21 The Study on Auto-ignition and Combustion Process of the Fuel Blended with Methane and DME in HCCI Engine

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The Homogeneous Charge Compression Ignition (HCCI) engine is regarded as the next generation engine in terms of high thermal efficiency and low emissions. However, it is difficult to control ignition timing in HCCI combustion because auto-ignition depends on oxidation reaction of the fuel. It is desirable for ignition temperature to be changed freely in order to control ignition timing. Changing ignition temperature by using only one component fuel is impossible. To solve this problem, fuel blended with Methane and DME was used in this study. In this study, the influence of the mixing ratio between Methane and DME on HCCI combustion is investigated.

Keywords: *Engine Combustion, Thermal Engineering, Fuel* / *HCCI, Methane, DME, IMEP*

1. INTRODUCTION

The Homogeneous Charge Compression Ignition (HCCI) engine is a type of engine in which the pre-mixture of fuel and air is introduced into the combustion chamber and ignited by adiabatic compression of the piston [1][2]. The HCCI engine is regarded as the next generation engine because of high efficiency and low emission. However, it still is not put to practical use because controlling ignition timing is difficult and knocking hampers high load operation.

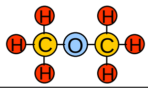
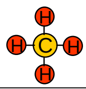
In the HCCI engine, ignition depends on the oxidation reaction of the fuel so it is necessary to understand the fuel characteristics of ignition and combustion. Shibata and others researched the effect that fuel types in gasoline have on HCCI combustion and suggested that using octane index as the index of HCCI combustion was wrong [3]. Konno and others used a Methane/DME fuel mixture in the HCCI engine [4]. They controlled ignition timing by changing the mixing ratio between Methane and DME and showed that rate of heat release (RHR) became suppressed when the combustion reaction appeared in the expansion stroke. On the other hand, the method of applying heterogeneity to the fuel or heterogeneity to the temperature was suggested for the purpose of high load operation avoiding knocking in the HCCI engine [5][6]. It was indicated that the distribution of ignition timing was scattered because of this method, causing RHR to become suppressed.

In this study, the Methane/DME fuel mixture was adopted in the HCCI engine and how the operation region was formed was investigated when the experimental parameters were Methane-based equivalence ratio and DME-based equivalence ratio. In addition, the effect of intake gas temperature, engine speed and compression ratio on this operation region was also studied.

2. TEST FUELS

In this study, Methane and DME were used as the test fuels. The properties of these fuels are shown in Table 1 and the Arrhenius plot of the ignition delay in several mixing ratios between the two fuels is shown in Fig. 1. Numerical calculation was done to create this Arrhenius plot. CHEMKIN II [7] and SENKIN [8] codes were used to calculate the chemical kinetics of the elementary reactions and Curran's scheme [9] (species: 79, reactions: 336) was selected as the elementary reaction scheme of Methane and DME. Each X_{CH4} and

Table1 Fuel properties

Fuel Name	DME	CH_4
Molecular Structure		
Molecular Weight	46.069	16.049
Cetane Number	55−60	0
Low Heat Release Value (MJ/kg)	28.8	48.3
Ideal Air/Fuel Ratio	9	9.52
Ignition Temperature (K)	623	905
Low Temperature Reaction	○	×

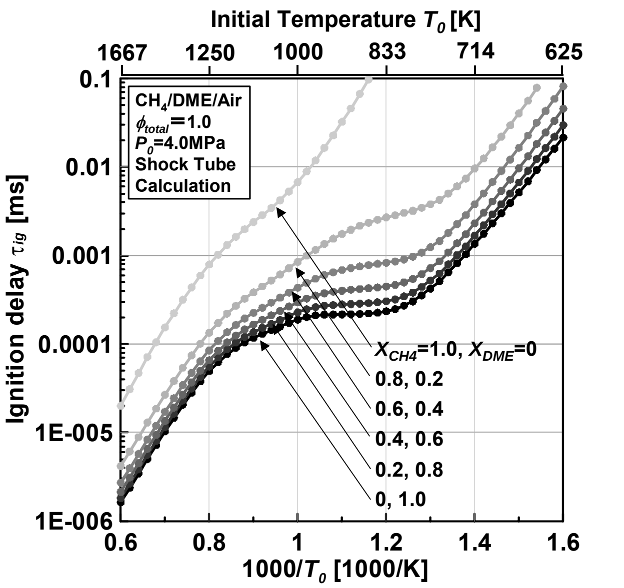


Fig. 1 The Arrehenius plot of Methane/DME fuel mixture

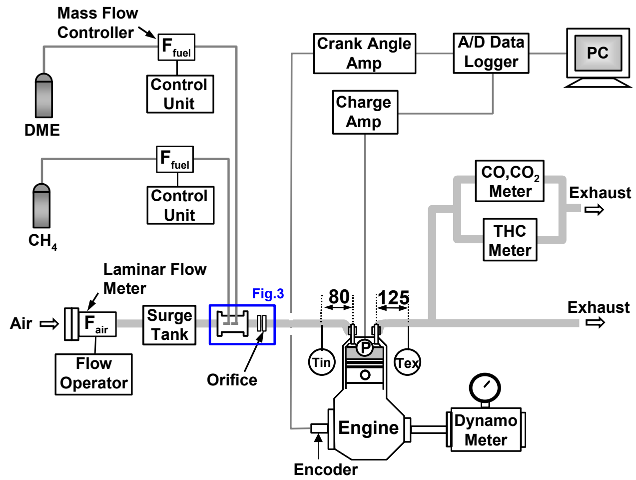


Fig. 2 Experiment system

Table2 Engine specification

Type of Engine	4-Stroke Water Cooled Single Cylinder
Displacement	1132 cc
Bore X Stroke	112 mm X 115 mm
Intake Valve Close	ATDC -132 degree
Exhaust Valve Open	ATDC 132 degree
Compression Ratio	21.6

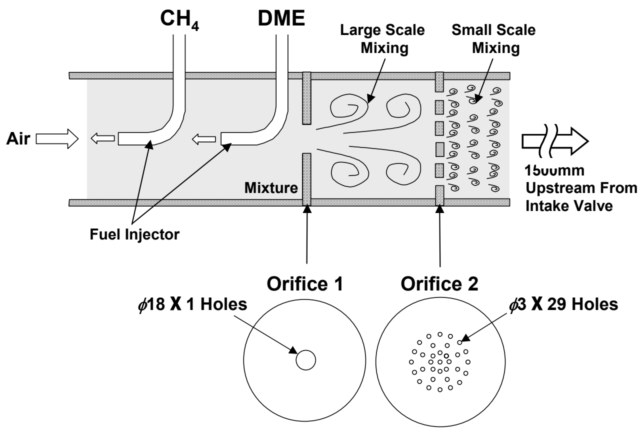


Fig. 3 Fuel supply port and orifices

Table3 Experimental conditions

Compression Ratio ε	Engine Speed Ne	Intake Gas Temperature T_{in}	Intake Gas Pressure P_{in}
21.6 16.4	960 rpm 600 rpm	300 K 350 K	0.1 MPa

X_{DME} indicates the mole fraction of Methane and DME in the fuel (X_{CH4}+X_{DME} = 1). When the mixing ratio of DME increased, ignition delay was shortened and the Negative Temperature Coefficient (NTC) area appeared clearly. As shown in Fig. 1, changing the mixing ratio enables to change combustion characteristics significantly.

3. RESEARCH METHODS

3.1 EXPERIMENTAL METHODS

The specifications of the 4-stroke engine used in the experiment are shown in Table 2, and the experimental apparatus in Fig. 2. Both Methane and DME were continuously injected into the intake manifold at approximately 1500mm upstream from the intake valve. They were injected in the direction counter to the flow of the intake air in order to form a homogeneous charge. In addition, two pieces of orifices were put in for the promotion of mixing (Fig. 3). The intake air was introduced into the combustion chamber without supercharging. The in-cylinder gas pressure was measured using a piezoelectric pressure transducer for all operating conditions. For each test point, the in-cylinder gas pressure was sampled 64cycles at intervals of 1degree crank angle. The intake gas temperature T_{in} was measured 80mm upstream from the intake valve and the exhaust gas temperature T_{ex} at 125mm downstream from the exhaust valve using a K-type thermocouple. The experimental conditions of this study are shown in Table 3.

3.2 ANALYSIS METHOD OF THE IN-CYLINDER GAS TEMPERATURE

In this experiment, in-cylinder gas temperature was calculated on the following ways. Temperature at the start of compression T_0 (ATDC-132degree) was calculated by the enthalpy balance Eq. (1), using fresh gas temperature T_f, residual gas temperature T_r, mass of fresh gas m_f, mass of residual gas m_r, specific heat at constant pressure of fresh gas c_{p_f} and specific heat at constant pressure of residual gas c_{p_r}. T_f was assumed to be equal to T_{in}, and T_r to be equal to T_{ex}. Before the ignition, in-cylinder gas temperature was calculated from Eq. (2) assuming adiabatic compression. After the ignition, in-cylinder gas temperature was calculated from the ideal gas Eq. (3). Ignition timing θ_{ig}, which is the boundary between Eq. (2) and Eq. (3), was defined as the timing when RHR exceeded 1J/deg, and ignition temperature T_{ig} is the temperature at this point.

$$T_0 = \frac{m_f \cdot c_{p\_f} \cdot T_f + m_r \cdot c_{p\_r} \cdot T_r}{m_f \cdot c_{p\_f} + m_r \cdot c_{p\_r}} \quad (1)$$

$$T_c(\theta_i) = \left(\frac{P_c(\theta_i)}{P_c(\theta_{i-1})} \right)^{\frac{\kappa-1}{\kappa}} T_c(\theta_{i-1}) \quad (2)$$

$$T_c(\theta_i) = \frac{P_c(\theta_i) \cdot V_c(\theta_i) \cdot n(\theta_{i-1})}{P_c(\theta_{i-1}) \cdot V_c(\theta_{i-1}) \cdot n(\theta_i)} T_c(\theta_{i-1}) \quad (3)$$

Quantifiers;

T : gas temperature [K], m : mass of gas [kg], c_p : specific heat at constant pressure [J/(kg·K)], θ: crank angle [deg], P : gas pressure [MPa], κ: specific heat ratio, V: gas volume [m^3], n : mole number [mol]

Subscripts;

0 : compression start timing, f : fresh gas, r : residual gas, c : in-cylinder gas

4. RESULTS AND DISCUSSION

4.1 THE EFFECT OF THE MIXING RATIO OF METHANE / DME ON HCCI COMBUSTION

(1) THE MAP OF THE OPERATION AREA The combustion experiment using the mixed fuel of Methane and DME was carried out by varying the Methane-based equivalence ratio ϕ_{CH4} and the DME-based equivalence ratio ϕ_{DME}. In this experiment, compression ratio ε was set at 21.6, engine speed Ne at 960rpm, intake gas temperature T_{in} at 300K and intake gas pressure P_{in} at 0.1MPa. All of the experimental plots and the map of the operation region are shown in Fig. 4. In Fig. 4, " x " indicates misfiring (combustion efficiency calculated by RHR was less than 10%), " ● " indicates a point that was able to realize stable HCCI combustion and "▲" indicates knocking (metallic clank from engine and cobs of pressure due to knocking). In addition, constant energy supply lines are shown as the index of total inlet heat quantities put into the combustion chamber during 1 cycle. When the DME ratio was large, the increase of inlet heat quantities was interrupted due to knocking. On the other hand, the narrow and horizontally- stretched stable combustion area avoiding both misfiring and knocking appeared when the Methane ratio was large. Especially at ϕ_{DME}=0.1,the region in which the engine could be operated was expanded to ϕ_{CH4}=0.5 (total equivalence ratio ϕ_{total}=0.6).

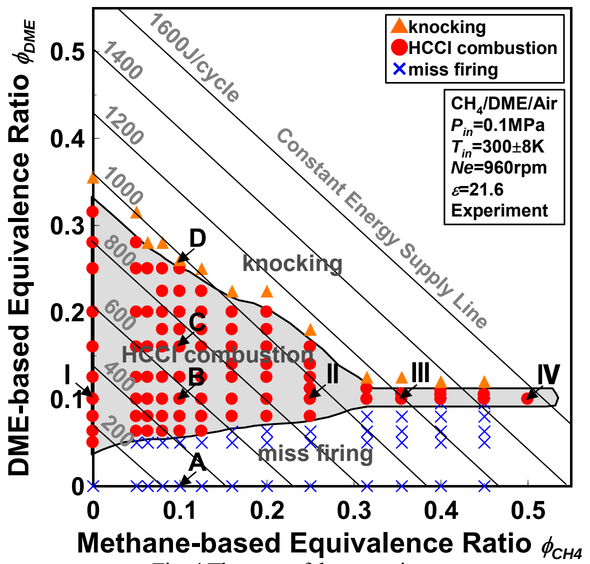


Fig. 4 The map of the operation area

(2) THE EFFECT OF THE DME-BASED EQUIVALENCE RATIO ON HCCI COMBUSTION Conditions A through D in Fig. 4 in which ϕ_{CH4} was constant at 0.1 and ϕ_{DME} was the parameter were focused on. Condition A (ϕ_{CH4}=0.1, ϕ_{DME}=0) was misfiring point, condition B (ϕ_{CH4}=0.1, ϕ_{DME}=0.1) and condition C (ϕ_{CH4}=0.1, ϕ_{DME}=0.16) were stable combustion points and condition D (ϕ_{CH4}=0.1, ϕ_{DME}=0.26) was a knocking point. In-cylinder gas pressure, in-cylinder gas temperature, RHR and combustion duration of conditions A through D are shown in Fig. 5. Low temperature reaction (LTR) start temperature T_{LTR}, high temperature reaction (HTR) start temperature T_{HTR}, intake gas temperature T_{in}, temperature at the start of compression T_0 and total heat release of LTR Q_{LTR} are shown in Fig. 6. LTR and HTR start timings were advanced with the increase of ϕ_{DME} in Fig. 5. Fig.6 shows that the advancement of LTR start timing was attributed to the fact that temperature at the start of compression T_0 became higher with the increase of ϕ_{DME}. In addition, the increase of LTR heat release with the increase of ϕ_{DME} caused the advancement of HTR start timing. Because of this advancement, combustion became too rapid and knocking occurred at condition D. From these results, the method of enlarging ϕ_{DME} in order to increase the inlet heat quantities was inadequate.

(3) THE EFFECT OF THE METHANE-BASED EQUIVALENCE RATIO ON HCCI COMBUSTION Conditions I through IV in Fig. 4 in which ϕ_{DME} was constant at 0.1 and ϕ_{CH4} was the parameter were focused on to research the reason for the appearance of the narrow and horizontally-stretched stable combustion area avoiding both misfiring and knocking. Condition I (ϕ_{CH4}=0, ϕ_{DME}=0.1), condition II (ϕ_{CH4}=0.25, ϕ_{DME}=0.1), condition III (ϕ_{CH4}=0.355, ϕ_{DME}=0.1) and condition IV (ϕ_{CH4}=0.5, ϕ_{DME}=0.1) were all stable combustion points. In-cylinder gas pressure, in-cylinder gas temperature, RHR and combustion duration of conditions I through IV are shown in Fig. 7. LTR start temperature T_{LTR}, HTR start temperature T_{HTR}, intake gas temperature T_{in}, temperature at the start of compression T_0 and total heat release of LTR Q_{LTR} are shown in Fig. 8. LTR and HTR start timings were delayed with the increase of ϕ_{CH4} in Fig. 7. Fig. 8 shows that the delaying of LTR start timing was attributed to the fact that LTR start temperature became higher. In addition, the rise in HTR start temperature and the decrease of LTR heat release with the increase of ϕ_{CH4} caused the delaying of HTR start timing. Because of this delay, the peak value of RHR decreased and pressure increase became slow from condition III to IV in spite of increasing inlet heat quantities. Z The experimental plots in the narrow and horizontally-stretched stable combustion area were the points at which the peak timing of RHR θ_{RHR_max} was delayed to the expansion stroke with the increase of the Methane ratio and knocking was avoided due to slow combustion.

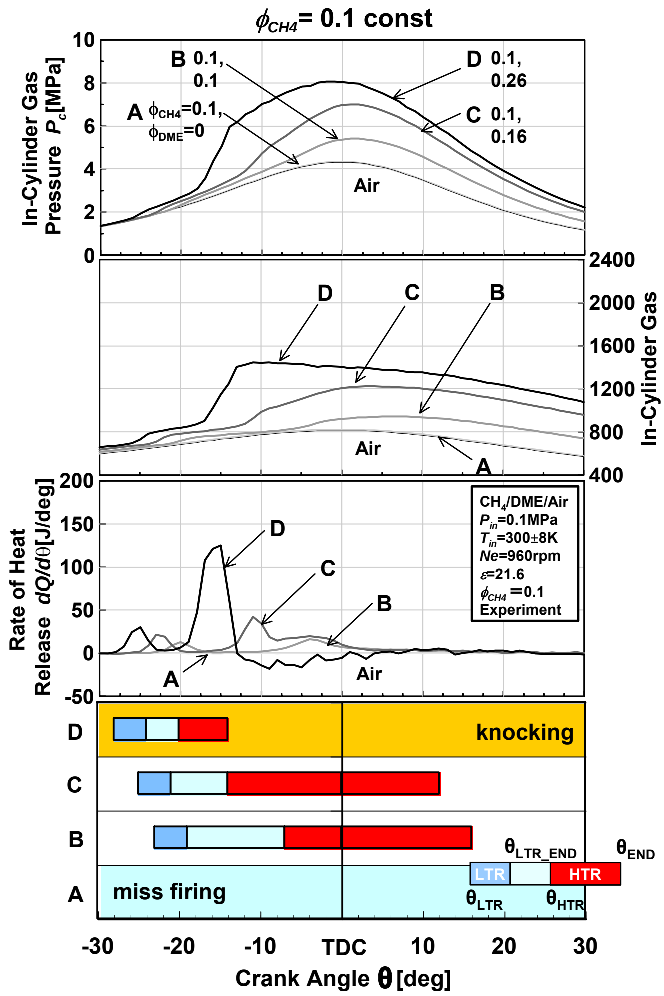


Fig.5 Pressure, Temperature, RHR history and combustion duration on the DME-based equivalence ratio ϕ_{DME} (ϕ_{CH4}=0.1)

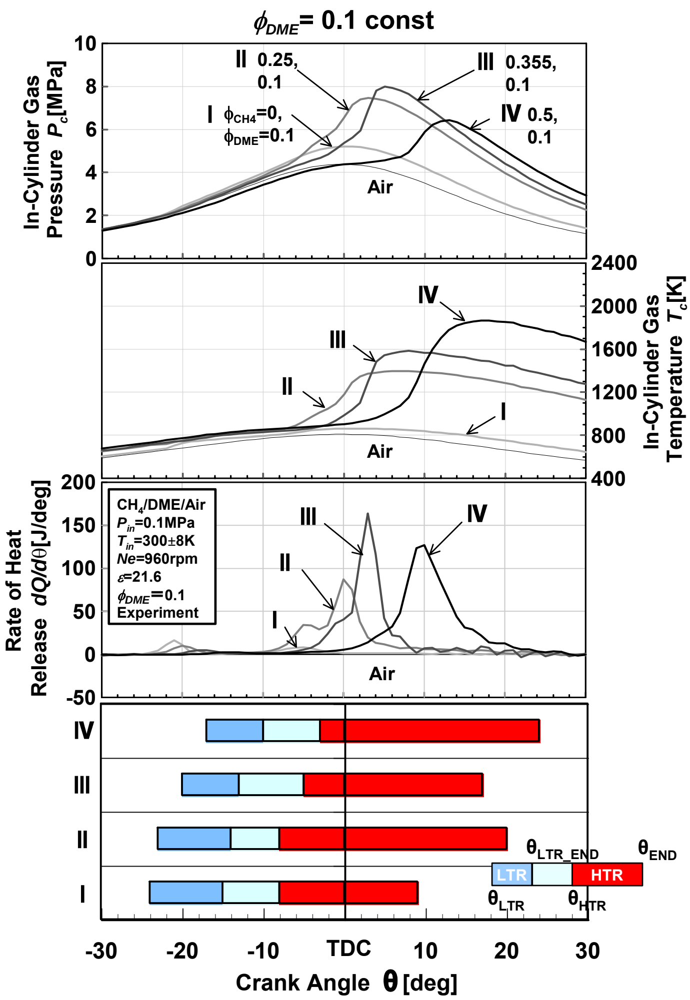


Fig.7 Pressure, Temperature, RHR history and combustion duration on the Methane-based equivalence ratio ϕ_{CH4} (ϕ_{DME}=0.1)

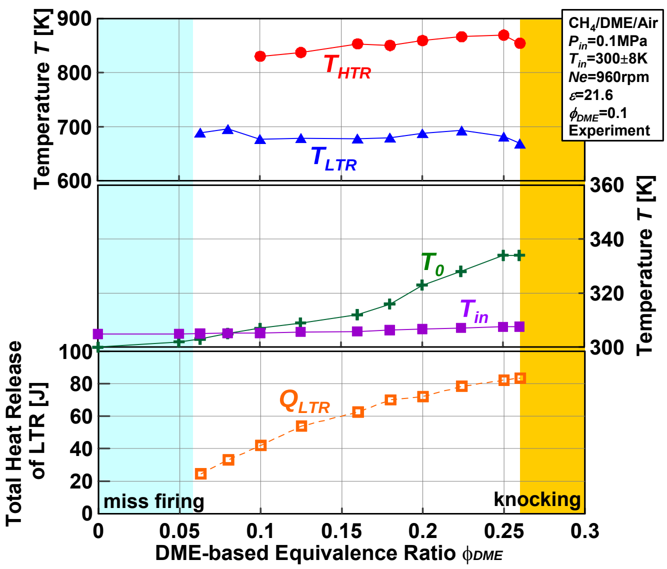


Fig.6 LTR start temperature T_{LTR}, HTR start temperature T_{HTR}, intake gas temperature T_{in}, temperature at the start of compression T_0 and total heat release of LTR Q_{LTR} on the DME-based equivalence ratio ϕ_{DME} (ϕ_{CH4}=0.1)

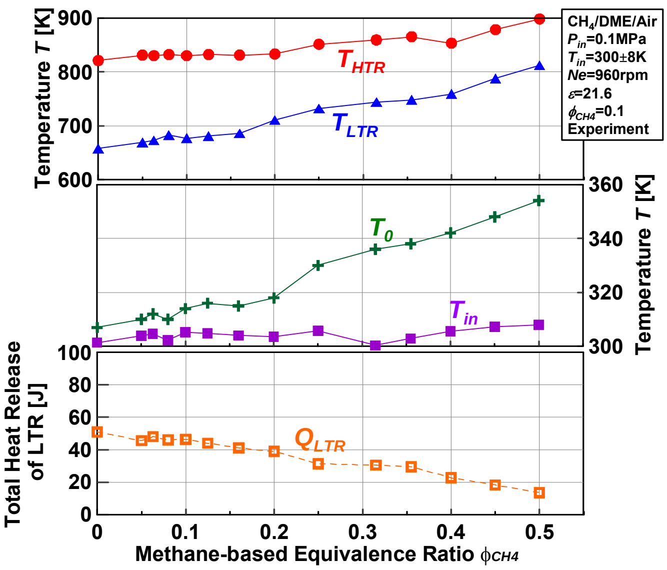


Fig.8 LTR start temperature T_{LTR}, HTR start temperature T_{HTR}, intake gas temperature T_{in}, temperature at the start of compression T_0 and total heat release of LTR Q_{LTR} on the Methane-based equivalence ratio ϕ_{CH4} (ϕ_{DME}=0.1)

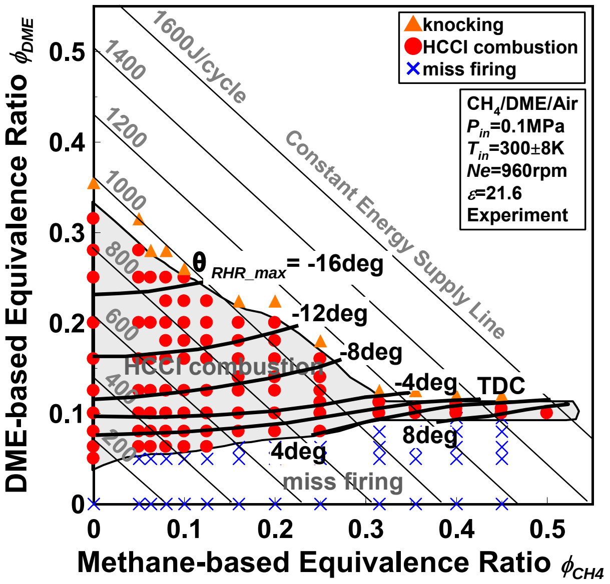


Fig. 9 Peak timing of RHR θ_{RHR_max} on map of operation area

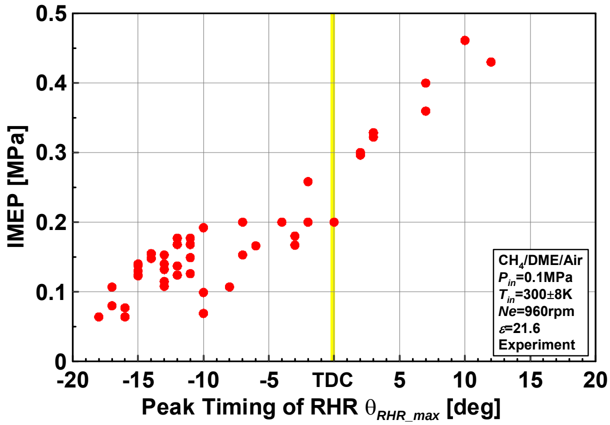


Fig. 10 The relation between IMEP and peak timing of RHR θ_{RHR_max}

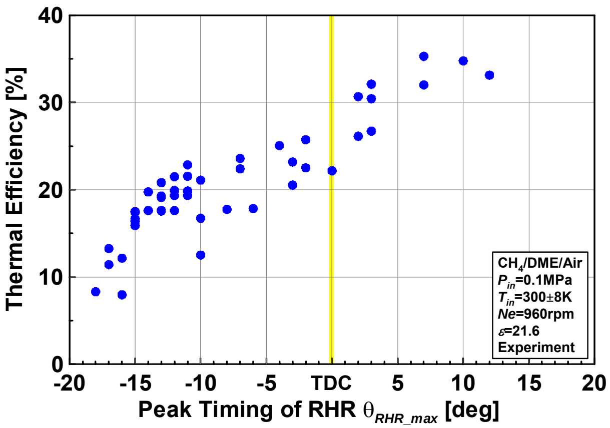


Fig. 11 The relation between thermal efficiency and peak timing of RHR θ_{RHR_max}

(4) THE RELATION BETWEEN IMEP, THERMAL EFFICIENCY AND THE PEAK TIMING OF RHR It was found that operation with a high equivalence ratio could be achieved when the peak timing of RHR θ_{RHR_max} was delayed to the expansion stroke. Therefore, the peak timing of RHR θ_{RHR_max} was focused on and was superimposed on the map of the operation area in Fig. 9. In the case of the stretched stable combustion area, the peak timing of RHR θ_{RHR_max} appeared after top dead center (TDC) in all of the experimental points. From these results, it was necessary to control the mixing ratio between Methane and DME in order for the peak timing of RHR θ_{RHR_max} to appear in the expansion stroke so that the inlet heat quantities could be increased without knocking. The relation of the peak timing of RHR θ_{RHR_max} to IMEP is shown in Fig. 10 and the relation of the peak timing of RHR θ_{RHR_max} to thermal efficiency is shown in Fig. 11. All experimental points in Fig. 10 and 11 are the points that combustion efficiency was over 50%. In Fig. 10, IMEP became higher as the peak timing of RHR θ_{RHR_max} became delayed. Especially, it was found that high IMEP operation could be achieved when the peak timing of RHR θ_{RHR_max} appeared after TDC. The reason for this was because inlet heat quantities could be ensured without knocking due to the slowness in pressure and temperature increases since the peak timing of RHR θ_{RHR_max} appeared in the expansion stroke. Thermal efficiency also became higher as the peak timing of RHR θ_{RHR_max} became delayed in Fig. 11. However, thermal efficiency generally continued to be flat after TDC. The reason for this was that the inlet heat quantities could be increased but thermal efficiency became worse because of too slow combustion in expansion stroke.

4.2 THE EFFECT OF COMPRESSION RATIO, ENGINE SPEED AND INTAKE GAS TEMPERATURE ON THE MAP OF OPERATION AREA

The effect of compression ratio ε, engine speed Ne and intake gas temperature T_{in} on the stretched stable combustion area was researched. The area in which the Methane-based equivalence ratio ϕ_{CH4} was over 0.4 in the map of the operation area under each condition is shown in Fig. 12. In Fig. 12, the leftmost map of the operation area was the base map (condition 1) under the condition in which compression ratio ε=21.6, engine speed Ne=960rpm, intake gas temperature T_{in}=300K. While on the other hand, the second map (condition 2) from the left was the map in which the compression ratio ε was changed to 16.4, in the third map (condition 3) the engine speed Ne was changed to 600rpm, and in the fourth map (condition 4) the intake gas temperature T_{in} was changed to 350K. It was found that the stretched stable combustion area appeared at different positions under each condition. In condition 1, it appeared on the spot where the DME-based equivalence ratio ϕ_{DME}=0.1. The spot was at ϕ_{DME}=0.165 in condition 2, ϕ_{DME}=0.08 in condition 3 and ϕ_{DME}=0.085 in condition 4. This fact meant that ϕ_{DME} in the stretched stable combustion was increased as the compression ratio ε was lowered. On the other hand, it was decreased as the engine speed Ne was lowered and the intake gas temperature T_{in} rose. The stretched stable combustion area that realizes high IMEP operation was significantly changed according to the experimental conditions.

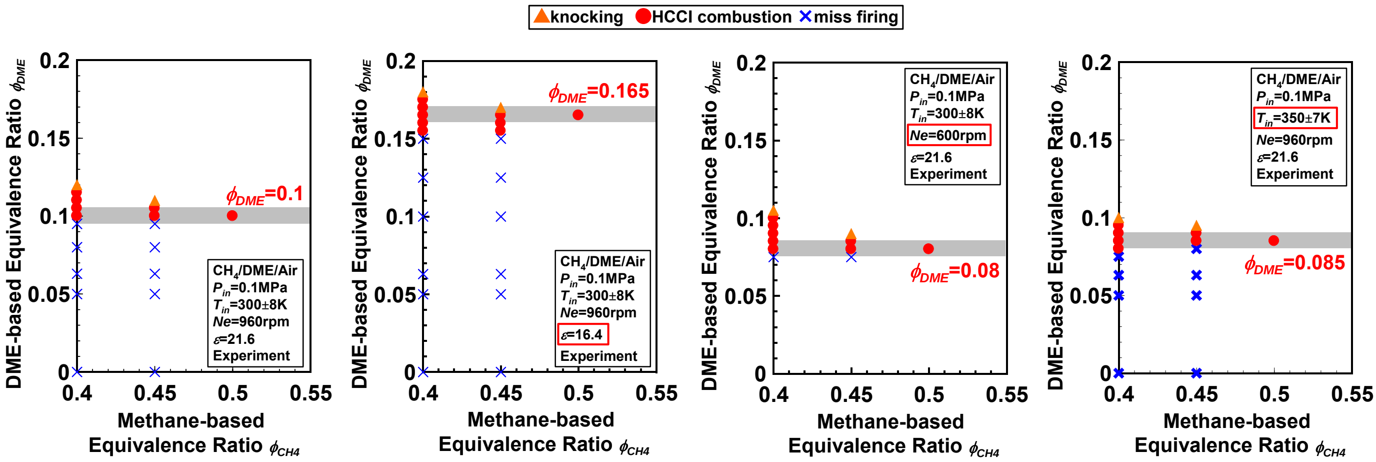


Fig. 12 The map of the operation area (under several experimental conditions)

5. CONCLUSIONS

The objective of this study was to investigate the effect of the mixing ratio between Methane and DME on HCCI combustion by experimentations.

(1) LTR and HTR start timings were advanced, the peak value of the rate of heat release was increased and combustion duration was shortened with the increase of the DME-based equivalence ratio ϕ_{DME}.

(2) LTR and HTR start timings were delayed, the peak value of the rate of heat release was decreased and combustion duration was lengthened with the increase of the Methane-based equivalence ratio ϕ_{CH4}.

(3) The narrow and horizontally-stretched stable combustion area avoiding both misfiring and knocking appeared on the map of the operation area when the Methane ratio was large. In the case of this area, the peak timing of RHR θ_{RHR_max} appeared after TDC in all experimental points. High load operation was desirable for to make combustion occur in the expansion stroke by means of controlling the mixing ratio between Methane and DME.

(4)The narrow and horizontally-stretched stable combustion area realizing high load operation was significantly changed according to experimental conditions such as compression ratio ε, engine speed Ne and intake gas temperature T_{in}.

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