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ANALYSIS OF DIRECT INJECTION SI STRATIFIED COMBUSTION IN HYDROGEN LEAN MIXTURE

- COMBUSTION PROMOTION AND COOLING LOSS BY HYDROGEN -

TOSHIO SHUDO[1)*] and KOICHIRO TSUGA[2)]

[1)]Musashi Institute of Technology, Tamazutsumi 1-28-1, Setagaya-ward, Tokyo, Japan
[2)]Jatoco Transtechnology Co., Imaizumi 700, Fuji-city, Shizuoka-pref., Japan

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ABSTRACT–Characteristics of methane direct–injection spark–ignition stratified combustion in lean hydrogen mixture were analyzed both in a single cylinder engine and in a constant volume combustion chamber. Combustion pressure and instantaneous combustion chamber wall temperature during the combustion process were measured with a thin-film thermocouple and used in analyses of combustion and cooling loss. Results in this research show that the premixed hydrogen increases cooling loss to combustion chamber wall while achieving combustion promotion, and the combustion system is effective especially in lean mixture conditions. Analysis of flame propagation was also done with Schlieren photography in the constant volume combustion chamber.

KEY WORDS : Stratified charge, Hydrogen, Methane, Lean combustion, Cooling loss

NOMENCLATURE

λ	: excess air ratio
LHV	: lower heating value
dQ/dt	: heat release rate
Q	: heat release
Q_{fuel}	: LHV of supplied fuel
Q_B	: real heat release
Q_C	: cooling heat
ϕ_w	: cooling loss ratio
η_i	: indicated thermal efficiency
η_u	: combustion efficiency
$\theta_{10\text{-}90}$	: 10-90% combustion period

1. INTRODUCTION

Although direct–injection(DI) natural–gas engines are expected to have higher thermal efficiency with lean combustion, there remain some problems such as low combustion velocity and relatively high unburned hydrocarbon exhaust emission at light load lean operation.

Direct–injection stratified charge combustion with two-stage fuel injection system has been reported to promote combustion and to expand range of knock free operation in the use of hydrocarbon fuels (Shudo, *et al.*, 1993, Miyamoto, *et al.*, 1994, Ando 1998). On the other hand, hydrogen has an extremely higher burning velocity and wider flammable limits compared to hydrocarbon fuels (Lewis and Elbe 1961). A hydrogen addition to methane has been reported to be effective to promote combustion at homogeneous lean operation (Kido, *et al.*, 1994, Shioji, *et al.*, 1995).

Authors propose the hydrogen addition to direct injection natural gas engines to increase combustion velocity and to reduce hydrocarbon exhaust emission. In this research, characteristics of methane direct injection spark ignition stratified combustion in lean hydrogen mixture were analyzed both in a single cylinder engine and a constant volume combustion chamber. Combustion pressure and instantaneous combustion chamber wall temperature during combustion process were measured with a thin-film thermocouple and used in analyses of combustion characteristics and cooling loss to combustion chamber wall.

Results in this research show that the combustion system can achieve lower hydrocarbon exhaust emission and higher thermal efficiency compared to methane DI spark–ignition combustion, however the premixed hydrogen increases cooling loss to combustion chamber wall while achieving the combustion promotion. The combustion system of methane DI stratified combustion in hydrogen lean mixture is effective especially in lean conditions.

**Corresponding author.* e-mail: shudo@herc.musashi-tech.ac.jp

2. EXPERIMENT

2.1. Single Cylinder Engine

The engine tested in this research was a four-stroke cycle single cylinder spark–ignition engine with a bore × stroke of 85 × 88 mm and a compression ratio of 13. Hydrogen was continuously supplied into the intake manifold, and methane was directly injected into the cylinder using a mechanical type gas injector at an injection timing of 35 degree CA ATDC with an injection pressure of 10 MPa. The fuel injection direction was toward the spark plug as shown in Figure 1. For each experimental condition, 200 cycles of in-cylinder pressure data were measured with piezoelectric type pressure transducer (AVL GM12D) which was installed in the cylinder head and used to analyze indicated thermal efficiency. NOx exhaust emissions was measured with a CLD gas analyzer, and THC emission was with an FID gas analyzer.

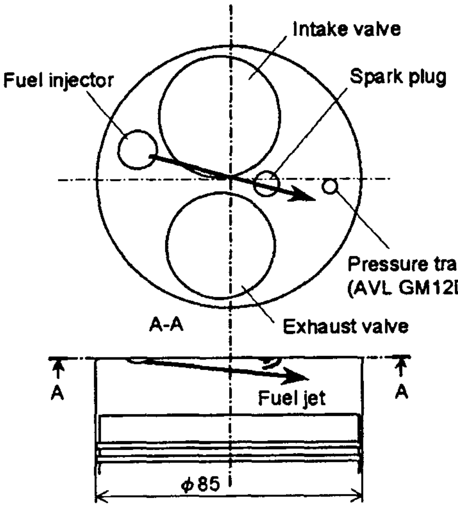


Figure 1. Tested single cylinder engine.

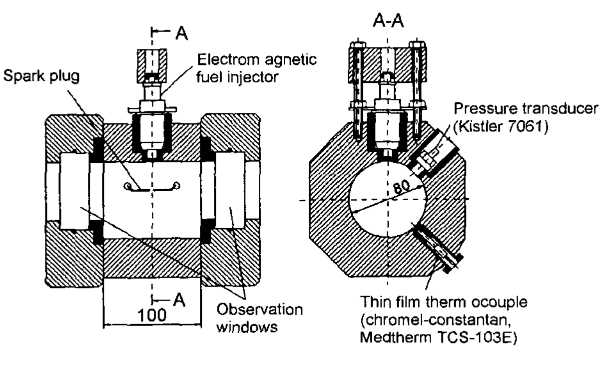


Figure 2. Constant volume combustion chamber in this research.

2.2. Constant Volume Combustion Chamber

A constant volume combustion chamber used in this research is shown in Figure 2. The chamber had transparent quartz observation windows on both sides. Methane was directly injected into lean mixture of hydrogen and air, and was ignited with a spark plug. The fuel injection direction was toward the spark plug. Methane was injected with an electromagnetic fuel injector that was installed with a nozzle (a hole of ϕ1 mm). Fuel injection pressure was at 3 MPa. Combustion pressure was measured with a piezoelectric type pressure transducer (Kistler 7061) and used in the analyses of heat release rate, heat release, and combustion period. Instantaneous temperature data of combustion chamber wall surface were measured with a thin-film type thermocouple (Medtherm TCS-103E, chromel-constantan type, response of 1 μs) and used in the analyses of cooling loss characteristics. Observations of flame propagation were done with the Schlieren method using a mercury lamp (Ushio USH-500D). Images were recorded with a memory type high-speed video camera (Photoron FASTCAM ultima).

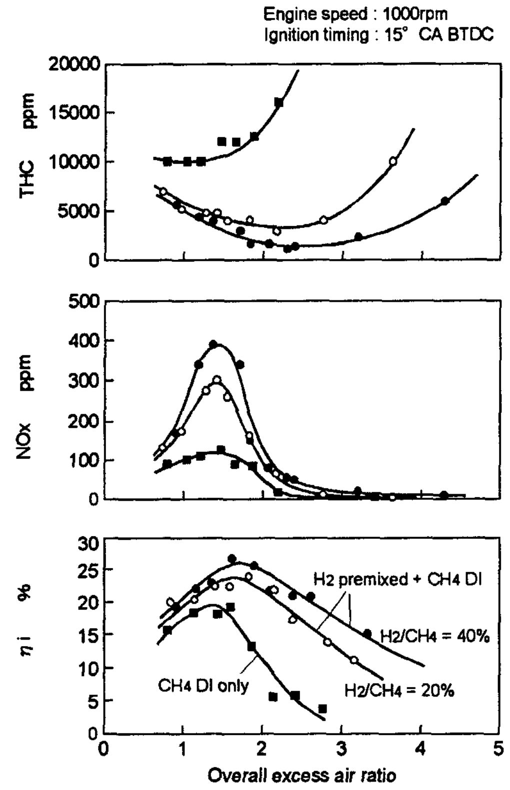
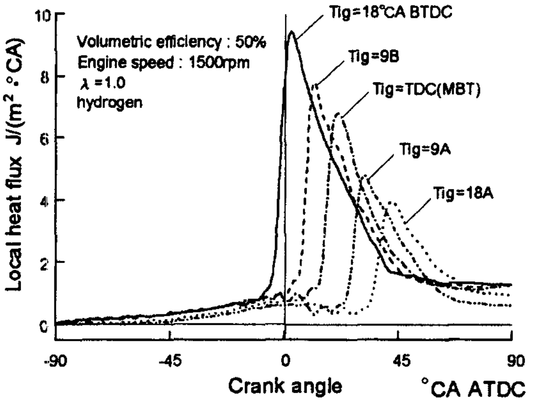
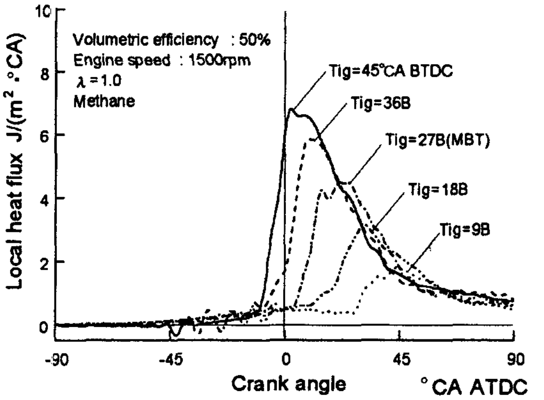


Figure 3. Influence of overall excess air ratio on thermal efficiency and exhaust emissions.



(a) Hydrogen combustion



(b) Methane combustion

Figure 4. Instantaneous heat flux of hydrogen combustion and methane combustion (Shudo, *et al.*, 1999). Tested in a 4-stroke 4-cylinder SI engine with bore × stroke of 85 × 88 mm and a compression ratio of 8.5.

3. RESULTS AND DISCUSSION

3.1. Results of Engine Experiments

Figure 3 is a result of engine experiment showing the influence of hydrogen premixing ratio on combustion and exhaust emissions. Engine speed was set at 1000 rpm, and ignition timing was at 15 degree CA BTDC. The overall excess air ratio was calculated with both premixed hydrogen and directly injected methane. The hydrogen premixing improves thermal efficiency and reduces THC largely over the wide range of excess air ratio. Although NOx increases especially at condition between stoichiometric to excess air ratio of 2.0, the hydrogen premixing enables operation at very lean conditions.

However, hydrogen combustion has higher cooling loss to combustion chamber wall than hydrocarbon (Shudo *et al.*, 1999). Burning velocity of hydrogen is around 7 times higher than hydrocarbons, and quenching distance is around 1/4 of hydrocarbons. The high flame propagation velocity increases forced convection between flame and chamber wall. The short quenching distance decreases width of temperature boundary layer on chamber wall. Figure 4 indicates the instantaneous heat flux of hydrogen combustion and methane combustion at the premixed combustion engine. Compared to methane combustion, hydrogen combustion has higher amount of heat flux during combustion period. It means that hydrogen combustion has higher amount of cooling loss.

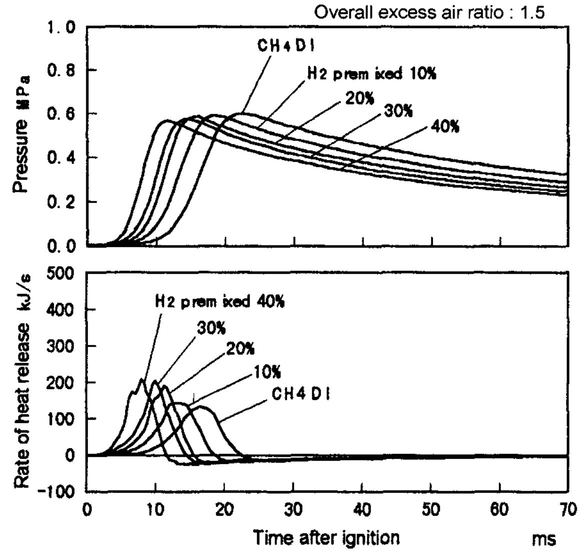


Figure 5. Influence of hydrogen addition on methane DI combustion.

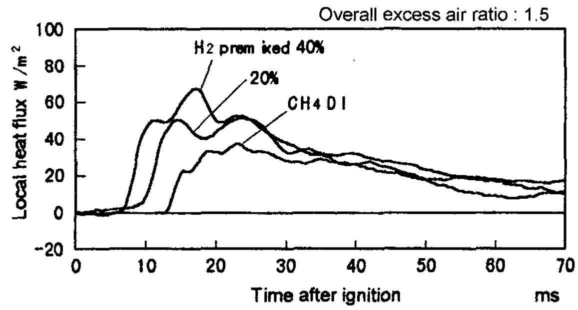


Figure 6. Influence of hydrogen addition on local heat flux.

From these results, the premixed hydrogen is supposed to influence cooling loss characteristics in the methane DI stratified charge combustion. This research analyzed combustion promotion and cooling loss of methane direct injection stratified charge combustion with hydrogen premixing using the constant volume combustion chamber.

3.2. Influence of Hydrogen Premixing Ratio

Figure 5 shows influence of hydrogen premixing ratio on combustion characteristics. Experiments were done with the constant volume combustion chamber shown in Figure 2. Overall excess air ratio, that was calculated with both premixed hydrogen and directly injected methane, was set at 1.5. Hydrogen premixing ratio in the figure shows proportion of premixed hydrogen to totally supplied fuel in low heating value. With an increase in hydrogen premixing ratio, combustion was promoted, and combustion period is shortened. The increase in hydrogen premixing ratio causes decrease in total fuel heat. But the difference is 2.4% at the most and its influence is negligible.

Figure 6 shows instantaneous heat flux to combustion chamber that was calculated from the instantaneous temperature of the combustion chamber wall surface. The instantaneous heat flux was calculated with an assumption of one-dimensional thermal conduction in the combustion chamber wall. With increase in hydrogen premixing ratio, the instantaneous local heat flux increases showing the increase in cooling loss to combustion chamber. These results were analyzed using following indexes;

(1) maximum value of heat release rate: dQ/dt_{max}

(2) 10-90% combustion period: $\theta_{10\text{-}90}$

(3) maximum value of instantaneous heat flux: q_{max}

(4) ratio of heat release to supplied fuel heat: Q/Q_{fuel}

Degree of combustion promotion was evaluated with maximum heat release rate dQ/dt_{max} and 10-90% combustion period $\theta_{10\text{-}90}$. Trend of cooling loss was evaluated with maximum value of instantaneous local heat flux q_{max} and Q/Q_{fuel}. The index Q/Q_{fuel} was calculated with total heat release Q and low heating value of supplied fuel Q_{fuel}. The Q calculated with pressure data is affected by cooling loss, and described using real heat release Q_B and cooling heat Q_C as follows.

$$Q = Q_B - Q_C \tag{1}$$

Here, the actual heat release Q_B is affected by combustion efficiency and is described as follows.

$$Q_B = \eta_u Q_{fuel} \tag{2}$$

And Q/Q_{fuel} can be described,

$$Q/Q_{fuel} = (Q_B - Q_C)/Q_{fuel} = (Q_B - Q_C)\eta_u/Q_B = \eta_u(1-\phi_w) \tag{3}$$

Where, $\phi_w = Q_C/Q_B$.

Therefore, the Q/Q_{fuel} corresponds to a function of combustion efficiency η_u and cooling loss ratio ϕ_w which is defined above with real heat release Q_B and cooling heat Q_C.

It is possible to evaluate the trend of cooling loss by using the Q/Q_{fuel}.

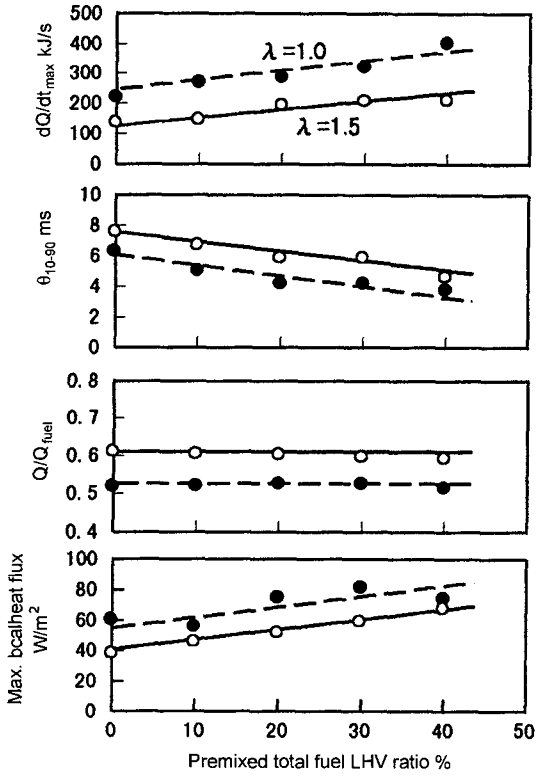
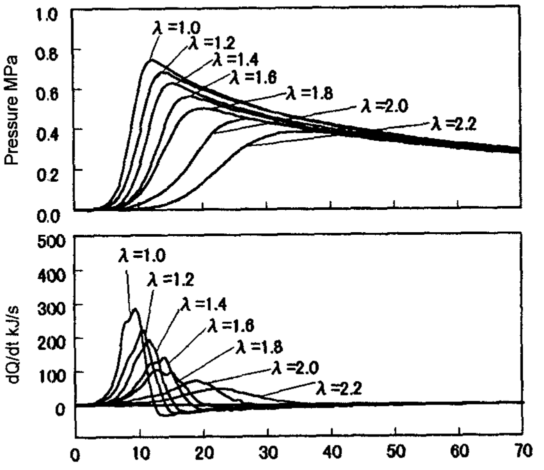


Figure 7. Influence of premixed hydrogen amount on combustion.

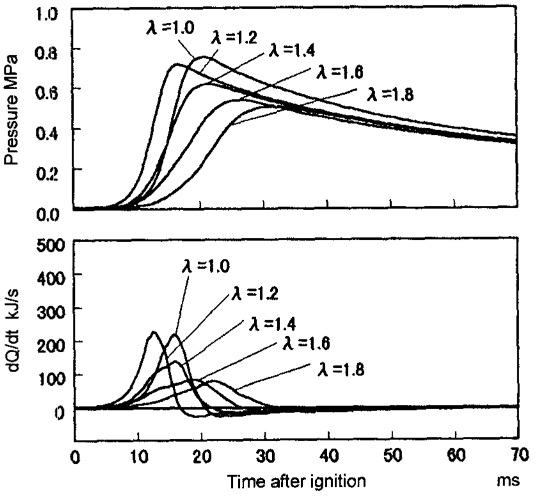
Figure 7 shows a result of the evaluation. Excess air ratios are λ=1.0 and 1.5. In both excess air ratios, maximum heat release rate increases and combustion period decreases with increase in premixed hydrogen. These prove combustion promotion by hydrogen premixing. On the other hand, maximum local heat flux shows increases in the cooling loss. However, change in Q/Q_{fuel}, the function of combustion efficiency and cooling loss ratio, is small. Premixed hydrogen increases combustion efficiency and cooling loss ratio. Therefore, those two factors are considered to be balanced and the change in Q/Q_{fuel} is small.

3.3. Influence of Excess Air Ratio

Figure 8 shows the influence of overall excess air ratio on combustion characteristics with and without hydrogen premixing. Hydrogen premixing ratio was set at 20% in LHV. In both conditions heat release pattern becomes sharper with decrease in excess air ratio. Methane DI combustion at stoichiometric is slower than that at excess air ratio of 1.2. It is due to over rich condition. At any excess air ratio, combustion with hydrogen premixing has higher and faster heat release than methane DI combustion. Instantaneous local heat fluxes in these cases are shown in Figure 9. In both combustion systems, instantaneous local heat flux decreases with increase in



(a) H_2 premixed 20% + methane DI



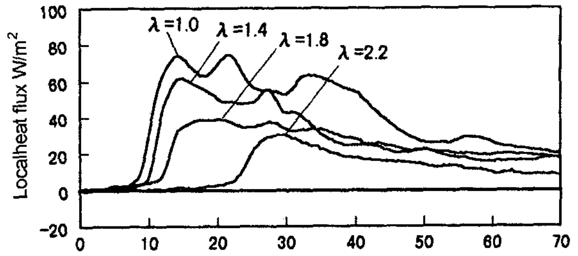
(b) Methane DI only

Figure 8. Influence of excess air ratio on combustion.

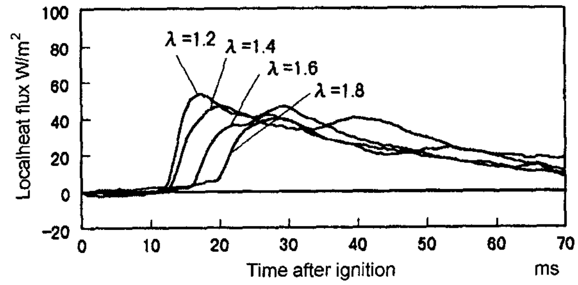
excess air ratio. Combustion with hydrogen premixing shows larger heat flux at any condition.

Figure 10 shows influence of overall excess air ratio on dQ/dt_{max}, $\theta_{10\text{-}90}$, Q/Q_{fuel}, and maximum heat flux. Premixed hydrogen reduces combustion period and increases maximum heat release rate. Although the result means combustion promotion, maximum heat flux is higher than methane at any excess air ratio. Because of the increased cooling loss, Q/Q_{fuel} is lower in conditions of excess air ratio from 1.0 to 2.0. However, in sufficient lean condition over excess air ratio of around 1.8, Q/Q_{fuel} of hydrogen premixing is higher than methane combustion.

Figure 11 shows relation between maximum heat release rate and maximum heat flux with and without hydrogen premixing. The hydrogen premixing ratio was 20% in LHV. In both combustion systems, maximum



(a) H_2 premixed 20% + methane DI



(b) Methane DI only

Figure 9. Influence of excess air ratio on heat flux to the wall.

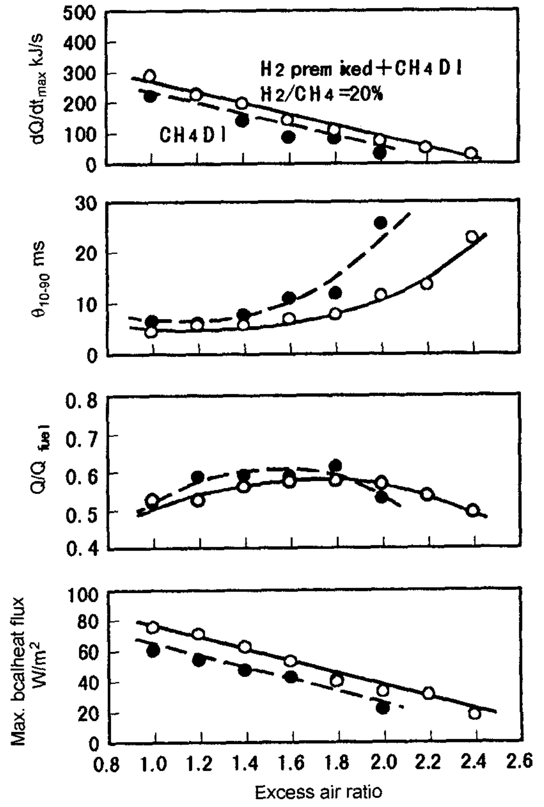


Figure 10. Influence of excess air ratio on combustion.

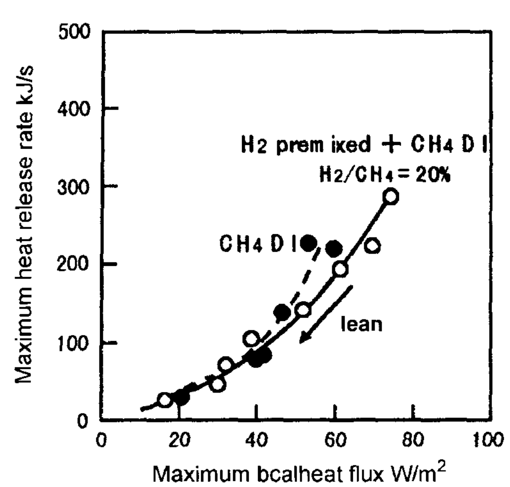


Figure 11. Relationship between maximum local heat flux and maximum rate of heat release.

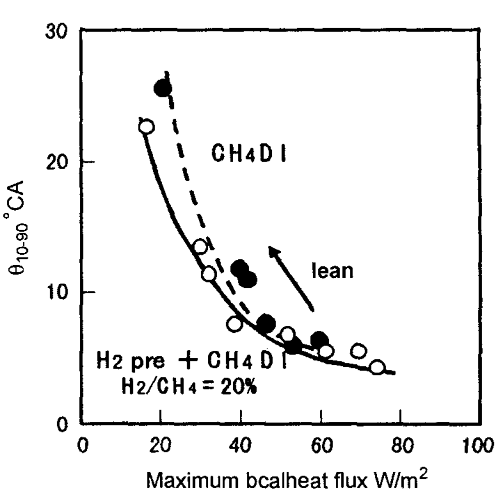
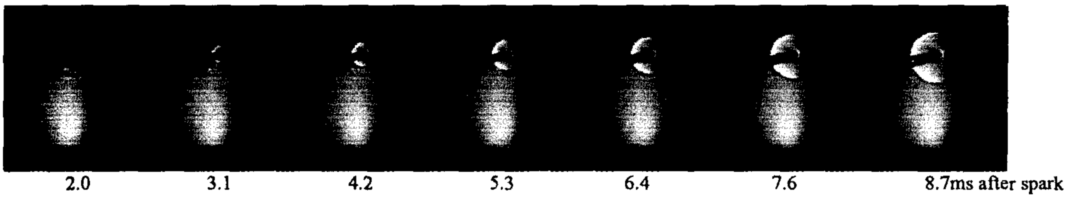


Figure 12. Relationship between maximum local heat flux and combustion period.

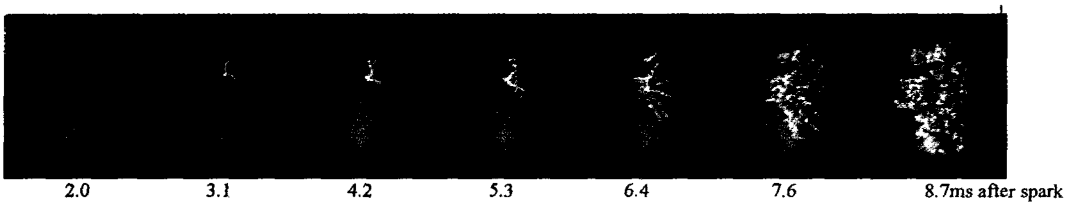
heat flux and maximum heat release rate decrease with increase in excess air ratio. However, In the cases with similar level of heat release rate, premixed hydrogen increases maximum heat flux. The difference becomes smaller in lean combustion.

Figure 12 shows relation between combustion period and maximum heat flux. With increase in excess air ratio, both combustion period and maximum heat flux increase. In the cases with similar combustion period, hydrogen premixing shows smaller heat flux than methane direct injection only.

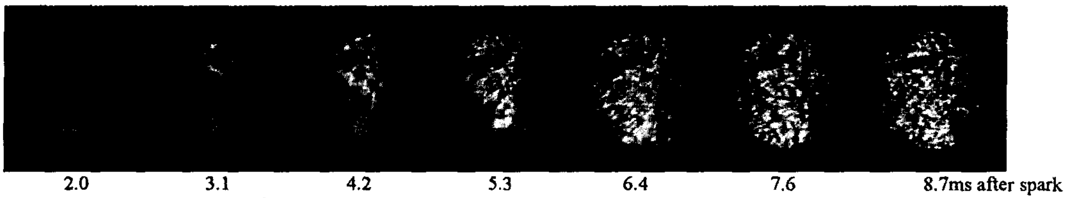
These results suggest that although the combustion promotion with hydrogen premixing causes increase in cooling loss, combustion promotion exceeds cooling loss in lean operation conditions. Therefore, the combustion system of methane DI stratified combustion in hydrogen



(a) Methane homogeneous combustion



(b) Methane DI stratified combusion



(c) Methane DI stratified combustion with hydrogen premixing (H_2 premixed 20% in LHV)

Figure 13. Schlieren photography of combustion flame at stoichiometric.

lean mixture is effective at lean operation.

3.4. Observation of Flame Propagation

Figure 13 shows schlieren photography of combustion flame for three operating conditions: methane homogeneous combustion, methane DI stratified combustion and methane DI stratified combustion with hydrogen premixing. Hydrogen premixing ratio was set at 20% in LHV. Overall excess air ratio was set at stoichiometric. Compared to the methane homogeneous combustion, methane DI combustion shows faster flame propagation, because of the turbulence generated by the fuel injection. The methane DI stratified combustion with hydrogen premixing shows highly promoted flame propagation. The increase in forced convection due to the higher flame propagation velocity is considered to increase heat transfer between flame and combustion chamber wall.

4. CONCLUSION

Results in this research can be summarized as follows:

(1) Premixed hydrogen in methane DI stratified charge combustion promotes combustion to shorten combustion periods and to increase maximum value of heat release rate.
(2) Hydrogen premixing tends to increase cooling loss to combustion chamber wall while achieving combustion promotion.
(3) Schlieren photography of combustion flame shows increase in flame propagation velocity by premixed hydrogen.
(4) Increase in forced convection due to higher flame propagation velocity of hydrogen is considered to increase heat transfer between combustion gas and combustion chamber wall.
(5) In lean operation, combustion promotion with premixed hydrogen exceeds cooling loss to increase Q/Q_{fuel} compared to methane direct injection stratified charge combustion.

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