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Research Article

SURROUNDING GAS PRESSURE AND TEMPERATURE DEPENDENCE OF THE AUTO-IGNITION PHENOMENON FOR ETHANOL-DIETYL 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. This paper focuses on the effects of surrounding gas pressure and temperature on auto-ignition. Spray mixture formation and auto-ignition phenomena of Ethanol-Diethyl ether blended fuels were visualized by shadowgraph method and images were recorded with high-speed camera (8213 fps). A large constant volume electrical heating chamber was used in the visualization tests. The results as the first step of 3D-mapping of ignition delay showed that the auto-ignition of Ethanol-Diethyl ether blended fuels was strongly influenced by surrounding gas pressure under relatively lower temperature condition (750K). In higher temperature condition (800K), surrounding gas pressure dependence of the ignition delay was smaller than those of the 750K case. This paper indicates that the engine control logic can be drawn and the high performance CI engines flexible for any kinds of bio-fuels can be developed when the database as 3D-mapping of the ignition delay is completed.

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.

Figure 1 shows the present social and industrial situations depending on the hydrocarbon combustion. In the automotive technologies, although one of the R&D trends for passenger car is on the HV (Hybrid Vehicle), PHV

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(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. 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. As well as the automotive industry, large amount of petroleum is consumed in the various kinds of industries. Heavy duty oil is main fuel of burners that used for temperature control in green houses where many kinds of vegetables, fruits and flowers are growing and is also used for drying of agricultural and fishing products such as tea leaves and seaweed. Heat pump is better in efficiency to obtain such low level heat. Co-generation system with diesel engine and heat pump is one of the effective ways for saving energy resource.

This study deals with the development of high performance diesel engines fueled by biomass-based alcohol. As well as the power unit of vehicles, diesel type high performance engines flexible for any kinds of bio-fuels including bio-Ethanol can be applied to agriculture and fishing industries as a small sized personal use electrical power generation. That is one of the essential components for co-generation system previously introduced, and can be also applied to a large sized backup system for huge electrical power generation plants. Stable electric power supply can be also realized by the best combination with any other natural energy utilization if the above proposed high performance alcohol diesel engine is developed. When renewable bio-fuel is their all power resources, sustainable community can be established. Figure 2 shows the image of the sustainable community with the combined utilization of natural energies such as solar, wind and biomass. With the improvements of bio-fuel production technology and the infrastructure of their supply, ideal way of energy use is expected. That is energy production and consumption is completed within a community. Alcohol diesel engines, needless to say, are applied to commercial trucks and personal use small vehicles. Therefore, success of this study induces the promotion of renewable biomass energy and a big contribution against the worldwide energy and environmental problems such as oil reserve depletion and global warming. Local community has larger potential of biomass production comparing to urban cities, therefore, large scale biomass plantation is expected in country side local areas. This generates various kinds of new businesses that correspond to the increase of employees, as the result of such social movements, civil life and industrial activities in each local community can be grown. Local communities in any countries have potential for the utilization of biomass energy. Especially in Asian countries such as Thailand and Indonesia, R&D of biomass energy utilization is promoted as their national energy strategies. If the above introduced sustainable community is appeared around the world, life style and industrial activities must be changed. Although energy saving and economic growth is the trade-off relations each other, these compatibility can be possible with the development of biomass energy production/conversion technologies. This is the author's expected future image.

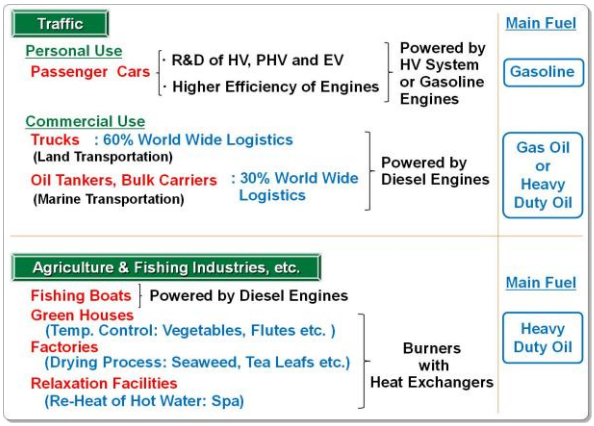

Fig. 1. Present social and industrial situations depending on petroleum combustion.

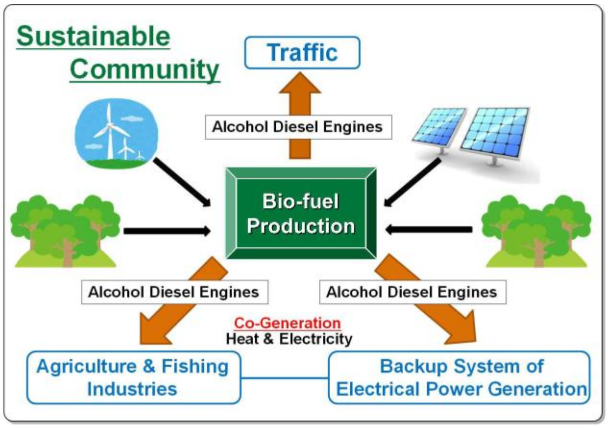

Fig. 2. Conceptual figure of sustainable community with biomass energy utilization.

1.2 The current technological state of the art with respect to the R&D of CI alcohol engines

Several companies were active in the development of direct injection CI (Compression Ignition) alcohol diesel engines with the support of their government R&D programs in 1980s-1990s. The biggest challenge in the development of alcohol diesel was ignition control due to well-known poor auto-ignition quality. Approaching way of ignition improvement is categorized by the two points of view. One is on the engine side measures as employing ignition-assist devices such as glow plug [1], spark plug [2] or heating surface [3] etc. The other is on the fuel side measures as adding of small amounts of ignition improver [4]. Almost all of those studies on engine side measures just concerned to seek the optimum configurations within each examined engine and their performance. While for the researches of additives, although the effect of each examined additive on ignition characteristics was investigated by using real engines, the effectiveness of examined additives was just verified for their test engines, which cannot be a fundamental knowledge. In spite of more than a thirty-year history, high performance alcohol diesel engines with controlled auto-ignition and combustion is not yet completely developed. Result of detailed paper survey as briefly summarized above is found in the reference paper [5]. Thailand is still now one of the active countries for the alcohol diesel development under their energy strategies. Fundamental studies on the ignition-improving additives have been conducted and reported intensively. Munsin and Laoonual [6-7] examined several additives in their CVCC (Constant Volume Combustion Chamber) and their effectiveness on the auto-ignition quality. Although they showed experimental results as auto-ignition characteristics of an Ethanol spray in the cases 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.

1.3 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 [5,8-13] have intensively investigated and reported this decade 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 is able to be established and high performance alcohol engines can be developed. The first trial of data reduction in a form of the 3D-mapping of ignition delay for Ethanol-Diethyl ether blended fuel is introduced in this paper.

2. Experimental Setup and Conditions

2.1 Test chamber

Figure 3 shows the construction of the constant volume electrical heating chamber used in the visualization test. Specification of the chamber is presented in table 1 and figure 4 shows the whole experimental setup. 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 figs. 3 and 4. 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 0.14mm in diameter was installed in the injector. In the experiments injection pressure was maintained at 50MPa by a booster pump and the injection duration was controlled as 4.76 ms by the signal from digital circuit board equipped in the control unit represented as “7” in fig. 4.

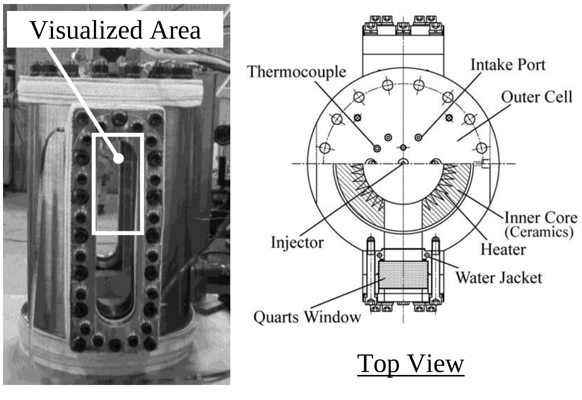

Fig. 3. Structure of the constant volume combustion chamber used in the visualization.

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)

2.2 Experimental Procedure and Conditions

Test gas was supplied from a bomb into the chamber up to the initial condition of pressure. Initial gas pressure before heating (P_o) was calculated based on the equation of state under constant volume condition expressed as follows:

$$\frac{T_o}{P_o} = \frac{T_t}{P_t} \quad \rightarrow \quad P_o = P_t \frac{T_o}{T_t} \qquad (1)$$

In equation (1), P_t and T_t, respectively, are target values of in-chamber gas pressure and temperature as surrounding gas conditions for fuel injection. Initial gas temperature represented as T_o 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 (gas oil and ethanol-diethyl ether blended fuels) was injected into the chamber when gas pressure indicated the target value of P_t during heating. Visualization of spray mixture formation was conducted by shadowgraph method. Shadowgraph optical system consists of Xenon light source and one pair of concave mirrors. Spray mixture formation process and auto-ignition phenomenon were recorded with high-speed camera at 8213 fps. Recording was synchronized with fuel injection.

Ethanol-Diethyl ether blend fuels were employed in the experiment in order to make clear the effect of fuel properties that listed in table 2 on auto-ignition. However, in the previous studies[8-9], 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.

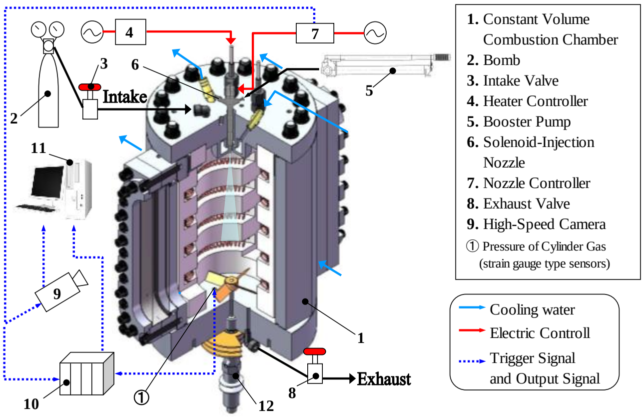

Fig. 4. General view of the experimental setup and recording system.

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 ↓ 3.0	750 ↓ 800	21%	79%	50	4.76
E:D=2:8 (ED28)						
E:D=1:9 (ED19)						
Diethyl ether (D)						
Gas Oil (G)						

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, surrounding gas pressure and temperature were varied, respectively, from 2.0MPa to 3.0MPa and from 750K to 800K under constant Oxygen concentration at 21% in volume.

2.3 Evaluation of auto-ignition quality

Auto-ignition quality of the tested fuels was evaluated by ignition delay time. It was defined as the time from fuel injection-start timing to auto-ignition timing. Occurrence of the auto-ignition was judged on the visualization images. Therefore, ignition delay contains 0.1217ms measurement error that corresponds to the frame interval of recording procedure by using a high speed camera (8213fps: 1s/8213=0.1217ms interval).

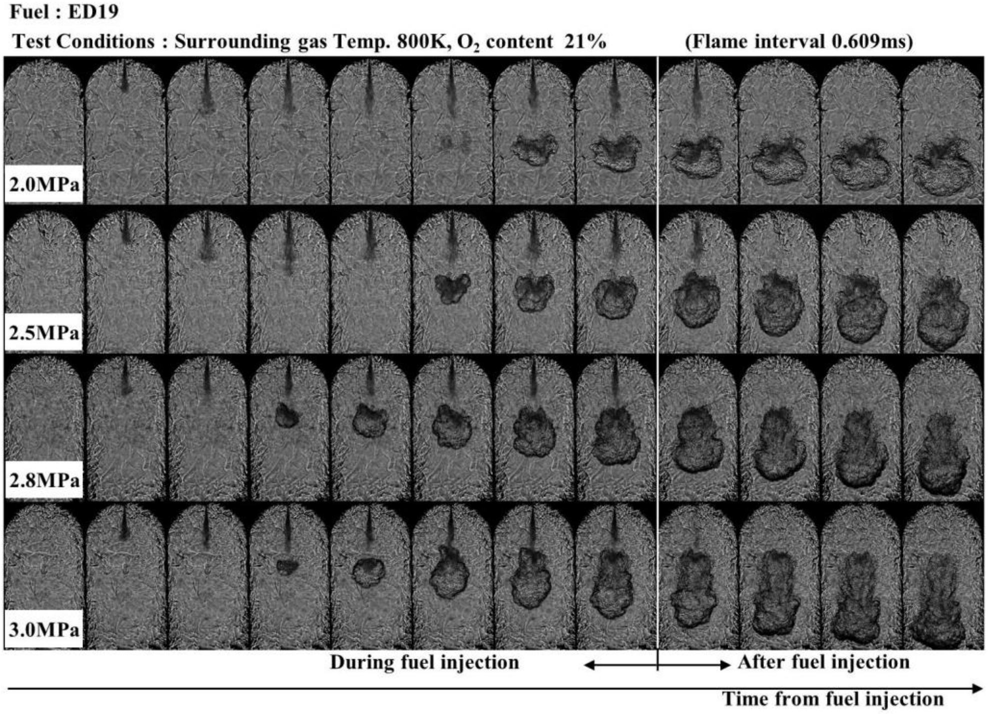

Fig. 5. Visualization results indicating the effect of the surrounding gas pressure on ignition delay.

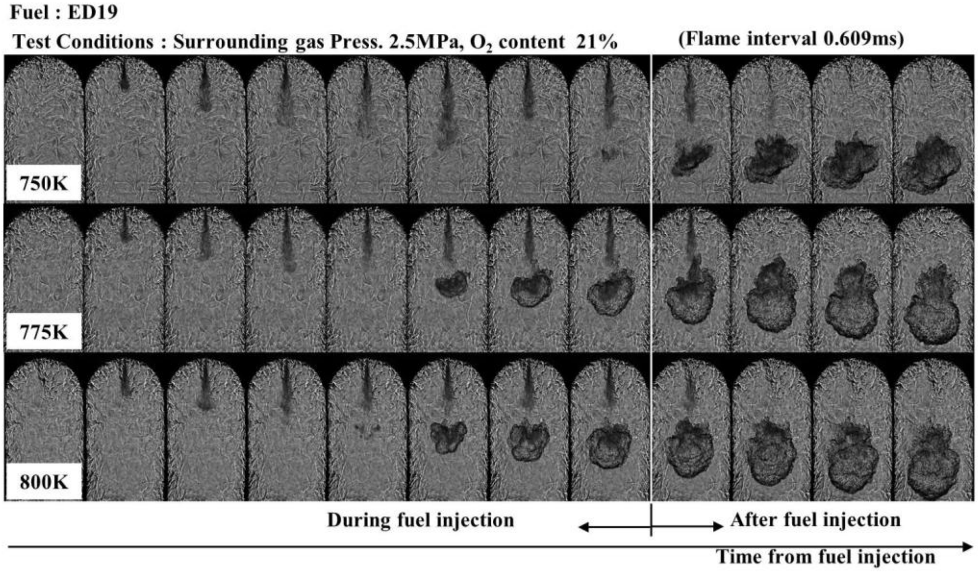

Fig. 6. Visualization results indicating the effect of the surrounding gas temperature on ignition delay.

3. Results and Discussion

Visualization results for ED19 fuel are shown in figs. 5 and 6. Figs 5 and 6 consists of every five frame interval visualized images from fuel injection (image interval is 0.609ms corresponding to the five times frame interval of 0.1217ms). Shorter ignition delay with higher surrounding gas pressure and temperature was confirmed. This tendency was obtained for any other tested fuels. However, each fuel had its own surrounding gas pressure and temperature dependence of ignition delay. This can be caused by the difference of fuel properties as "internal factor".

Figure 7 represents the 3D-surface data of ignition delay depending on the surrounding gas pressure and temperature for each fuel: (a) Diethyl ether, (b) ED19, (c) ED28 and (d) ED37. Under lower temperature condition at 750K, ignition delay was decreased with raising the surrounding gas pressure. This tendency, however, was clearly seen with increase of Ethanol blend ratio. In addition, auto-ignition was not observed for ED19, ED28 and ED37 when surrounding gas pressure was less than 2.5MPa. Therefore, it is understood that auto-ignition is strongly influenced by surrounding gas pressure under 750K condition. On the other hand under higher temperature condition at 800K, surrounding gas pressure dependence of ignition delay was smaller than those of 750K case. Negligible small change of ignition delay was obtained when surrounding gas pressure was higher than 2.8MPa for all the tested fuels except for ED37. Similarly higher surrounding gas pressure condition yielded smaller temperature dependence of ignition delay although ignition delay was decreased for each tested fuel with raising the surrounding gas temperature regardless of surrounding gas pressure value.

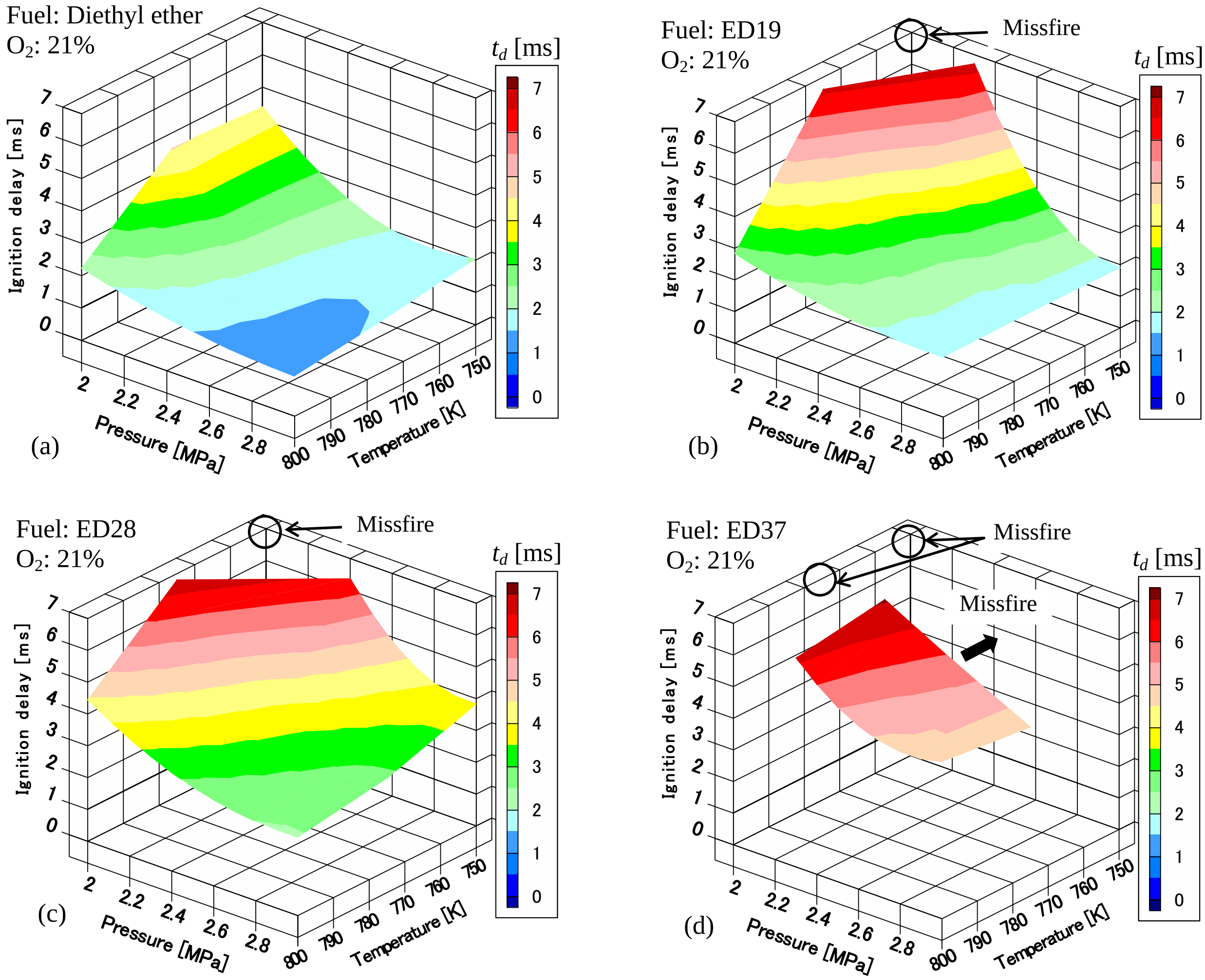

Fig. 7. Surrounding gas pressure and temperature dependence of auto-ignition represented in a form of 3D-surface data of ignition delay for each tested fuel.

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. In the spray mixture formation process, concentration and temperature distribution and their temporal history depends on the surrounding gas conditions. The authors[8-9] concluded in the past that spatial and temporal matching of ignition suit mixture concentration and temperature is necessary for stable auto-ignition. It is generally recognized that auto-ignition is occurred when mixture is going to be lean from over rich situation under sufficient higher temperature condition. Namely concentration-dominant condition is required in order to obtain stable auto-ignition by fuel injection. Higher surrounding gas pressure corresponds to higher gas density of the entrained gas into a spray, which induces simultaneously increase the amount of heat supplied into a spray and faster lean situation due to the increase of mass of the entrained gas. As well as higher surrounding gas temperature, therefore, faster temperature rise of a spray mixture is also caused by higher surrounding gas pressure. Based on the above stated recognition on auto-ignition phenomenon, we can understand the surrounding gas pressure and temperature dependence of auto-ignition as shown in fig. 7. Small surrounding gas pressure and temperature dependence of ignition delay seems to be attributed to the attainment of stable auto-ignition condition as spatial and temporal matching of ignition suit mixture concentration and temperature in the spray mixture formation process. On the other hand, in the cases of strong influence of surrounding gas pressure and temperature, it is not expected the concentration-dominant condition for auto-ignition. As the result of mismatch of ignition suit mixture concentration and temperature, it seems that long ignition delay and strong surrounding gas pressure and temperature dependence was indicated.

4. Future Work

As the first trial of data reduction for auto-ignition phenomenon, 3D-surface data of ignition delay was presented. This can be a useful database to quantitatively predict the ignition delay of test fuels. However, 3D-mapping of ignition delay indicating the combined effects of the “external factors” (surrounding gas pressure, temperature and Oxygen concentration) on auto-ignition is not completed yet. The authors would like to show the external factor’s dependence of auto-ignition in a form of 3D-contour diagram. Further investigation on the effect of Oxygen concentration of the surrounding gas on ignition delay, which has been now in progress, is required. To make experimental conditions wider close to the conventional CI engine operating conditions is also required. Siebers and Edwards[14] suggested more than 1100K of air at the fuel injection timing in order to obtain acceptable ignition delay. They firstly pointed out the one fundamental knowledge in 1987 and they showed an important direction that researchers and engineers should pay an attention in the design process. This can be recognized as a threshold of the surrounding gas temperature for stable auto-ignition of neat Ethanol. Original designed and manufactured RCEM (Rapid Compression and Expansion Machine) will be employed in the future work in order to realize surrounding gas temperature higher than 1100K under feasible compression ratio around 21-23. Experiments can be conducted for Ethanol rich ED blend fuel and neat Ethanol by using the RCEM. Final goal of our research is to make clear the physical and chemical mechanisms of alcohol’s spray auto-ignition phenomena, and to propose the controlled ignition technology. In order to reach this goal, numerical analysis on the mixture formation, auto-ignition and combustion also will be performed with the consideration of detailed chemical reaction.

5. Conclusions

1. As one of data reduction ways, 3D-mapping indicating the effects of surrounding gas pressure and temperature on auto-ignition is useful enough to have quantitative prediction of ignition delay for each tested fuel.

2. Diethyl ether rich Ethanol-Diethyl ether blended fuels show their own surrounding gas pressure and temperature dependence of ignition delay, although they have the same tendency of shorter ignition delay with higher surrounding gas pressure and temperature.

6. Acknowledgement

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NOMENCLATURE

P	: surrounding gas pressure	[MPa]
T	: surrounding gas temperature	[K]
t_d	: ignition delay	[ms]

Subscriptions

0	: initial
t	: target

Acronyms

CI : Compression Ignition
CVCC : Constant Volume Combustion Chamber
ED : Ethanol-Diethyl ether blended fuels
R&D : Research and Development
RCEM: Rapid Compression and Expansion Machine

REFERENCES

[1] Havenith, C., Kuepper, H. and Hilger, U. Performance and emission characteristics of the Deutz glow plug assisted heavy-duty methanol engine, 1987, SAE-872245.

[2] Niemi, S. and Pitkanen, J. Development of a turbocharged and inter-cooled spark-assisted direct-injection ethanol engine, 1993, Proc. of 20th CIMAC, D14.

[3] Ramesh, A., Nagalingam, B. and Gopalakrishnan, K.V. Investigation on the design and performance of two types of hot surface ignition engines, 1992, SAE-921632.

[4] Simonsen, H. and Chomiak, J. Testing and evaluation of ignition improvers for ethanol in a DI diesel engine, 1995, SAE Technical Paper 952512.

[5] Saitoh, H. and Uchida, K. On the main factors governing auto-ignition phenomenon of alcohol spray: A study from the view point of fuel properties, SAE Int. J. Fuels and Lubricants, Vol. 2(1), 2009, pp. 911-920.

[6] Munsin, R., Laoonual, Y., et al. Investigation of effects of ignition improvers on ignition delay time of ethanol combustion with rapid compression and expansion machine, SAE Technical Paper 2012-01-0854.

[7] Munsin, R., Laoonual, Y., et al. Effect of glycerol ethoxylate as an ignition improver on injection and combustion characteristics of hydrous ethanol under CI engine condition, Journal of Energy Conversion and Management, Vol. 98(1), 2015, pp. 282-289.

[8] H. Saitoh and K. Uchida, Effect of surrounding gas oxygen content on the spray mixture formation and auto-ignition phenomenon for ethanol-diethyl ether blended fuels, SAE Paper No.2013-01-0076.

[9] H. Saitoh and K. Uchida, A study on the conditions of controlled ignition for the fuels with poor auto-ignition quality, Journal of Flow Visualization and Image Processing, Special Issue of PSFVIP-9, 2014, pp. 1-16.

[10] Saitoh, H., Uchida, K. and Tateishi, M. Effects of heat supply methods into a spray of alcohol fuels on ignition and combustion characteristics in a small DI alcohol engine, Proc. CD of 30th FISITA World Automotive Congress, 2004, Paper F2004V222.

[11] Saitoh, H., Uchida, K. and Tateishi, M. Effect of hot EGR on combustion and emission characteristics in a diesel type alcohol engine, 2004, 24th CIMAC World Congress on Combustion Engine Technology, Paper No.162.

[12] Uchida, K., Saitoh, H. and Tateishi, M. Combined effects of fuel injection timing and hot EGR on ignition, combustion and thermal efficiency in a small DI alcohol engine, 13th International Pacific Conference on Automotive Engineering, 2005, Paper 41.

[13] Saitoh, H. and Uchida, K. Difference of spray mixture formation between gas oil and ethanol in a constant volume electrical heating chamber, SAE Technical Paper 2007-01-3617.

[14] Siebers, D.L. and Edwards, C.F. Auto-Ignition of methanol and ethanol sprays under diesel engine conditions, 1987, SAE Technical Paper SAE-870588.