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STUDY ON PRE-MIXTURE COMBUSTION IN A SUB-CHAMBER TYPE CVC WITH MULTIPLE PASSAGE HOLES

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ABSTRACT−An experimental study was carried out to obtain the fundamental data about the effect of sub-chamber on pre-mixture combustion. A CVC (constant volume combustor) divided into a sub-chamber and a main chamber was used in this experiment. The volume of the sub-chamber was varid from 0.45% to 1.4% about the whole combustion chamber. The sub-chamber has twelve narrow radial passage holes and a spark plug to ignite the pre-mixture. As the ignition occurs in the sub-chamber by a spark discharge, burned and unburned gas including a great number of radicals is injected into the main chamber, then the multi-point ignition occurs in the main chamber. The combustion pressure is measured to calculate the burning velocity mainly as a function of the sub-chamber volume, the diameter of the passage holes, and the equivalence ratio. In the case of RI (radical ignition) methods, the overall burning time became very short and the maximum burning pressure was slightly increased as compared with that of SI (spark ignition) method. The optimum design value of the sub-chamber is near 0.11 cm^{-1} in the ratio of total area of holes to the sub-chamber volume.

KEY WORDS : Sub-chamber, Pre-mixture, Multiple passage holes, Multi-point ignition, Radical ignition

1. INTRODUCTION

The lean burn of a pre-mixture is known as a very useful technology in gasoline engines with respect to clean emissions and high thermal efficiency. Some specific techniques on lean burn have been developed and used in actual engines like the Lean-Burn of Hyundai and the GDI engines of Mitsubishi. However, considering the upcoming emissions regulation and Kyoto protocol, higher lean burn technology must be developed.

The defect of the premixed lean burn technology is slow combustion velocity, so the lean burn engine generally shows high cycle variations and low power. Therefore, various combustion techniques have been suggested and adapted to solve these problems (Park, 2005; Lee and Kim, 2001; Shudo *et al.*, 2003; Choi *et al.*, 2003; Choi *et al.*, 2004). One example of which is increasing the discharge energy of spark-plugs (Bae *et al.*, 1998). Another example is to intensify the mixture flow and form the stratified mixture through the change of the combustion chamber shape and injection timing (Kim *et al.*, 2001).

In the present study, a specially designed combustion method was adapted to increase the combustion velocity of the pre-mixture. When considering higher thermal efficiency and lower unburned hydrocarbon in actual engines, higher combustion velocity is more preferable.

Moreover, this can be the cause of the leaner pre-mixture combustion since the quantity of heat transfer from the combustion chamber to the outside is reduced.

To test the above-mentioned special combustion method, an experimental apparatus was made from a copy of the combustion chamber of the sub-chamber-type diesel engine. It is a CVC (constant volume chamber) divided into a sub-chamber and a main combustion chamber. However, the shape of the sub-chamber is quite different from that of the usual diesel engine. It has twelve small passage holes as well as a spark-plug inside it. Therefore, it corresponds to the sub-chamber type gasoline engine. After spark discharging to the pre-mixture in the sub-chamber, flame propagation occurs and the pressure increases. Then, the combustion gas burned or unburned, including many radicals, is ejected through the holes into the main-chamber, which initially has the same concentration of pre-mixture as the sub-chamber. Then the ignition of pre-mixture occurs at 12 points in the main-chamber. Ejection of the combustion gas generates entrainment flow of the mixture in the main-chamber near the surface of sub-chamber, and this phenomenon increases the combustion velocity. We call it the "RI (radical ignition) method" in this study. In the literature of related studies, it's called 'flame-jet ignition' (Date and Yagi, 1974) or 'torch ignition' (Yamaguchi *et al.*, 1985) and so

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on. However, the term 'RI' seems to be more relevant because it follows the suggestion of Higelin (Higelin and Robinet, 1999) that the radical ejection induced from the sub-chamber promotes the pre-mixture combustion in the main-chamber.

The combustion velocity is strongly affected by the volume and hole-diameter of the sub-chamber. So, in this study, the effect of those factors on the combustion velocity is identified through systematic experiments. From the experimental results, the characteristics of the RI method are obtained in comparison with the SI (spark ignition) method using only a spark plug without a sub-chamber in the same CVC.

2. EXPERIMENTAL APPARATUS AND METHOD

2.1. Combustion Mechanism of RI Engine

Figure 1 shows the operation concept of the sub-chamber type gasoline engine mentioned in the introduction. The combustion chamber is physically divided into a sub and a main chamber. The combustion process of this engine is as follows. If the pre-mixture is formed in every chamber at the intake stroke, the combustion occurs near the TDC by the spark-plug installed in the sub-chamber. Then, combustion gases are ejected into the main-chamber, as in sub-chamber type diesel engines, and the multi-point ignition is generated at the main chamber.

2.2. Constant Volume Combustor

A specially devised CVC shown in Figure 2 is used in this experiment to confirm the RI combustion method. The main chamber is 487cc in volume and two quartz-glasses are installed in the observing windows so as to take the flame propagation from the outside. A sub-chamber is attached on the upper part of the main chamber. One of the most important research purposes is to determine the optimum design value of the sub-chamber as volume and passage holes diameter minimizing the combustion duration of pre-mixture formed in the CVC. So, all experiments are carried out as the function of the volume and holes diameter of sub-chamber. An enlarged and detailed view of the sub-chamber is shown at Figure 2.

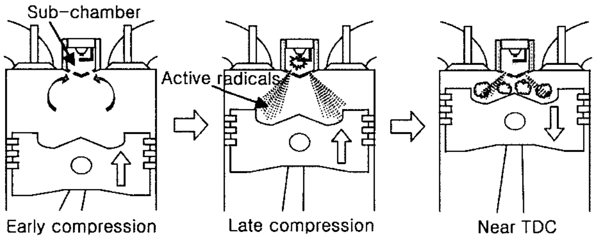


Figure 1. Combustion process of a sub-chamber type gasoline engine.

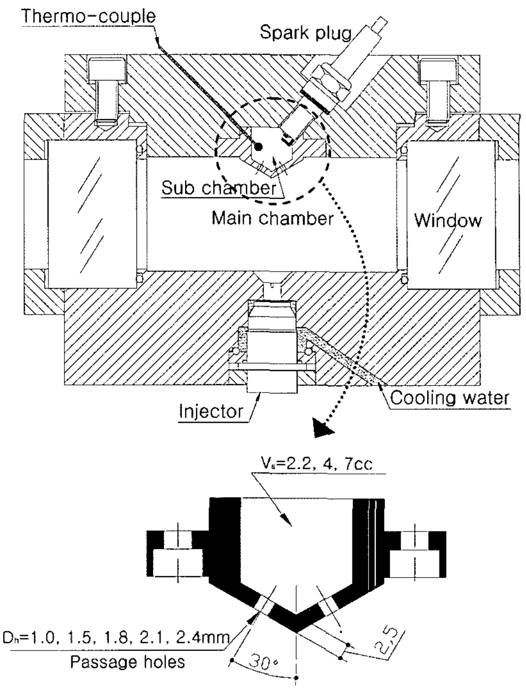


Figure 2. Sectional view of the constant volume combustor.

To set an experimental temperature, several electric heaters of 4 kW are installed in the CVC wall, and the temperature is adjusted by a signal of K-type thermocouple of 0.1 mm in diameter. To form the pre-mixture in the CVC, a GDI injector is installed. The injection quantity, according to the solenoid opening time, has already been measured before carrying out this experiment.

To set the pre-mixture and the experimental pressure, pressurized air (at a constant pressure by a regulator) is supplied to the CVC after dehumidification by dry filters. As the air comes into the CVC, the air temperature rises by transferred heat from the heated CVC. Therefore, the experimental pressure is naturally decided by the temperature of CVC and the regulated pressure. The mass of the air can be estimated from the CVC's pressure, temperature and volume. In this experiment, the value of the regulated air pressure is obtained by a number of repetitions. Since the injection quantity of fuel can be controlled in proportion to the air mass, the desired equivalence ratio is achieved. Residual gas in the CVC after combustion is scavenged by a vacuum pump.

The relationship between combustion pressure and time elapsed after spark-discharge must be measured accurately in order to obtain the combustion characteristics according to the change of sub-chamber specifications. A specially devised experimental system sche-

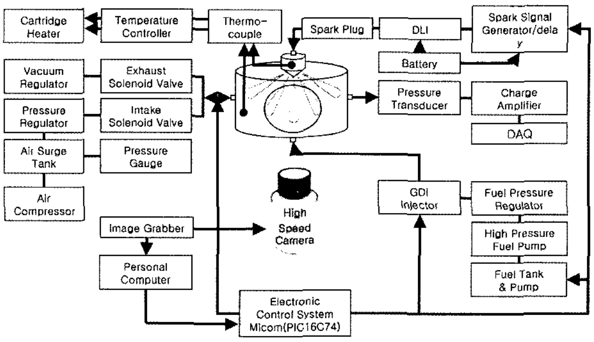


Figure 3. Experimental system for measuring on combustion of pre-mixture in CVC.

matically shown in Figure 3 is used for this purpose. This has the CVC, the fuel supplying part, an ignition device, pressure measuring instruments, a high-speed camera and other components. A high-pressure regulator and a high-pressure pump with a cam drive device were prepared to keep an exact 5MPa fuel injection pressure.

The combustion pressure is measured with a piezo-electric pressure transducer (Kistler Co, 6051B) and stored in a data acquisition system after passing through an amplifier (Kistler Co, 5011). The flame in the CVC is photographed by a high-speed digital camera (Kodak, max. 15000 fps).

2.3. Experimental Procedure and Conditions

Figure 4 shows the experimental sequence of practicing one time of combustion. If the temperature in the CVC reaches the desired temperature, the fuel of the determined quantity is injected by a GDI injector. After that, the intake solenoid valve opens and the constantly pressurized air comes into this main chamber. Then the air and fuel mixture are formed in the sub and main-chambers.

Spark is discharged after 10 seconds to settle the stationary state of pre-mixture (Choi *et al.*, 2003). To scavenge the exhaust gas of the CVC after finishing the combustion process, both the exhaust and intake valves are repeatedly opened and shut without fuel injection. Vacuum pump is also used for a more perfect scavenge.

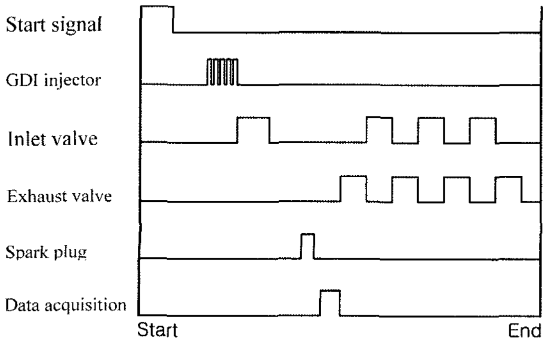


Figure 4. Time chart of electronic control system.

Table 1. List of parameters on experiment.

Parameters		Conditions
Fuel		n-heptane
Initial pressure (P_i)		0.5 MPa
Initial temperature (T_i)		403 K
Equivalence ratio (Φ)		Lean limit, 0.8, 1.0
Volume of CVC	Main (V_m)	487 cc
	Sub (V_s)	2.2, 4, 7cc
Number of passage holes (N_h)		12
Diameter of passage holes (D_h)		1.0, 1.5, 1.8, 2.1, 2.4 mm

In this experiment, the most important thing is to obtain the optimum design value of the sub-chamber as the diameter of the holes and volume of the sub-chamber.

Table 1 shows the experimental conditions for the optimization of the sub-chamber geometry. The number of passage holes of the sub-chamber is fixed at 12, and various sub-chamber volumes and various hole diameters shown in Table 1 are used. In this experiment, n-heptane is used as the test fuel having a boiling point of about 373 K. The experimental temperature and pressure are fixed at 473 K and 0.5 MPa.

3. EXPERIMENTAL RESULTS

3.1. Role of the Sub-chamber in Combustion

Combustion experiment of the pre-mixture is carried out using the experimental system mentioned above. Figure 5 shows the relationship between the combustion pressure and the time elapsed after spark discharge. These factors do not change in all the experiment. It is supposed that the equivalence ratio, Φ, of the mixture in the main and sub-chambers would be same because the pre-mixture

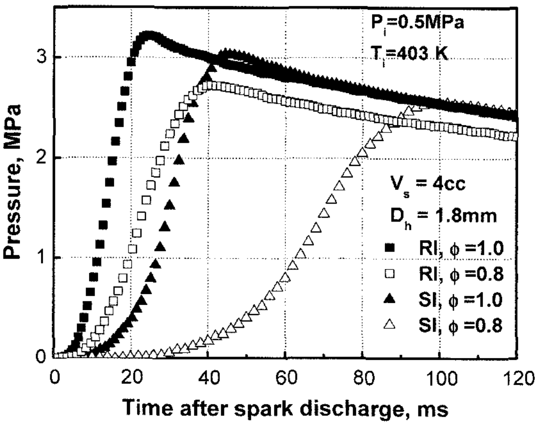


Figure 5. Comparison of combustion pressure characteristic between RI and SI method.

formed in the main chamber comes into the vacuum condition of sub-chamber. However, the concentration of the equivalence ratio of both the sub and main chamber was not measured in this experiment. The flow of the pre-mixture is required to be low enough to obtain generally useful data. The flow of the mixture in the main and sub-chambers is little enough because the spark signal is given to the pre-mixture ten seconds from intake valve open. The decision of the ten seconds is referenced by the same kinds of study (Choi *et al.*, 2003).

Assuming that the combustion finishes at the maximum pressure, the whole combustion period of the RI is shortened by 52% and 45% compared with the same condition of SI.

We think these results are caused by two reasons as follows. Because combustion gas injected into main chamber contains many kinds of radicals, multi point ignitions occur in the main-chamber. By the flame-like awl injected into the main-chamber at all 12 holes, a strong flow is generated around the outside of the sub-chamber. Therefore, these self-flows promote the combustion velocity.

Figure 6 shows the burning images taken by a high-speed camera to show the combustion characteristic by SI and RI. The initial conditions of the CVC are settled at 0.5 MPa in pressure, 403 K in temperature and 1.0 in equivalence ratio. The hole of the sub-chamber is 1.5 mm in diameter. In this figure, the time written under each picture displays the time after spark discharge.

In case of SI, in all ranges, the flame front proceeds with a smooth spherical shape as a laminar flame burning in regular sequence without any other flow generation.

But, in case of RI, the flame shape is largely different from the SI. Namely, it is difficult to distinguish between burned and unburned area compared with SI. This is caused by the holes' effect on the combustion. The flame ignited by the combustion gas from the holes seems to be propagating to the unburned gas with strong turbulence. Therefore, the combustion velocity by RI is faster than SI, and the difference in the combustion velocities can be confirmed by this photograph.

3.2. Effect of Holes' Diameter and Volume on Combustion

To obtain the optimum design value of the sub-chamber, a series of systematic measurements are carried out on the combustion characteristics of RI according to the change of the sub-chamber's volume and the holes diameter. The optimum design value can be obtained by the following. If the holes' diameter is extremely small, they do not have the value to exist in. On the other hand, if the holes diameter is extremely large, the RI method is equal to the SI method.

Figure 7 shows the relationship between the time after spark discharge and the combustion pressure as functions of volume, V_s and the holes' diameter, D_h, of the chamber. The equivalence ratio, Φ, is set at 1.0 in case of (a), and at 0.8 in the case of (b). In this Figure, the combustion pressure has the same meaning to the combustion velocity or combustion duration as mentioned in the explanation of Figure 5.

The combustion velocity in all cases, in Figure 7, is faster than the result of SI shown in Figure 5. The only exception is in an experimental condition. The combustion velocity of $\Phi=1$, in the case of (a), is faster than the lean mixture, in the case of (b).

The combustion velocity is remarkably affected, as expected, by the change of the holes' diameter irrespective of the equivalence ratio change. In each figure in Figure 7, the holes' diameter, which signifies the fastest combustion velocity, shows a different value depending on the scale of the sub-chamber's volume. Therefore, the optimum design value of the sub-chamber can be decided from the diameter of passage hole in the case of RI method.

Figure 8 shows the recomposed diagram from the data

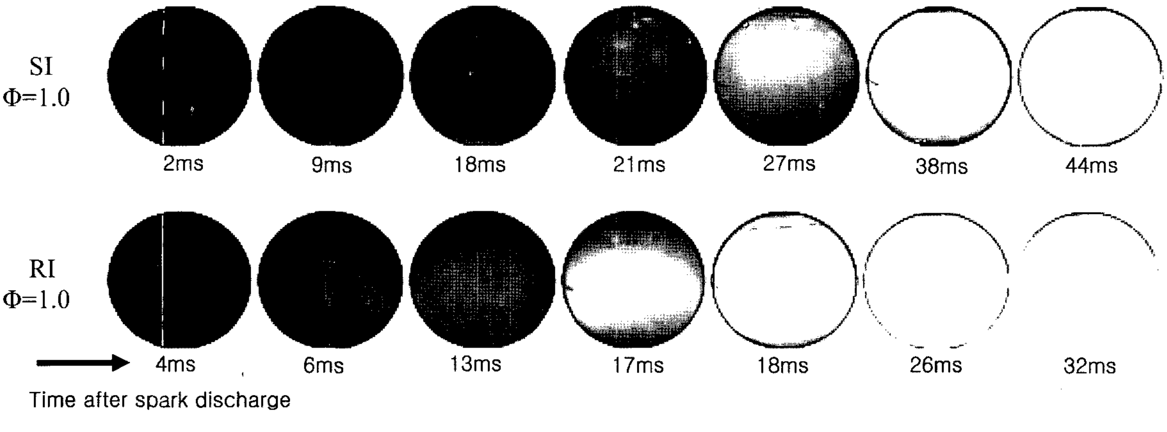
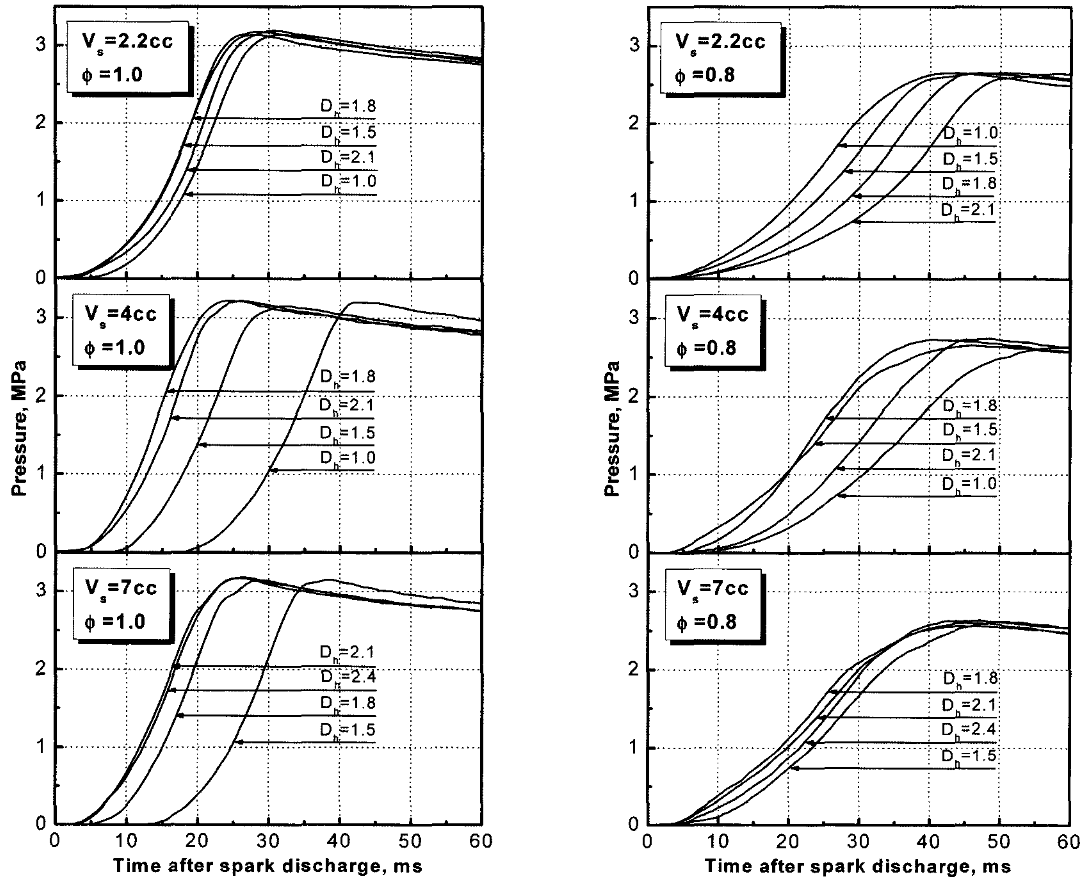


Figure 6. Visualized images of flames in the main chamber in the case of SI and RI.



(a) (b)

Figure 7. Comparison of pressure variation according to the diameter of passage hole in the case of RI method.

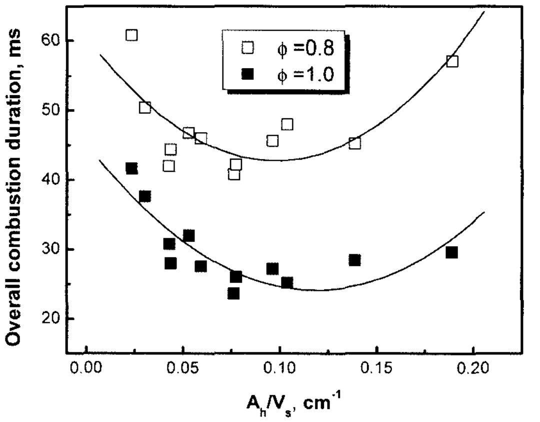


Figure 8. Overall combustion duration for various A_h/V_s ratio.

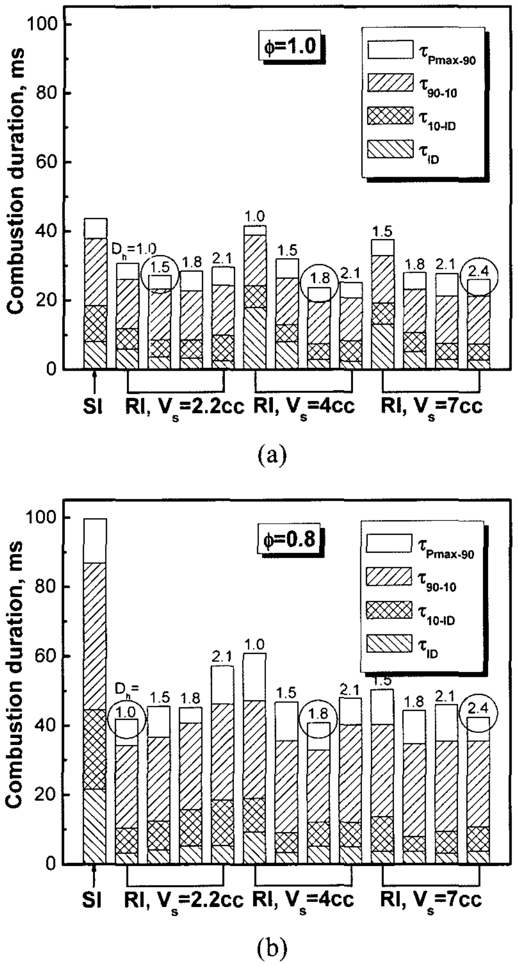
of Figure 7. The ordinate indicates the variation of the combustion duration, having the same concept the time needed to reach the maximum combustion pressure.

The abscissa is the ratio of the total holes area, A_h, to the volume of the sub-chamber, V_s.

The ratio which can minimize the duration of combustion is easily discovered from Figure 8 and the tendency is maintained irrespective of change of the equivalence ratio. The optimum design value of the sub-chamber is shown at 0.101 cm^{-1} and 0.122 cm^{-1} in the A_h/V_S ratio at the condition of 0.8 and 1.0 in the equivalence ratio respectively. Because the leaner or richer condition in equivalence ratio than this experiment is not needed in a regular condition of real engine, it is acceptable that the optimum design value of the sub-chamber is the average value of both, 0.11 cm^{-1}, obtained from this experiment.

In these kinds of studies, detailed information on combustion histories as the ignition delay and the maximum pressure is sometimes discussed to see the combustion phenomenon at a micro point of view.

Figure 9 shows an example of the detailed combustion histories according to the change of the combustion method. In the legend of Figure 9, τ_{id}, $\tau 10$, τ_{90} and τ_{Pmax} have the following meaning: The τ_{id} and τ_{Pmax} is the ignition delay and the maximum pressure, respectively,



(a)

(b)

Figure 9. Detailed information of a combustion process.

and τ_{10} and τ_{90} is the required time to reach 10% and 90% of maximum pressure, respectively. The circled values, in this figure, display the holes' diameter which can minimize the combustion duration at each condition of the volume.

In case of RI, in Figure 9(a), τ_{id} and τ_{10} are considerably shortened compared with SI so these largely affect to the total combustion duration. At the conditions of D_h=1.0 mm of 4cc and D_h=1.5 mm of 7cc in the volume of the sub-chamber, however, τ_{id} of RI is longer than SI. Therefore, it is very important to investigate the effect of the sub-chamber's volume and holes diameter on each process in order to obtain the optimum design value of the sub-chamber.

On the other hand, the specifications of the sub-chamber which can minimize the combustion duration are 4cc in the volume and 1.8 mm in the holes' diameter. Especially, the case of 2.2cc in volume shows a good performance in the combustion duration in spite of a 0.45% in volume compared with that of the main-chamber.

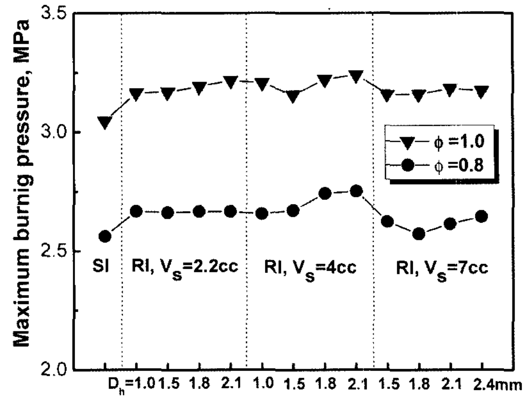


Figure 10. Effects of the holes' diameter and the sub-chamber volume on the maximum combustion pressure.

Figure 9(b) shows the combustion duration for the leaner case than Φ=1 expressed in Figure 9(a). The tendency of the duration is very similar with Figure 9(a). However, the combustion duration of the RI is greatly shortened compared with the decreasing ratio in the case of Φ=1. These means that the RI is more suitable to the leaner mixture combustion.

Figure 10 shows the scale of maximum combustion pressure according to the change of the holes' diameter. The value of the SI is indicated on the left side of the figure. Since, the maximum pressure and combustion duration are in inverse proportion to each other, the heat loss becomes larger according to the combustion duration.

For this reason, if the combustion duration is shorter, the maximum pressure is higher. Therefore, the tendency of the maximum pressure is similar contrary to the tendency of combustion duration shown in Figure 9. However, in case of Φ=0.8 of Figure 10, the difference of the maximum pressure between the SI and the RI is not very large compared with the difference of the combustion duration shown in Figure 9(b). It is influenced by the low temperature caused by the combustion of the relatively lean mixture compared with Φ=1.0.

4. CONCLUSIONS

A sub-chamber type spark ignition is designed to obtain the higher combustion velocity of the pre-mixture. Because the combustion velocity is strongly affected by the holes' diameter and volume of the sub-chamber, a series of systematic experiments are carried out to obtain the optimum design value of the sub-chamber maximizing the combustion velocity. In this experiment, a specially designed CVC and experimental system are used and the main results are as fallows:

(1) The combustion duration by RI is shortened by 59%

compared with SI at 0.8 in the equivalence ratio, and by 45% at 1.0. And the maximum combustion pressure of RI is increased by 6~7% more than SI.

(2) The combustion of RI can be realized at the sub-chamber volume of 0.45% of the main-chamber volume.

(3) The optimum design value of the sub-chamber is near 0.11 cm^{-1} in the ratio of total area of holes to the sub-chamber volume.

(4) By high-speed digital camera, the combustion phenomenon of RI and SI is measured, and the effect of the physical factors on the combustion velocity can be visually estimated.

(5) Combustion duration is largely affected by the ignition delay and initial combustion duration.

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REFERENCES

Bae, C. S., Lee, J. S. and Ha, J. Y. (1998). High-frequency ignition characteristics in a 4-valve SI engine with tumble-swirl flow. *SAE Paper No.* 981010, 115–119.

Choi, G. H., Han, S. B. and Dibble, R. W. (2004). Experimental study on homogeneous charge compression ignition engine operation with exhaust gas recirculation. *Int. J. Automotive Technology* **5**, **3**, 195–200.

Choi, S. H., Jeon, C. H. and Chang, Y. J. (2004). Combustion characteristics of inhomogeneous methane-air mixture in a constant volume combustion chamber. *Int. J. Automotive Technology* **5**, **3**, 181–188.

Choi, S. H. and Joen, C. H. (2003). Combustion characteristics of methane-air mixture in a constant volume chamber. *Trans. Korean Society of Mechanical Engineers* **11**, **3**, 48–57.

Date, T. and Yagi, S. (1974). Research and development of the Honda CVCC engine. *SAE Paper No.*740605.

Higelin, P. and Robinet, C. (1999). A new combustion concept for internal combustion engines. *Prec. 15th Internal Combustion Engine Symp. (Int.),* 413–418.

Kim, M. H., Park, J. S. and Lee, J. H. (2001). Combustion characteristics of plasma jet ignition for different swirl velocity in a constant volume vessel. *Trans. Korean Society of Mechanical Engineers* **9**, **2**, 75–83.

Lee, K. H. and Kim, K. S. (2001). Influence of initial combustion in SI engine on following combustion stage and cycle-by-cycle variation in combustion process. *Int. J. Automotive Technology* **2**, **1**, 25–31.

Park, K. S. (2005). Combustion characteristics and heat flux distribution on premixed propane mixture in a constant volume combustion chamber. *Int. J. Automotive Technology* **6**, **2**, 79–85.

Shudo, T., Nagano, T. and Kobayashi, M. (2003). Combustion characteristics of waste-pyrolysis gases in an internal combustion engine. *Int. J. Automotive Technology* **4**, **1**, 1–8.

Yamaguchi, S., Ohiwa, N. and Hasegawa, T. (1985). Ignition and burning process in a divided chamber bomb. *Combustion and Flame,* **59**, 177–185.