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THE INFLUENCE OF INJECTION TIMING ON THE COMBUSTION CHARACTERISTICS FOR THE HETEROGENEOUS COMBUSTION FIELD USING IMPINGING INJECTION

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Abstract

It is very important to achieve the low particulate and low emissions under high power operation conditions in practical industrial engine and turbine combustion. Several techniques for reducing the emissions have been proposed and a large amount of experimental data has been published. It is well known that the combustion field in practical industrial diesel engine are strongly influenced by the behaviour of injection, distribution of droplets and the premixed ratio of the combustion chamber. As the first step of this study, experiments have been carried out to examine the combustion characteristics of heterogeneous combustion field by using impinging injection and Split injection in a closed chamber. The combustion chamber is equipped with pintle type injection nozzles on each of the opposite walls along the length of the bomb. In this study, we call it "impinging injection" when the injection is performed at same time by two nozzles facing each other and "split injection" when the impinging injection is performed at two different timing. The main conclusions are as follows: 1) the most suitable conditions of injection timing exists for improving the maximum burning pressure and total burning time by using impinging injection; 2) the flame speed can be possible to control by using impinging injection timing from the ignition; 3) the heat release rate for Split injection is larger than that of standard impinging injection.

Keywords: *impinging injection, split injection, heat release rate*

1. Introduction

Global environmental problems and global energy saving problems became very serious. Naturally, internal combustion engines are main causes of these have problems. Furthermore, it is very important to achieve the low emissions under high-load operation conditions in practical internal combustion engines. So it is necessary to achieve low emissions and low fuel consumption for internal combustion engines. Especially, in automotive diesel engines, low-particulate and low-NO_X emissions are very much needed for the heterogeneous combustion field. Over the past few decades, a considerable number of studies have been conducted on these problems from the multiple points. For example, several techniques were developed for reduction of NO_x, CO, HC emissions from the diesel engines such as DI (Direct Injection), EGR (Exhaust gas recirculation), lean combustion, HCCI (Homogeneous Charge Compression Ignition) and blended fuels [1-13]. However, very few attempts have been made at heterogeneous combustion field from the viewpoint of impinging injection for the combustion improvement.

As the first step of this study, experiments have been carried out to examine the combustion characteristics of heterogeneous combustion field by using impinging injection and Split injection in a closed bomb.

2. Experimental apparatus and procedure

Experimental setup is depicted a schematic diagram show in Fig. 1. It consists of a cylindrical combustion chamber, which is equipped with injection nozzles (4A31type GDI: Mitsubishi Motors

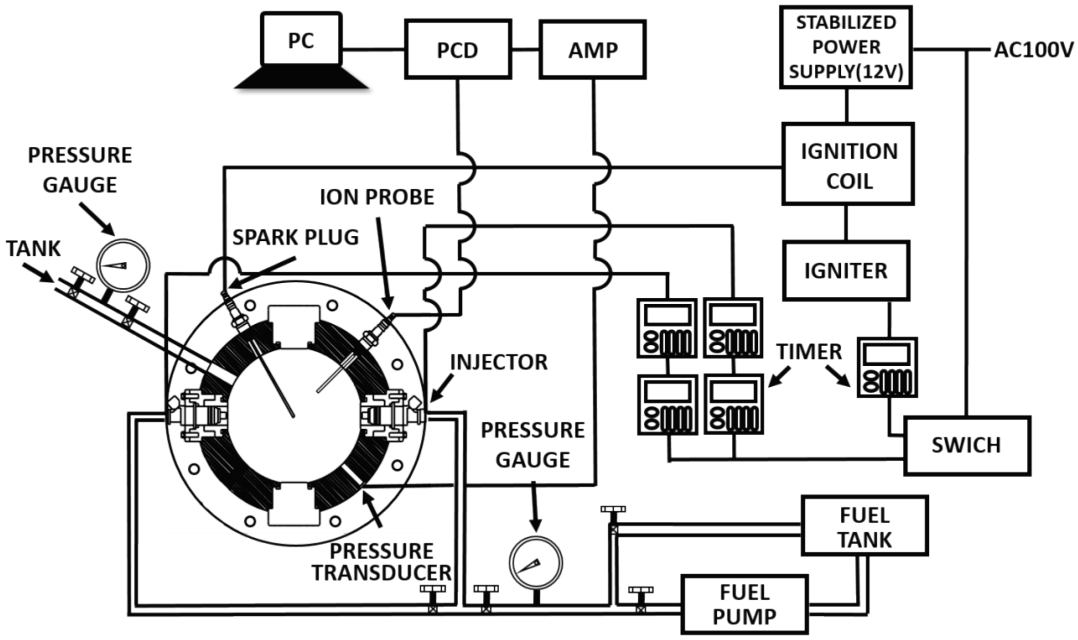

Fig. 1. Schematic diagram of experimental apparatus

Corporation each of the opposite walls is along the length of the combustion chamber. The size of combustion chamber is 160 mm in diameter by 120 mm in length and its volume is approximately 2500 cc. The Bosch type fuel pump (0-580-254-950) is provided to each injection nozzle. The combustion chamber is fitted with a piezo-electric pressure transducer for the measuring the pressure during combustion process. The experiments were carried out under the heterogeneous combustion field by injection of hexadecane in propane-air mixtures for the condition of the atmosphere and room temperature. The behaviour of combustion in a closed chamber is observed by the high-speed digital video camera (Nikon 1 J5) and the Schlieren system (Mizojiri-opt.co: SCHLIEREN COMPACT200). The travel time of flame front is measure by ionization proves located at two different positions from the centre of combustion chamber. The data of 25 tests for each experimental condition were averaged arithmetically, the standard deviation being less than 5%. In these experiments, a mixture before the fuel injection of 79% nitrogen and 21% oxygen by volume is used as a substitute for air. Tab. 1 shows the fuel properties in this study.

Tab. 1. Fuel properties

Fuel\Properties	n-Hexadecane	Propane
Molecular formula	$C_{16}H_{34}$	C_3H_8
Molecular weight (g/mol)	226.4	44.1
Boiling point (ºC)	287	-42.1
Ignition points (ºC)	201	432
Calorific value (kJ/mol)	10691	2204

3. Results and discussion

Figure 2 shows the flame behaviour of impinging injection by using high-speed video camera. The overall equivalence ratio is $\Phi = 0.95$ (After injection of n-hexadecane in propane-air mixtures: $\phi = 0.7$). From the figure it can be seen that after the impinging injection it is occurs the quick combustion at the centre of combustion chamber.

Figure 3 shows the maximum burning pressure versus the injection timing as a function of the equivalence ratio of propane-air mixture. The injection timing was defined the time of difference from injection to ignition (– : before injection, + : after injection, 0.00 [sec] : same timing injection

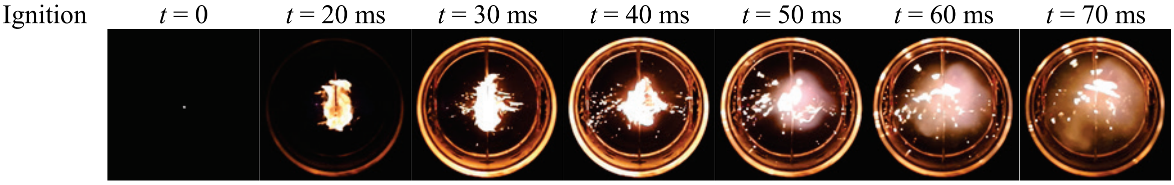

Fig. 2. Flame behaviour of Impinging injection – over all equivalence ratio (after n-hexadecane injection): $\Phi = 0.95$ equivalence ratio of propane-air (before n-hexadecane injection): $\phi = 0.7$

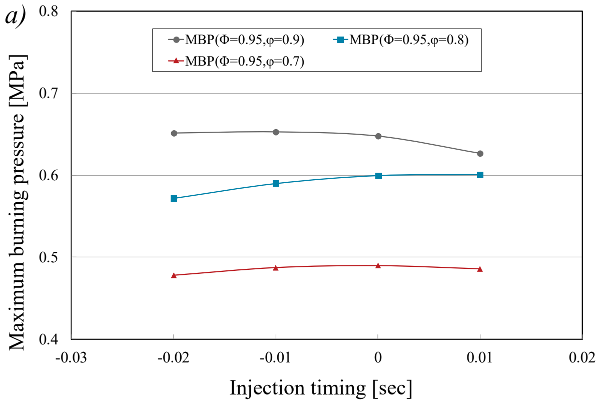

Fig. 3. Maximum burning pressure

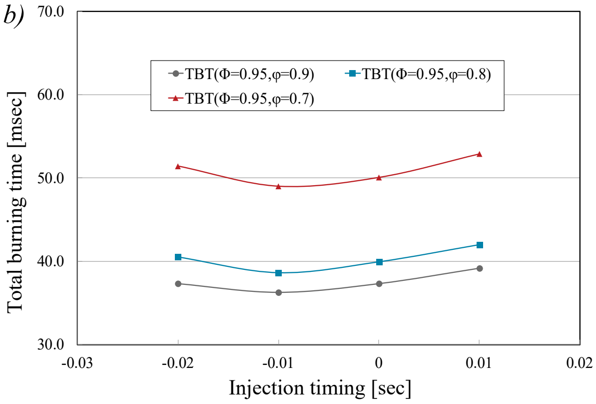

Fig. 4. Total burning time

and ignition). From this figure it can be seen that at constant overall equivalence ratio $\Phi = 0.95$, the maximum value can be observed the equivalence ratio $\phi = 0.9$ of propane-air mixture at any injection timing to ignition. These results suggest that the equivalence ratio of propane-air mixtures (before injection) is a very important factor to achieve the improvement of heterogeneous combustion by using impinging injection. Furthermore, the most suitable conditions of injection timing exist for improving the maximum burning pressure by using impinging injection at any constant equivalence ratio of propane mixtures.

Figure 4 shows the total burning time versus the injection timing as a function of the equivalence ratio of propane-air mixture. As seen from this figure the total burning time decreases with increasing the equivalence ratio of propane-air mixtures (before injection). On the other hand, the minimum value of the total burning time can be observed at injection timing = -0.01 sec. This phenomenon probably means that the fuel distribution near stoichiometric condition (Overall equivalence ratio $\phi = 0.95$) depends on the time difference from injection to ignition.

Figure 5 shows the Schlieren photograph at initial combustion stage (time from ignition 10~20 ms) of different injection timing at overall equivalence ratio $\Phi = 0.95$ and equivalence ratio of propane-air mixture $\phi = 0.7$ by using impinging injection. From this figure, it can be seen that the Schlieren photograph almost same behaviour at initial stage without the injection timing -0.02 sec. This fact indicated that the influence of injection timing on initial combustion stage is smaller than that of middle combustion stage (time from ignition 30~60 ms). Namely, it wants discussion of effects of the injection timing on combustion behaviour under the middle combustion stage.

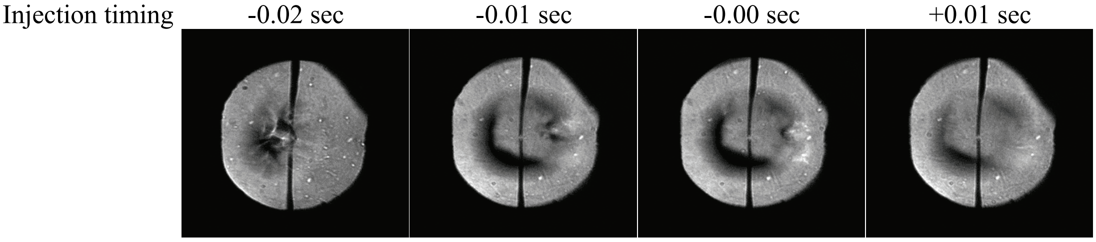

Fig. 5. Schlieren photograph at initial combustion stage of different injection timing

Figure 6 shows the flame behaviour of middle combustion stage (time from ignition: 50 ms) of different injection timing by impinging injection. From this figure, it can be seen that the combustion behaviour for luminous area and number of droplets combustion changes by injection timing. These results suggest that the injection timing is a very important factor to achieve the improvement of middle combustion stage for the heterogeneous combustion field.

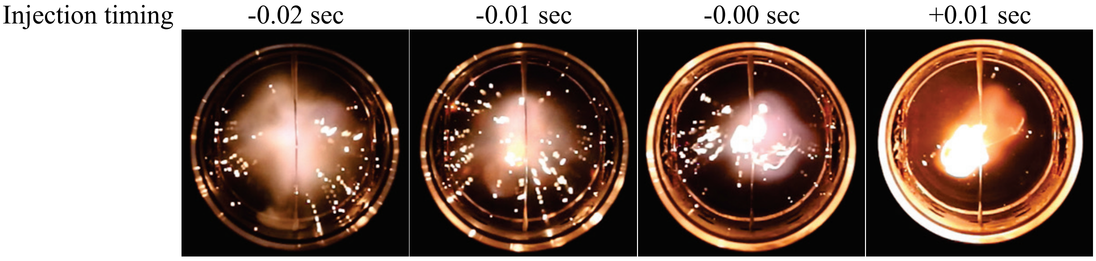

Fig. 6. Flame behaviour of middle combustion stage (time from ignition: 50 ms) of different injection timing by impinging injection – Over all equivalence ratio (after n-hexadecane injection): $\Phi = 0.95$, equivalence ratio of propane-air (before n-hexadecane injection): $\phi = 0.7$

Figure 7 shows the flame speed versus injection timing as a function of overall equivalence ratio (equivalence ratio of propane-air mixture $\phi = 0.7$: constant). From this figure, it can be seen that the maximum flame speed can be observed at -0.01 sec: injection timing for all the overall equivalence ratio. Furthermore, the increasing ratio of flame speed depends on the overall equivalence ratio. It is very interesting fact that the flame speed can possible to control by using impinging injection timing.

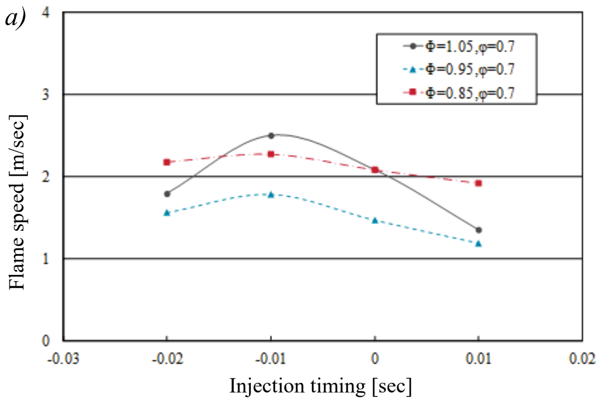

Fig. 7. Flame speed

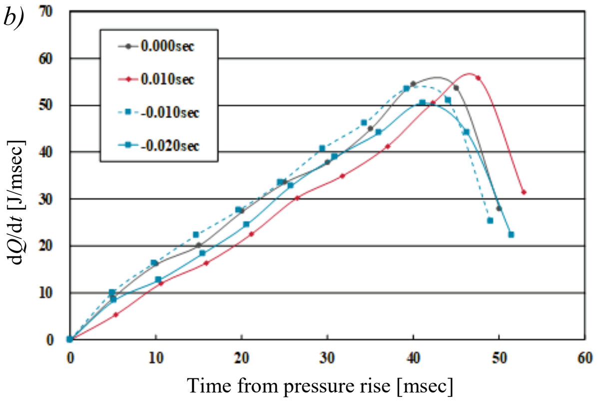

Fig. 8. Heat release rate

Figure 8 shows the heat release rate versus time from pressure rise as a function of injection timing. The heat release rate is given by:

$$\frac{\mathrm{d}Q}{\mathrm{d}\theta} = \frac{\kappa}{\kappa - 1} p \frac{\mathrm{d}V}{\mathrm{d}\theta} + \frac{\kappa}{\kappa - 1} V \frac{\mathrm{d}p}{\mathrm{d}\theta}, \tag{1}$$

$$\frac{\mathrm{d}Q}{\mathrm{d}t} = \frac{C_v}{R} V \frac{\mathrm{d}p}{\mathrm{d}t}, \tag{2}$$

where
dQ/dt - Heat release rate,
C_v – specific heat at constant volume,
R – gas constant,
p – pressure,
V – volume of combustion chamber,

θ – crank angle,
κ – ratio of specific heats.

From this figure it can be seen that the maximum value of heat release rate can be observed by using an after injection timing (+0.01 sec) from the ignition at near the end of combustion. On the other hands, at the first and middle time from pressure rise (10~40 ms), the heat release rate of before injection (-0.01 sec) are bigger than that of other injection timing. This fact indicated that the injection timing has an important role to control for the heterogeneous combustion field. The next step in this study was to examine the effects of Split injection on the heat release rate.

Table 2 shows the Split injection timing of first and second injection (two-stage injection). The amount of total fuel injections is almost constant.

Tab. 2. Injection timing of sprit injection

Split injection	type-I	type-II
First injection	-0.01 sec	-0.02 sec
Second injection	+0.01 sec	+0.01 sec

Figure 9 show the heat release rate versus time from pressure rise as a function of injection timing. From this figure, it can be seen that the maximum value of heat release rate can be observed by using a sprit injection I from the ignition at near the end of combustion. Furthermore, the increasing ratio about 15% than that of normal impinging injection (0.00 sec). This fact indicated that the split injection could be very useful for increasing the maximum heat release rate.

Figure 10 shows the increasing value of the heat release rate versus time from pressure rise as a function of injection timing. Where the increasing value defined that the each heat release rate – standard heat release rate (0.000 sec) at same time from pressure rise. As seen from this figure it can be seen that the increasing value are changeable of the injection timing.

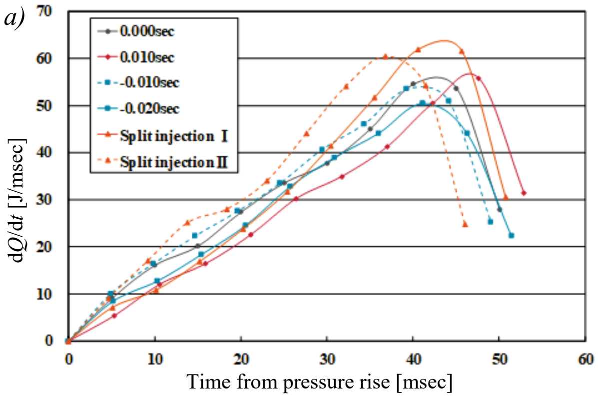

Fig. 9. Heat release rate

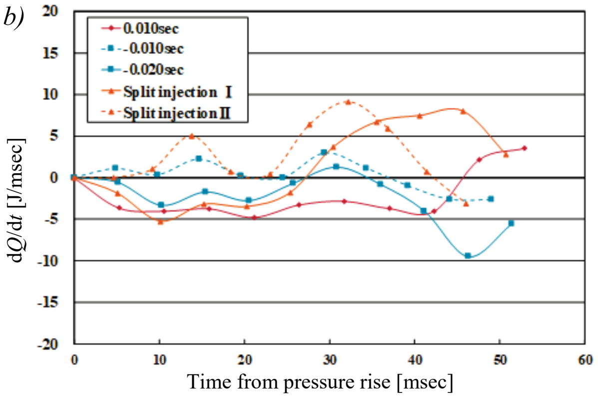

Fig. 10. Heat release rate

4. Conclusions

Experiments have been carried out to examine the combustion characteristics of heterogeneous combustion field by using impinging injection and split injection in a closed bomb. The main conclusions are as follows:

1) The most suitable conditions of injection timing exists for improving the maximum burning pressure and total burning time by using impinging injection.
2) The flame speed can be possible to control by using impinging injection timing from the ignition.
3) The heat release rate for split injection is larger than that of standard impinging injection.

References

[1] Peterson, B., Reuss, D. L., Sick, V., *On the ignition and flame development in a spray-guided direct-injection spark-ignition engine*, Combustion and Flame, Vol. 161, pp. 240-255, 2014.

[2] Iijima, A., Shoji, H., *A study of HCCI combustion characteristics using spectroscopic techniques*, SAE Paper No. 2007-01-1886, 2007.

[3] Tsutsumi, Y., Hoshina, K., Iijima, A., Shoji, H., *Analysis of the combustion characteristics of HCCI engine operationg on DME and methane*, SAE Paper No. 2007-32-0041, 2007.

[4] Lim, O. T., et al., *The fuel unmixedness effect on DME HCCI combustion using rapid compression and expansion machine*, SAE Paper No. 2007-42-0042, 2007.

[5] Daisho, Y., et al., *Contolling combustion and exhaust emissions in a direct-injection diesel engine dual-fueled with natural gas*, SAE Paper, No. 952436, 1995.

[6] Tomita, E., et al., *Effects of EGR and early injection of diesel fuel on combustion characteristics and exhaust emissions in a methane dual fuel engine*, SAE Paper No. 2002-01-2723, 2002.

[7] Hill, P. G., et al., *NO_x reduction from heavy-duty diesel engine with direct injection of natural gas and cooled exhaust gas recirculation*, International Journal of Engine Research, Vol. 5, No. 2, pp. 175-191, 2003.

[8] Tomita, E., et al., *Combustion characteristics and performance of supercharged micro-pilot natural gas engine*, Proceedings of FISITA 2006 World Automotive Congress, Paper No. F2006 p230, pp. 1-10, 2006.

[9] Ozaki, J., Iida, N., *Effect of degree of unmixedness on HCCI combustion based on experiment and numerical analysis*, SAE Paper No. 2006-32-0046, 2006.

[10] Sugiyama, H., Kawakami, T., *Influence of blend fuels on combustion characteristics for small diesel engine*, Small Engine Technology Conference SAE of JAPAN and SAE International, 20076523/2007-32-0023, 2007.

[11] Kawakami, T., *Combustion characteristics for small diesel engine by using emulsified blend fuels of vegetable oil and light oil*, Journal of KONES Powertrain and Transport, Vol. 18, No. 4, pp. 185-190, 2011.

[12] Kawakami, T., *A study of emission reduction by using alcohol blend fuel for small diesel engine*, Journal of KONES Powertrain and Transport, Vol. 21, No. 1, pp. 125-130, 2014.

[13] Kawakami, T., *Experimental study of emission reduction by using alcohol blended fuel for small gasoline engine*, Journal of KONES Powertrain and Transport, Vol. 22, No. 2, pp. 115-120, 2015.

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