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Research Article

SURROUNDING GAS PRESSURE AND OXYGEN CONCENTRATION DEPENDENCE OF THE SPRAY AUTO-IGNITION PHENOMENON FOR ETHANOL-DIETHYL ETHER BLENDED FUELS

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ABSTRACT:

This study deals with the development of controlled-ignition technology for high performance compression ignition alcohol engines. The objective of this study is quantitative evaluation of main factors that influence auto-ignition of an alcohol spray. The quantitative evaluation that can be finally as the database in a form of 3D-mapping of ignition delay is now in progress. When the mapping is completed by a number of systematic experiments, engine control logic is able to be established and high performance alcohol engines are developed. This paper mainly focuses on the effect of surrounding gas pressure and oxygen content on auto-ignition. Spray mixture formation up to auto-ignition of ED (Ethanol-Diethyl ether) blended fuels in a large constant volume electrical heating chamber was visualized by shadowgraph method. The results showed that ignition delay was depended on surrounding gas pressure and oxygen concentration. However, ED blend fuels showed small dependence of O_2 content on ignition delay when its value was higher than 30%. In further O_2 rich condition of 35%, diffusion combustion was observed when ignition position was shifted to upstream region of a spray with increasing of O_2 content for diethyl ether rich ED blended fuels.

Keywords: *Auto-ignition, Mixture formation, Alcohol spray, CI engine, 3D-mapping*

1. INTRODUCTION

1.1 Background

As well-known various kinds of energy and environmental problems such as oil reserve depletion, air pollution and global warming have been appeared. Under such situations, utilization of natural and renewable energy has been highlighted. This movement has been widely extended in the world after the great East Japan earthquake and tsunami terribly damaged the Fukushima nuclear power plant. Reconsideration of national strategies on nuclear power has been seen in many countries. At present, therefore, utilization of renewable energy is promoted and appropriate R&D (research and development) is required much more than before the 3.11 disasters in Japan. In the automotive technologies, although one of the R&D trends for passenger car is on the HV (Hybrid Vehicle), PHV (Plug-in Hybrid Vehicle) and EV (Electric Vehicle), further improvements of diesel engines are still demanded for various kinds of trucks due to their huge required power density.

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In particular, land transportation for approximately 60% of worldwide logistics, as evaluated by weight×distance (ton×km), depends on the long-distance trucks powered by diesel engines.

Alcohol fuels especially Ethanol is understood as one of the promising candidates replacing from petroleum derivatives. Although alcohol is generally recognized as the most feasible alternative fuel for premixed SI (Spark Ignition) engines, several companies have been active in the development of direct injection CI (Compression Ignition) alcohol diesel engines in the past. Almost all of the studies reported in the past sought optimum configurations of ignition-assist devices such as spark-plug[1], glow-plug[2] and laser[3] to realize stable auto-ignition for alcohol fuels. Studies on the ignition-improving additives[4-7] also have been conducted and reported intensively. Munsin and Laoonual[4] examined several additives and their effectiveness on the auto-ignition quality. Although they used their original designed CVCC (Constant Volume Combustion Chamber) and showed experimental results as auto-ignition characteristics of an Ethanol spray with and without additives, physical and chemical mechanisms of auto-ignition quality improvement is still at question. Even in the study of additives, fundamental understanding of spray mixture formation of the base oil (fuel) is very important and essential, for the development of DI alcohol engines.

1.2 Previous Study

As the general understanding of the conditions of auto-ignition there are two essential factors in mixture formation process. One is the concentration factor: a mixture has to be in a mixing ratio sufficient to advance chemical reactions. The other is a temperature factor: temperature of mixture has to exceed a certain value that pre-combustion chemical reactions are promoted. Based on this recognition, this study defined the concentration and temperature factors as follows:

Concentration factor : $\lambda_{tip}=1$ (1)

Temperature factor : $T_{spm}>T_{ig}$ (2)

In Eq. (1), $\lambda_{\rm tip}$ indicates mean excess air ratio of a spray tip. T_{spm} and T_{ig} in Eq. (2) represent, respectively, mean temperature of a spray and minimum ignition point of tested fuels.

Figure 1 is the first result of our research[8] on the auto-ignition quality of an alcohol splay. Mixture formation processes of Ethanol and Gas oil sprays were theoretically estimated. This indicates that auto-ignition is dominated by concentration factor for a Gas oil spray because temperature factor is already satisfied when concentration factor is attained. On the contrary for an Ethanol spray, T_{spm} does not reach to temperature factor when concentration factor is cleared, and leaner situation is easily expected by the time when temperature factor is satisfied. We can understand from this theoretical approach that it is difficult for Ethanol to realize auto-ignition compared with Gas

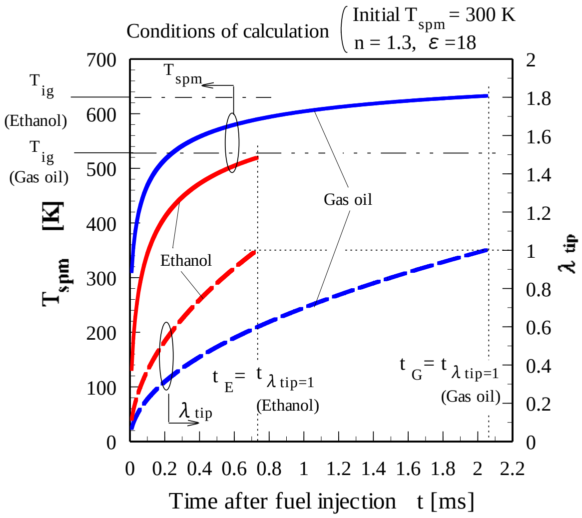


Fig.1. Estimation of time dependent data of mean temperature of a spray and mean excess air ratio of a spray tip.

oil, because large amount of heat-supply into a small sized spray is required in much shorter time. Through the series of our researches[8-14] including Fig. 1, the reason of poor auto-ignition quality of alcohol spray was theoretically and experimentally revealed. That is difficulty of simultaneous attainments of ignition-suitable concentration and temperature in a spray mixture formation. Fuel properties of alcohol fuels such as smaller stoichiometric air/fuel ratio (L_{th}) and larger latent heat of evaporation (γ) respectively induce faster lean situation and slower temperature rise in comparison with conventional diesel fuels. In terms of fuel properties, Gas oil and Ethanol are, respectively, recognized as concentration-factor-dominant and temperature-factor-dominant fuel. In order to obtain the stable auto-ignition by fuel injection, concentration-factor-dominant conditions are required. Namely, it is possible to improve the auto-ignition quality of alcohol fuels by simultaneously realizing the retardation of lean mixture situation and faster temperature rise by the method such as hot EGR.

1.3 Objectives

The objective of study, therefore, is to make quantitatively clear the main factors that govern auto-ignition phenomenon of an alcohol spray. Governing parameters for auto-ignition of a fuel spray are categorized as two kinds of factors. One can be called “internal factor” related to fuel properties. The other can be called “external factor” corresponded to the surrounding gas conditions such as pressure, temperature and oxygen concentration. The authors[8-14] have intensively investigated and reported on the effects of internal and external factors on auto-ignition phenomenon of an alcohol spray, and are now in progress of drawing the map/data base that indicates how great is the influence on ignition delay for each governing parameter of auto-ignition. When the mapping is completed, engine control logic can be drawn and high performance alcohol engines can be realized. This paper mainly focuses on the effect of surrounding gas pressure and oxygen content on auto-ignition.

2. EXPERIMENTAL SETUP AND CONDITIONS

2.1 Test Chamber

Figure 2 shows the construction of the constant volume electrical heating chamber used in the visualization test. Principal particulars of the chamber are presented in Table 1. The chamber consists of outer cell and inner core with one pair of Quartz glass windows. Outer cell is made of Cr-Mo alloy durable for high pressure of 5.0MPa. Inner core is made of ceramics with an electrical heater embedded in it as shown in Fig. 2. A solenoid type injector as used in common rail fuel injection systems for commercial right trucks was employed. The nozzle tip was converted for fundamental spray visualization tests. A single hole nozzle with 0.14 mm in diameter was installed in the injector. In the experiments injection pressure was maintained at 50 MPa by a booster pump and the injection duration was controlled as 4.76 ms by the signal from digital circuit board.

2.2 Experimental Procedure and Conditions

Figure 3 shows the whole experimental setup. Test gas was supplied from a bomb into the chamber up to the initial condition of pressure. Initial gas pressure before heating was calculated based on the equation of state under constant volume condition. Initial gas temperature was measured by a K-type thermocouple. In-chamber gas pressure was measured with strain gauge type pressure sensor and it was monitored during the experiment. Test fuel was injected into the chamber when gas pressure indicated the target value during heating. Visualization of spray

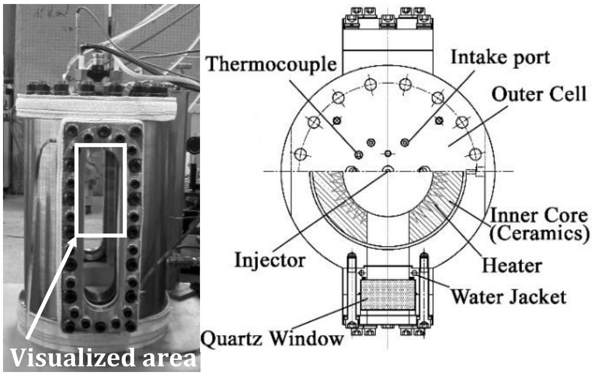


Fig.2. Structure of the Constant Volume Combustion Chamber used in the visualization.

Table 1: Specification of the test chamber.

Chamber	Outer Cell	Material (φ×H)	Cr - Mo Alloy (355 mm × 546 mm)
	Inner Core	Material (φ×H)	Ceramics (150 mm×410 mm)
		Volume	7250cc
	Durable Pressure		5.0 MPa
Heater	Max. Electric Power (Voltage×Ampere)		14 kW (AC 200 V × 70 A)
Windows	Material Thickness		Quartz Glass 50 mm
Injector	Type		Solenoid Type
	Injection	Pressure	50 MPa
		Duration	4.76 ms
	Nozzle Type (φ×N)		Hole Type (0.14 mm × 1)

mixture formation was conducted by shadowgraph method. Spray mixture formation process and auto-ignition phenomenon were recorded with a high-speed camera at 8213 fps. Recording was synchronized with fuel injection.

Ethanol-Diethyl ether blend fuels were employed in experiments in order to make clear the effect of fuel properties that listed in Table 2 on auto-ignition. However, in our previous studies[13], auto-ignition was not observed for neat Ethanol and ED blend fuels with Diethyl ether blend ratio less than 60% under all the examined pressure and temperature conditions of surrounding gas. Therefore Diethyl ether rich ED blend fuels and neat Diethyl ether were tested. Gas oil was also tested as the reference fuel.

Table 3 presents the experimental conditions. Blend ratios between Ethanol and Diethyl ether were 3:7, 2:8 and 1:9. They are indexed as ED37, ED28 and ED19 in this paper. In the experiments, oxygen content was varied from 17% to 25% with its interval of 2% and two cases of 30%, 35% under the constant temperature (800K) conditions. Surrounding gas pressure 2.0MPa, 2.5MPa and 2.8MPa cases were also examined for all the oxygen content conditions and for all the tested fuels.

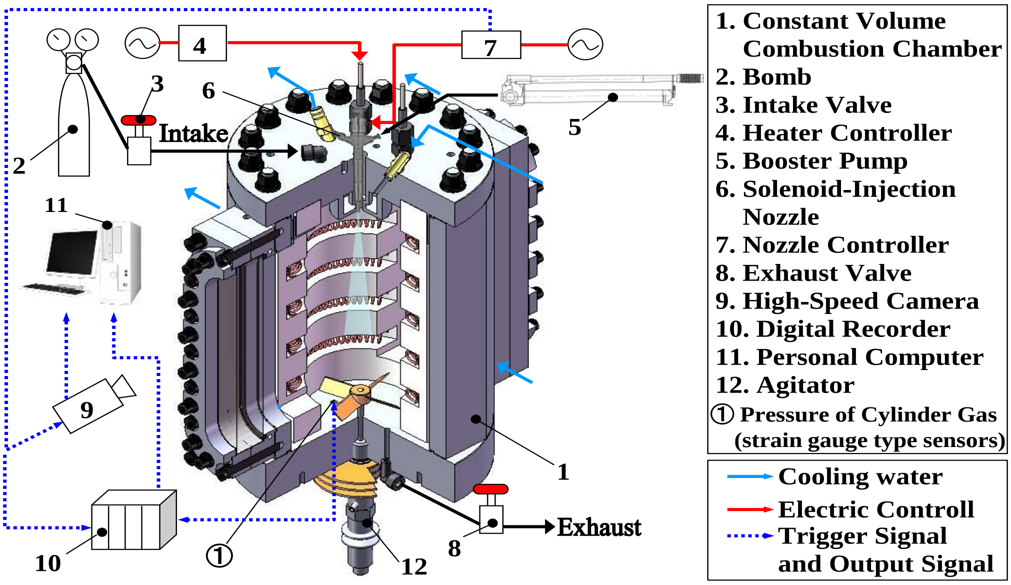


Fig.3. General view of the experimental setup and recording system.

Table 2: Thermal and fuel properties of tested fuels

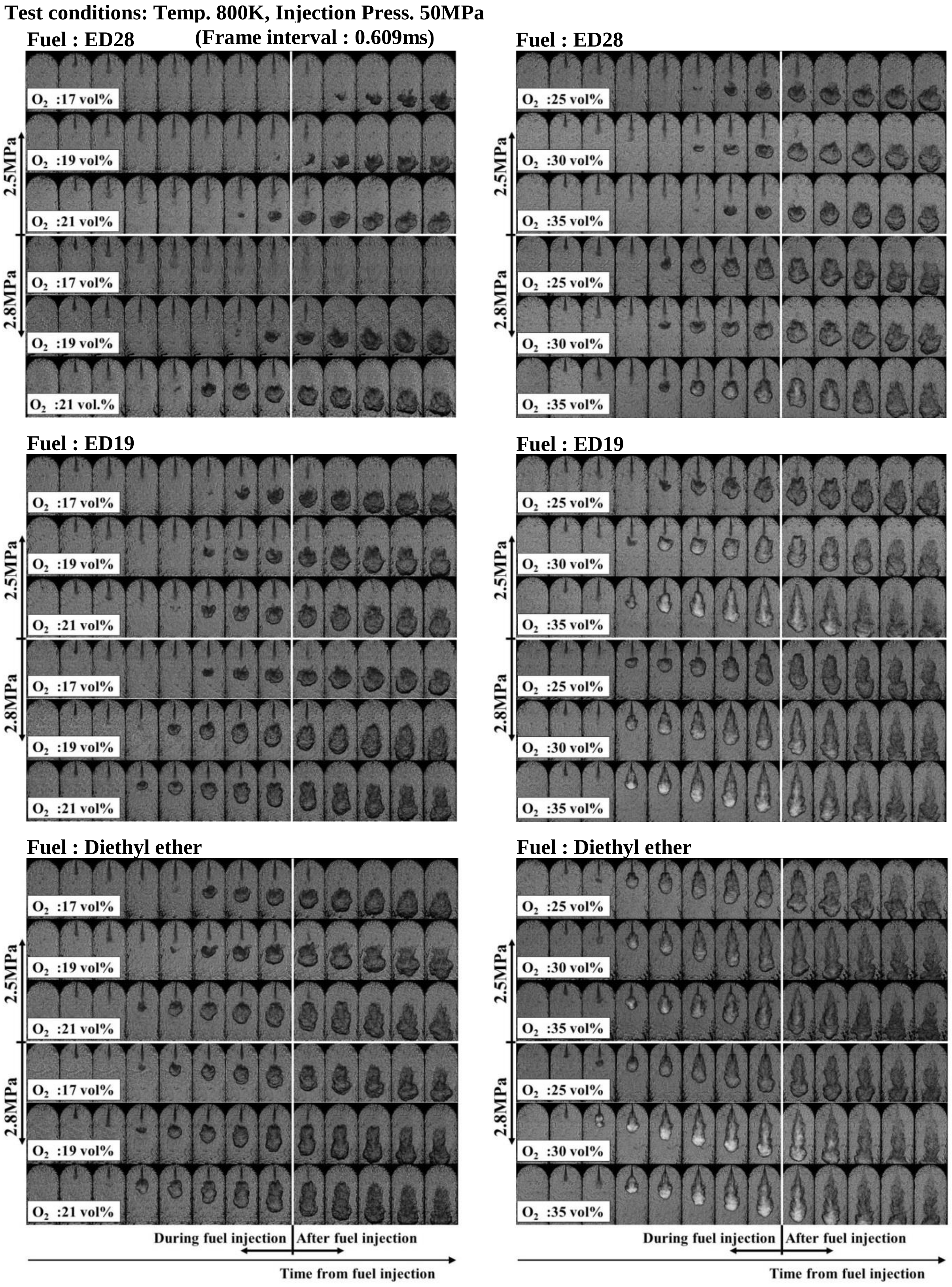
Fuel notation		Ethanol	(E)&(D) Mixing fuel			Diethyl ether	Gas oil
		C_2H_5OH	E:D=3:7	E:D=2:8	E:D=1:9	$(C_2H_5)_2O$	-
		(E)	(ED37)	(ED28)	(ED19)	(D)	(G)
Stoichiometric air/fuel ratio	[kg/kg]	9.01	(10.529)	(10.746)	(10.963)	11.18	14.6
Density	[kg/m^3]	785	(731.1)	(723.4)	(715.7)	708	825
Specific heat (liquid)	[kJ/(kg·K)]	2.723	(2.7034)	(2.7006)	(2.6978)	2.695	2.372
Specific heat (gas)	[kJ/(kg·K)]	2.329	(2.0378)	(1.9962)	(1.9546)	1.913	1.915
Boiling point	[K]	351.7	351.7 307.8	351.7 307.8	351.7 307.8	307.8	443～ 663
Heat of vaporization	[kJ/kg]	854.8	(530.91)	(484.64)	(438.37)	392.1	187.2
Minimum ignition temp.	[K]	636	―	―	―	433	530
Lower heating value (Hu)	[MJ/kg]	26.8	(31.7)	(32.4)	(33.1)	33.8	44.4

Table 3: Experimental conditions.

Fuels	Surrounding Gas Conditions				Injection Perssure	Injection Duration
	Press.	Temp.	O_2	N_2		
	[MPa]	[K]	[vol. %]	[vol. %]	[MPa]	[ms]
E:D=3:7 (ED37)	2.0 2.5 2.8	800	17～25 (Interval of 2%) 30 35	83～75 70 65	50	4.76
E:D=2:8 (ED28)						
E:D=1:9 (ED19)						
Diethyl ether (D)						
Gas Oil (G)						

3. RESULTS AND DISCUSSION

Visualization results of mixture formation and auto-ignition are presented in Figure. 4. Left side (a) in Fig. 4 shows visualization results under the conditions of O_2 concentration less than 21vol.%. On the other hand, Fig. 4 (b) shows visualization results from 25vol.% to 35vol.% in O_2 rich air conditions. One set of visualized image for each tested fuel consists of two pressure conditions of 2.5MPa (upper part of Fig. 4) and 2.8MPa (lower part of Fig. 4). It is clearly seen from Fig. 4 (a) that shorter ignition delay was obtained with increasing of O_2 concentration, regardless of tested fuels. Focusing on the surrounding gas pressure, we can find that earlier ignition timing was obtained with increasing of surrounding gas pressure for all the O_2 concentration conditions. In the case of O_2 rich air condition (Fig. 4 (b)), negligible small change of ignition timing was confirmed regardless of surrounding gas O_2 concentration under both the 2.5 and 2.8 MPa conditions in surrounding gas pressure. However, the same tendency of surrounding gas pressure dependence of auto-ignition, which shorter ignition delay with higher surrounding gas pressure, was indicated also under the O_2 rich air conditions. In further O_2 rich conditions of 30% and 35%, diffusion combustion was observed for diethyl ether rich ED blend fuels. This combustion characteristic is clearly seen from Fig. 4 (b), regardless of surrounding gas pressure.



(a) Case of O_2 lean air conditions (b) Case of O_2 rich air conditions

Fig.4. Visualization results of mixture formation and auto-ignition for ED blended fuels and Diethyl ether.

In addition, it can be also observed from Fig. 4 that effect of Ethanol-Diethyl ether blended ratio on spray penetration and spray angle is negligible small. We confirmed this fact with visualized images for all the tested conditions. This can be recognized as reasonable due to approximately less than ten percent difference in their density, among the fuel properties, density is the main factor of spray penetration and angle (See Eq.(3), (5) in appendix and Table 2).

Figure 5 represents the 3D-surface data of ignition delay depending on the surrounding gas pressure and O_2 concentration for each fuel: (a) Diethyl ether, (b) ED19, (c) ED28 and (d) Gas oil. Ignition delay was defined as the duration between injection start timing and auto-ignition timing judged on visualized images. Under lower pressure condition at 2.0MPa for ED19, strong surrounding O_2 concentration dependence of ignition delay was indicated. Liu and Yao[15] , Wu and Zhang[16] reported the same characteristics for n-butanol and Acetone-Butanol-Ethanol (ABE)-Diesel blended fuel. However, negligible small change of ignition delay was obtained when O_2 concentration was higher than 27vol.%. Those tendencies were clearly seen with increase of Ethanol blend ratio (See Fig. 5(c)). Therefore, it is understood that auto-ignition is strongly influenced on O_2 concentration under 2.0MPa condition. On the other hand, under higher pressure condition of 2.8MPa, O_2 concentration dependence of ignition delay was smaller than those of 2.0MPa case. However value of ignition delay for all the O_2 concentration conditions was decreased with increase of surrounding gas pressure regardless of each tested fuel. Based on those results, in order to understand how such auto-ignition characteristics are attributed to what sort of mixture formation process, estimations of λ_{tip} and T_{spm} at auto-ignition timing were performed.

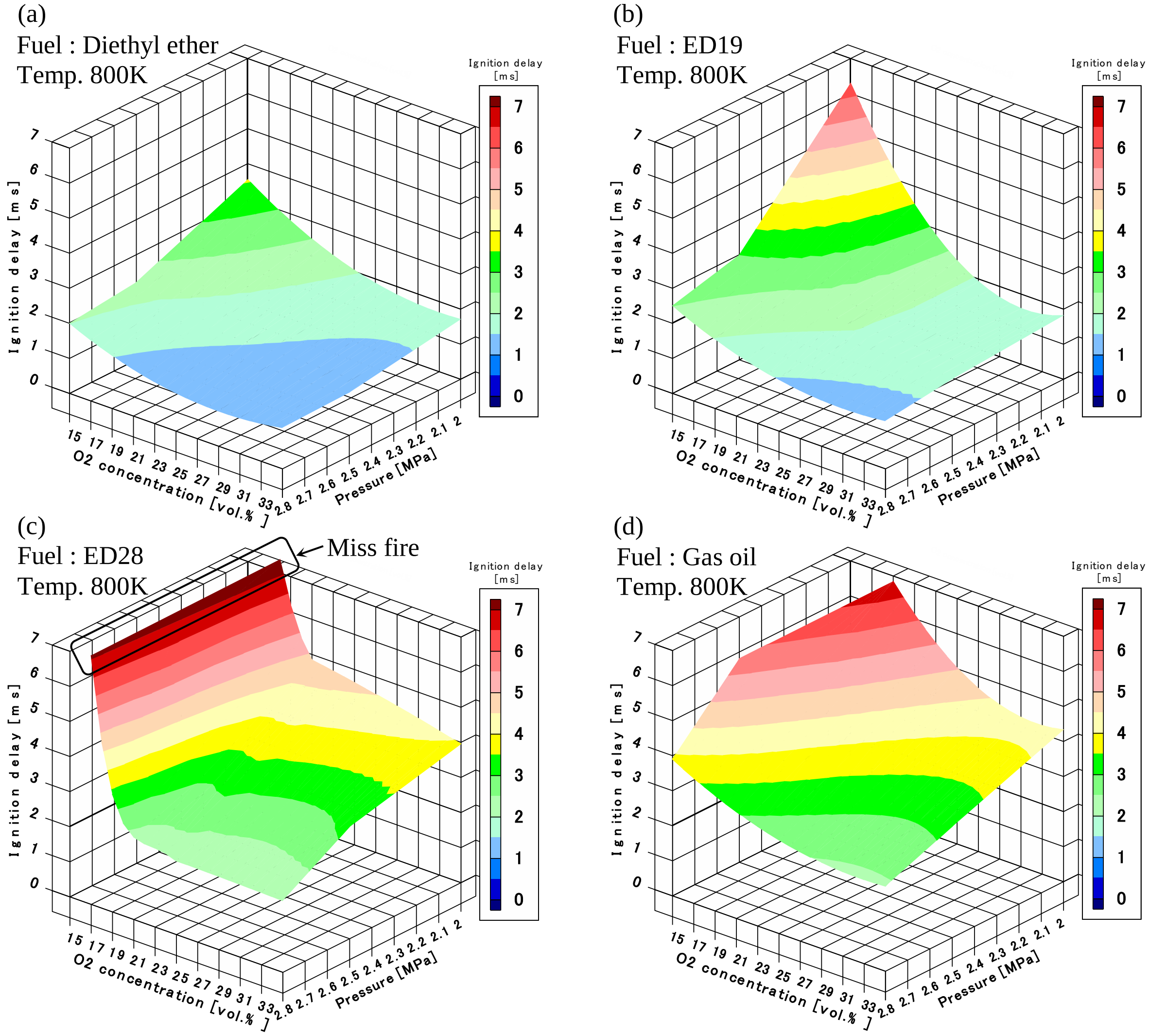


Fig.5. Surrounding gas oxygen concentration and pressure dependence of auto-ignition represented in a form of 3D-surface data of ignition delay for each tested fuel.

Figure 6 shows the results of the analysis for ED19. In the calculation introduced in the appendix, thermal and fuel properties listed in Table 2 were substituted in each equation. Substitution of measured spray penetration (X_{tip}) at ignition timing into Eq. (4) resulted plotted data of λ_{tip} and T_{spm} when auto-ignition was occurred. Colors of plots correspond to those of estimated λ_{tip} lines. Filled and open symbols respectively correspond to continuous lines (case of 2.5MPa) and dashed lines (case of 2.8MPa).

Mean temperature of a spray (T_{spm}) showed no dependence of O_2 concentration and T_{spm} lines were coincided with each other due to negligibly small differences of G_a (mass of entrained gas) and c_a(specific heat) although T_{spm} was overestimated due to the instantaneous heat balance being assumed to be satisfied as represented in Eq. (10). For λ_{tip}, leaner situation of mixture was theoretically predicted with the increase of O_2 concentration due to the change of stoichiometric air/fuel ratio (L_{th}) with the consideration of different O_2 content air. In comparison with the case of 2.8MPa,λ_{tip} lines for each O_2 condition were higher than those of 2.5MPa case and T_{spm} lines under 2.8MPa surrounding gas condition were a little higher than those of 2.5MPa case. The reason of these results can be explained as follows:

Higher surrounding gas pressure corresponds to higher gas density of the entrained gas into a spray, which induces simultaneous increase of heat supply into a spray and faster lean situation due to the increase of mass of the entrained gas.

The plotted data of λ_{tip} at ignition timing were approximately within 1 to 1.5 for all the experimental conditions except for the cases of O_2 30vol.% and 35vol.% conditions. It is understood from Fig. 6 that auto-ignition for each tested condition was dominated by the concentration factor. Ignition delay was decreased with increasing of O_2 content because the attainment of temperature factor is earlier than that of concentration factor. However, in case of O_2 rich air conditions of 30vol.% and 35vol.%, value of λ_{tip} at ignition timing was higher than these of other experimental conditions in spite of approximately the same ignition delay. In order to understand the above introduced analytical results, we focused on the ignition position within a spray.

Figure 7 stands for the effect of surrounding gas oxygen concentration on auto-ignition position for each tested fuel

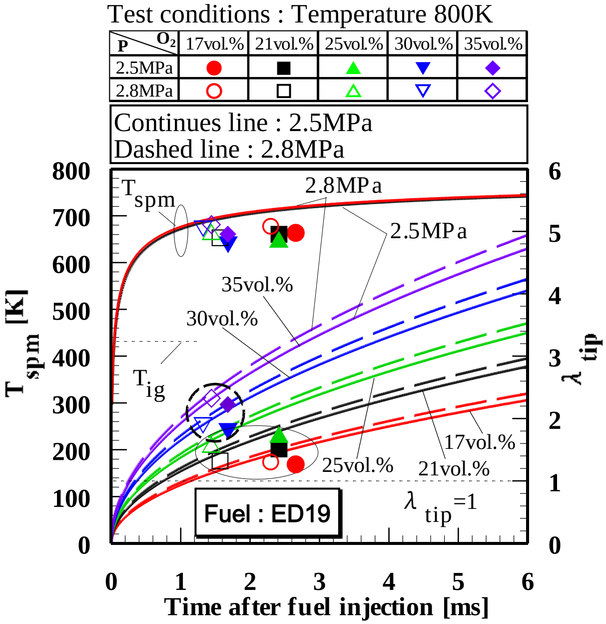


Fig.6. Estimation of λ_{tip} and T_{spm} at auto-ignition timing calculated from the theory of spray penetration for ED19 blended fuel.

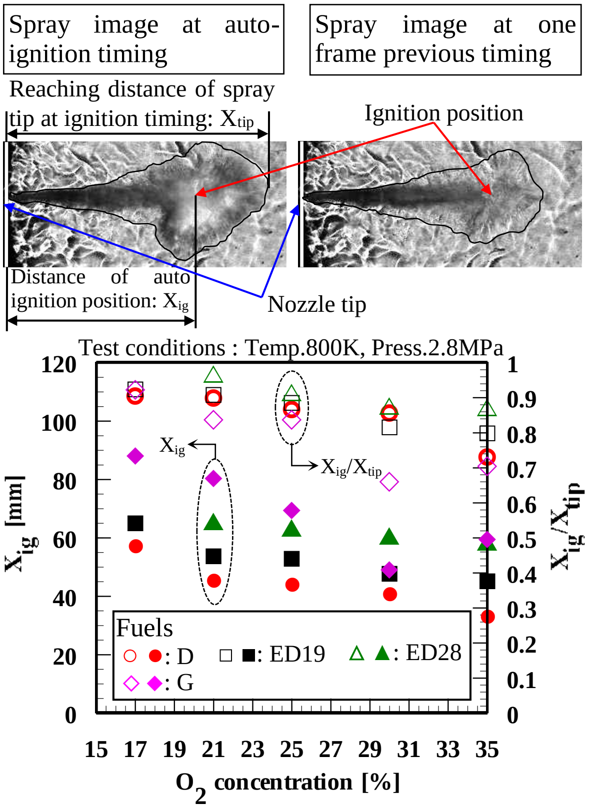


Fig.7. Effect of surrounding gas oxygen concentration on auto-ignition position.

under the 800K and 2.8MPa surrounding gas conditions. The value of X_{tip} defined as distance between the nozzle tip and tip of outline edge of a spray at ignition timing. The value of X_{ig} is the distance between the nozzle tip and ignition position along the spray axis. It was difficult to identify the ignition position on the visualized image at auto-ignition timing, therefore we defined it as the center of evaporated fuel in the visualized images at one frame previous from ignition timing. In this definition, $X_{ig}/X_{tip}=1$ means that auto-ignition occurred at a spray tip and $X_{ig}/X_{tip}<1$ means that it occurred in upstream region of a spray. It is clearly seen from Fig. 7 that auto-ignition position of each tested fuel was shifted upstream region in a spray under the O_2 rich air conditions of 30vol.% and 35vol.%. In order to know the cross sectional mean excess air ratio at X_{ig}, we performed the following calculation. Substitution of X_{ig} in Eq. (3) yielded the imaginaryλ_{tip} as the auto-ignition assumed to be occurred at the outer edge of a spray. The results of imaginaryλ_{tip} for the cases of O_2 rich air conditions of 30vol.% and 35vol.% at ignition timing were approximately within 1.0 to 1.5. This analysis allow us to reach one recognition. That is auto-ignition occurs at the time and location of the transition from fuel rich mixture to lean situation which corresponds to 1.0 – 1.5 in the cross sectional excess air ratio.

Based on the above stated recognition, focusing on the visualization results as previously shown in Fig. 4 (b), we can understand that combustion characteristics was strongly influenced on auto-ignition position when auto-ignition was occurred during fuel injection. Under O_2 rich air conditions, combustion of ED blended fuels yielded luminous flame when auto-ignition position was sifted to upstream region, because mixture concentration was fuel rich situation by continuously injected fuel. After auto-ignition, flame was lifted to upstream region in a spray, because diffusing velocity of oxygen and fuel with increasing of O_2 concentration in the entrained gas was getting faster. Therefore, diffusion combustion was obtained for Diethyl ether rich ED blended fuels under O_2 rich conditions of 30vlo.% and 35vol.%.

4. CONCLUSIONS

1. Ignition delay for ED blended fuels were depended on surrounding gas pressure and oxygen concentration, and this tendency become significant with increasing of Ethanol blend ratio. However, surrounding gas O_2 concentration dependence of auto-ignition for ED blended fuels is negligible small when its value is higher than 30%.

2. Auto-ignition is occurred at the edge of a spray under O_2-lean-air conditions lower than 21vol.%. On the other hand under O_2-rich-air conditions of higher than 30vol.%, auto-ignition is obtained during fuel injection and its position shifts upstream region. As the result of the change of ignition timing and place, diffusion combustion occurs. These auto-ignition and combustion characteristics of Diethyl ether rich ED blended fuels are significant with increasing of oxygen concentration.

5. APPENDIX

Calculations of λ_{tip} and T_{spm} in the theoretical analysis of mixture formation process. According to the theory of momentum for the spray penetration by Wakuri et al.[17], reaching distance of spray tip "X" depends on time after fuel injection and is expressed as equation (3)

$$X = \left(\frac{2C\Delta P_{inj}}{\rho_a}\right)^{0.25} \cdot \left(\frac{t \cdot d_N}{tan\theta}\right)^{0.5} \tag{3}$$

Cross sectional mean excess air ratio of a spray at X location and the injection angle (2θ) are represented as equations (4) and (5), respectively

$$\lambda_X = \frac{2tan\theta}{L_{th} \cdot C^{0.5}} \cdot \left(\frac{\rho_a}{\rho_f}\right)^{0.5} \cdot \frac{X}{d_N} \tag{4}$$

$$tan\theta = 0.427 \left(\frac{\rho_a}{\rho_f}\right)^{0.325} \tag{5}$$

Concentration factor was decided as λ_{tip}=1, situation of the spray suitable for auto-ignition can be predicted from the viewpoint of probability, because the location of $\lambda(X,r)$ =1 must exists in any cross section along the axis of a spray. Reaching distance of spray tip, volume of spray and the time when λ_{tip}=1 are expressed as equations (6), (7) and (8), respectively.

$$X_{\lambda_{tip}=1} = \frac{d_N}{\left(\frac{2tan\theta}{L_{th}\cdot C^{0.5}}\right)\cdot\left(\frac{\rho_a}{\rho_f}\right)^{0.5}} \tag{6}$$

$$V_{\lambda_{tip}=1} = \frac{1}{3}\pi \cdot X^3_{\lambda_{tip}=1} \cdot tan^2\theta \tag{7}$$

$$t_{\lambda_{tip}=1} = \frac{X^2_{\lambda_{tip}=1}}{\left(\frac{2C\Delta P_{inj}}{\rho_a}\right)^{0.5}\cdot\frac{d_N}{tan\theta}} \tag{8}$$

At the time indicated by equation (8), stable auto-ignition can be obtained if mean temperature of a spray is higher than fuels minimum ignition point ($T_{spm}>T_{ig}$). Required heat that increases the temperature of the spray up to T_{ig} is expressed as follows:

$$Q = G_f\left[c_{fl}(T_b - T_0) + \gamma_f + c_{fg}(T_{ig} - T_b)\right] \tag{9}$$

First and third terms of equation (9) correspond to apparent heat in liquid and gas phase, respectively, and the second term means latent heat of evaporation. Mean temperature (T_{spm}) was obtained from equation (10) as instantaneous heat balance assumed to be satisfied.

$$G_f\left[c_{fl}(T_b - T_0) + \gamma_f + c_{fg}(T_{spm} - T_b)\right] = G_a c_a(T_a - T_{spm}) \tag{10}$$

In the calculation of λ_{tip} and T_{spm} as shown in Figs. 1 and 6, fuel properties listed in Table 2 were substituted in equations (3)-(10). Minimum ignition point (T_{ig}) of Ethanol and diethyl ether in Table 2 are the values at atmospheric pressure. For the ED blend fuels, T_{ig} of diethyl ether was used as the temperature factor with the assumptions of that diethyl ether auto-ignition would be first occurred regardless of blend ratio.

As mentioned above the estimation of T_{spm} and the discussion of temperature factor are based on those assumptions, therefore, calculation of T_{spm} was not correct quantitative simulation. However, the authors recognize that estimation of T_{spm} history from fuel injection is useful to qualitatively understand what is the main factor within fuel properties that govern T_{spm}.

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NOMENCLATURE

C	discharge coefficient
c	specific heat, kJ/kg・K
d_N	hole nozzle diameter, m
G	mass, kg
L_{th}	stoichiometric air fuel ratio, $\mathrm{kg_{(fuel)}/kg_{(air)}}$
n	polytropic exponent
ΔP_{inj}	pressure, MPa
T	temperature, K

T_{spm}	mean temperature of a spray, K
t	time, ms
X	reaching distance of spray, mm
γ	latent heat (heat of vaporization), kJ/kg
ε	compression ratio
θ	injection angle, rad
λ	excess air ratio
ρ	density, kg/m^3

Subscriptions

a	air (entrained gas)
b	boiling point
f	fuel
fg	gas phase (fuel)
fl	liquid phase (fuel)
ig	minimum ignition point/ignition position at auto ignition timing
o	initial
tip	spray tip

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