slightly reduced or almost the same value with increasing ignition time except under the overall pressure of 0.60 MPa and ignition time of 10000 ms, which is the quiescent flow condition.

Generally, CO_2 is increased and O_2 and UHC are decreased under the ignition time of 10000 ms compared to the conditions of faster ignition times. This means that the larger amount of air-fuel mixture is combusted at 10000 ms, but the maximum combustion pressure has a lower value than that of faster ignition time of 300 ms. From these results, it is confirmed again that the flow characteristics are very important parameters to improvement of combustion. These results are replotted in Figure 15. The arrow symbol indicates the increment of the concentration.

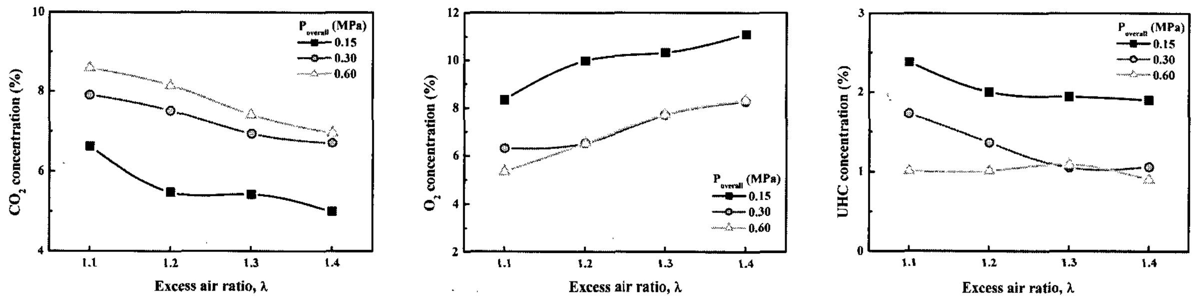
4. CONCLUSIONS

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

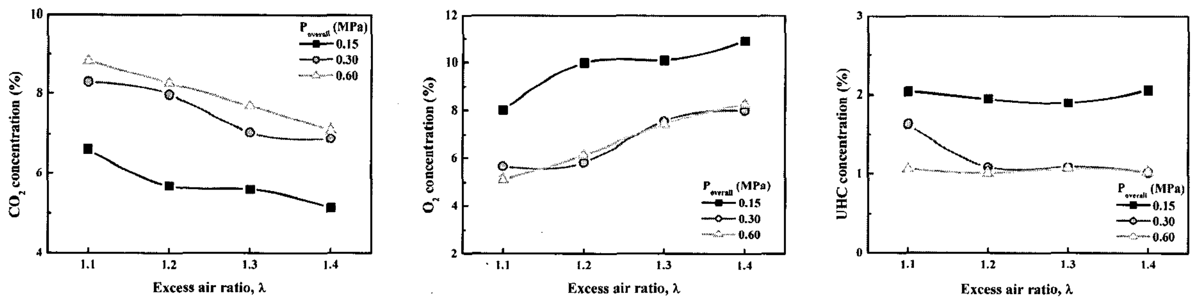
(1) The mean velocity and turbulence intensity, which are measured by HWA, have the maximum value at 200 ms under the overall pressure of 0.15 MPa and at 300 ms under 0.30 MPa and then decreased beneath 0.3 m/s and 0.05 m/s at 3000 ms at the spark electrodes gap respectively.
(2) From the results of the effect of ignition time on the maximum combustion pressure and the combustion duration, it is confirmed that the flow characteristics are very important parameters to improve the combustion rate.
(3) The flame speeds have the values of 80–235.7 cm/s



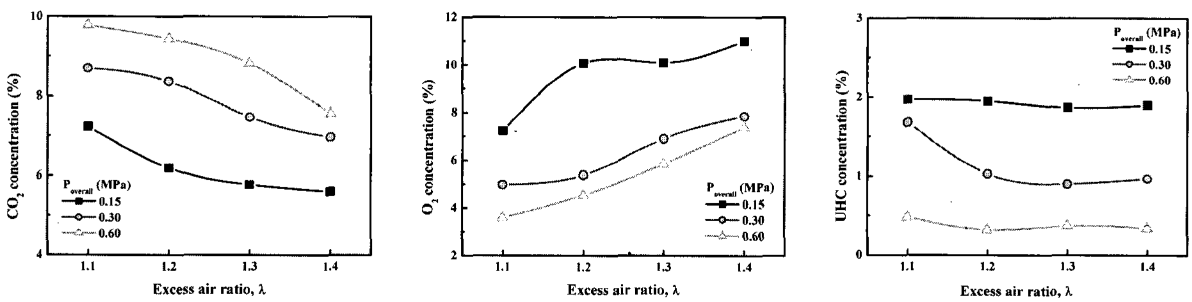
(a) τ_{ig} = 300ms



(b) τ_{ig} = 500ms



(c) τ_{ig} = 1000ms

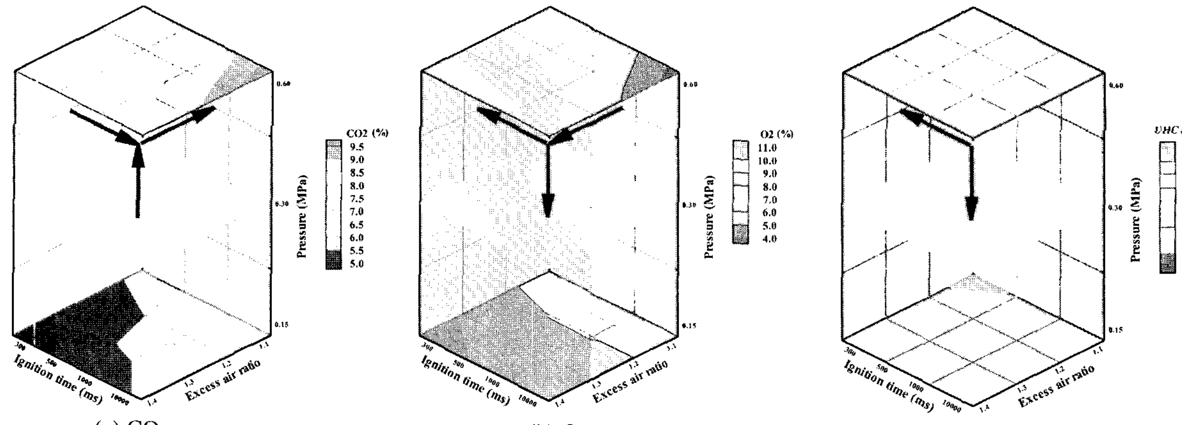


(d) τ_{ig} = 10000ms

Figure 14. Effects of the excess air ratio and the overall pressure on exhaust emissions.

in the present CVCC and the maximum value is 235.7 cm/s under the condition of the overall pressure of 0.15 MPa, the excess air ratio of 1.1 and the ignition time of 300 ms.

(4) As the overall pressure and excess air ratio increases, the burning velocity tends to be decreased. The



(a) CO_2 (b) O_2 (c) HUC

Figure 15. Effects of ignition time, excess air ratio and overall pressure on exhaust emissions.

maximum burning velocity of 32.8 cm/s is acquired in the premixed methane-air mixture under the same condition of the maximum flame speed.

(5) As the excess air ratio increases, CO_2 has been decreased, O_2 has been increased and UHC has no vraiation. As the ignition time increases, CO_2 has been increased, O_2 has been decreased and UHC has been decreased or has almost the same value. And as the overall pressure increases, CO_2 has been increased and O_2 and UHC have been decreased.

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