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Effect of Ambient Temperature and Oxygen Concentration on Ignition and Combustion Process of Diesel Spray

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ABSTRACT

The mixture formation prior to the ignition process plays as a key element in the diesel combustion. Parametric studies of ignition process in a low oxygen concentration and low ambient temperature have received considerable attention in potential for reducing emissions. Purpose of this study was to clarify the effects of ambient temperature and oxygen concentration parameters during ignition delay period which have to be significantly influences throughout the combustion process that strongly affects the exhaust emissions. This study investigated the effects of ambient temperature and oxygen concentration on diesel combustion fundamentally using rapid compression machine. The detail behavior of mixture formation during ignition delay period was investigated using the schlieren photography system with a high speed camera. This method can capture spray evaporation, spray interference, mixture formation and flame development clearly with real images. Ignition process and flame development were investigated by direct photography method using a light sensitive high-speed color digital video camera. The sensitive camera can capture flame development clearly with the mixture of dark, bright and blue flames. The oxygen availability and ambient temperature are important variable that strongly affect to the fuel evaporation, endothermic and pyrolysis process during ignition delay. Decreased ambient temperatures, the ignition delay period is extended and enhanced fuel-air premixing which promotes the initial heat release. However, lowering oxygen concentration in volume slightly increases the ignition delay and generates low-luminosity flames at ignition. The flames develop very slowly to the combustion chamber. This type of flame development produces two-stage history of heat release rate after ignition. Further, initial heat generation after ignition is strongly dependent on oxygen mass concentration.

Key words: Mixture formation, diesel combustion, ignition delay, ignition process, spray, rapid compression machine, flame pattern, image analysis

INTRODUCTION

The diesel engine has undergone continues improvements through the development of engines technologies especially in controlling the combustion process. Although, it is very important to control the ignition process in order to reduce the NOx and PM levels (Anbese *et al*., 2011; Reddy *et al*., 2008; Miwa *et al*., 2001).

The major problem in diesel combustion chamber design is achieving sufficient rapid mixing between the injected fuel and the air in cylinder. There were many studies on the fuel-air premixing that responsible the ignition of diesel spray which linked to the improvement of exhaust emission (Khalid *et al.*, 2011; Lashkarpour *et al.*, 2011; Kidoguchi *et al.*, 2008). Ishiyama *et al.* (1995) has reported that the ignition process in diesel combustion, oxidation begins very early during ignition delay period and its supplies heat to the spray and causes cracking and gasification of fuel (Ishiyama *et al.*, 1995; Abdullah *et al.*, 2008). It was reported that evaporation and atomization process during ignition delay prior to ignition process, combustible mixture is first formed at midstream of the spray. Thus, combustion process and exhaust emissions are more clearly observed by examining the characteristics of the evaporation of fuel spray and initial heat recovery process during the ignition delay period (Khalid and Manshoor, 2012a; Aoyagi *et al.*, 2005). However, it is complicated to clarify the effects of oxidation reactions on ignition and initial heat recovery, while it having influences from the ambient temperature and oxygen concentration.

There have been many findings regarding the interaction between fuel spray and surrounding air toward the improvement of emissions (Khalid and Manshoor, 2012b; Yatsufusa *et al.*, 2009; Goda *et al.*, 2003). It is suggested that the interaction between fuel spray and surrounding gas is important for the combustion efficiency and exhaust emissions. However, in spite of these efforts, key factors that determine ignition delay, ignition and initial heat recovery are still unclear. It is important to clarify the effects of ambient temperature and oxygen concentration into the spray on the heat release process during ignition delay periods in detail.

In this study, the characteristics of diesel combustion in low oxygen mixtures and low ambient temperature are discussed focusing on heat release during ignition delay period. Experiment used a rapid compression machine together with the schlieren photography and direct photography methods. The main objective of this study was to make clear the influence of the effect of ambient temperature and oxygen concentration on heat recovery process, ignition and combustion characteristic.

MATERIALS AND METHODS

Rapid compression machine and injection system: A Rapid Compression Machine (RCM) was used to generate the actual diesel combustion over a wide range of temperatures, pressure and swirl velocities, as shown in Fig. 1. The RCM has a disc type combustion chamber with a diameter of 60 mm and a width of 20 mm. The chamber was made in an optically-accessible. The diesel sprays and flame development were observed through pyrex glass at base surfaces and the other side surface had an injector holder. The oxygen concentration and temperature were varied systematically by adjusting the input of ambient gas and temperature. Ambient temperature and oxygen concentration were changed as experimental parameters to observe the combustible mixture of fuel-air mixing during ignition delay period.

A portable swirler with a port of 14×16 mm-size section installed at inlet of chamber was used to simulate swirl flow inside the chamber. Swirl velocity is defined as the velocity at 2/3-location of radial direction from the chamber center. Standard swirl velocity is $r_s = 19$ m sec^{-1}, corresponding to the swirl velocity of the real engine in our laboratory. The velocity can be controlled by changing the port inclination against the chamber.

Table 1 summarizes the operating parameters and fuel injection system, including nozzle specification. A single-shot common-rail fuel injection system was used to inject JIS#2 diesel fuel (a density of 836 kg m^{-3} and lower heating value of 42.7 MJ kg^{-1}) into the spray chamber. The

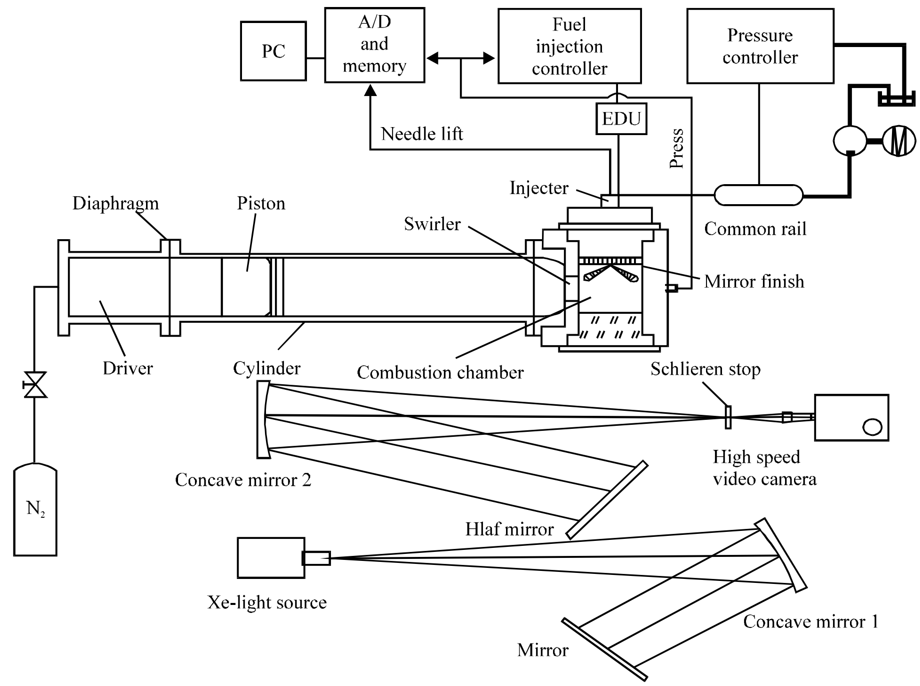

Fig. 1: Experimental setup

Table 1: Experimental conditions as ambient temperature and oxygen concentration were varied

		Effect of ambient temperature				Effect of oxygen concentration				
Fuel	Injector type	**6 holes, d = 0.129 mm**								
	q_i	**0.05 mL**								
	P_{inj}	**100 MPa**								
		0.37				0.37	0.47	0.62	0.93	1.24
Ambient gas	T_i K	700	750	**850**	950	**850**				
	r_s msec^{-1}	**19**								
	kg m^{-3}	**16.6**								
	O_2 vol%	**21**				**21**	16.8	12.6	8.4	6.3

Bold values are baseline

injection period was controlled at the fixed quantity at q_i = 0.05 mL. Equivalence ratio was ϕ = 0.37 at base condition, that is ambient density of ρ = 16.6 kg m^{-3} (ambient pressure of p_i = 4 MPa), ambient temperature of T_i = 850 K and oxygen concentration of 21 vol%. Injection commencement was measured from the needle lift detected by a hole sensor installed in the injector. Pressure inside the chamber was measured by a piezoelectric pressure transducer (Kistler, 601A). NOx concentration was measured by a chemiluminescence analyzer (Yanako, ECL-77A). The heat release rate dQ/dt was calculated from the combustion pressure.

In this study, the images of mixture formation and flame development were observed by using the direct and schlieren optical photography methods. The optical arrangement of schlieren photography is also shown in Fig. 1. The atmosphere was filled by nitrogen gas in the schlieren photography in order to observe spray evaporation and mixture formation without ignition. The monochromes spray images were recorded by a high-speed digital video camera (Eastman Kodak Ektapro, HS4540) with frame speed of 13500 fps. To obtain the detail flame development after ignition, direct photography method was employed. In this method, the flame development was captured by a high light-sensitive and high-speed color digital video camera (NAC,GX-1) with frame speed of 10000 fps.

Effect of ambient temperature and oxygen concentration on ignition and combustion: Aim of this study was to clarify the ignition process under different of ambient temperature and oxygen concentration. The effect of ambient temperatures on the combustion development was first investigated at the base oxygen concentration O_2 = 21 vol% for ambient temperature T_i of 750, 850 and 950 K. The investigated initial charging pressure was kept at p_i = 4 MPa that corresponds to ambient density of ρ = 16.6 kg m^{-3}. Next, the effect of oxygen concentration on combustion was also investigated at the same T_i = 850 K and ρ = 16.6 kg m^{-3}. Oxygen concentration were varied at O_2 = 21, 16.8, 12.6, 8.4 and 6.3 vol% that corresponds to the equivalence ratio ϕ was ϕ = 0.37, 0.47, 0.62, 0.93 and 1.24, respectively.

Figure 2 shows the effect of ambient temperature and oxygen concentration on ignition delay, τ. In this study, ignition delay is defined as time interval from start of injection to ignition accompanying with truly heat recovery. In this definition, the pressure difference between the pressure in firing condition, p_f and the pressure after compression without fuel injection, p_a, is taken into account. The pressure difference, p_f-p_a, indicates the net pressure excluding the effect of the heat loss to the chamber wall. Firstly, p_f-p_a shows negative value just after start of injection due to heat absorption caused by fuel evaporation and fuel decomposition. Then, it soon shows a rising curve due to heat recovery when heat generation exceeds the absorption. We define ignition point where p_f-p_a recovers to zero after decline in negative value by heat absorption. According to the Fig. 2, reductions of ambient temperature lengthen the ignition delay and enhanced fuel-air premixing will occur. Longer ignition delay may provide better mixture preparation but the lower

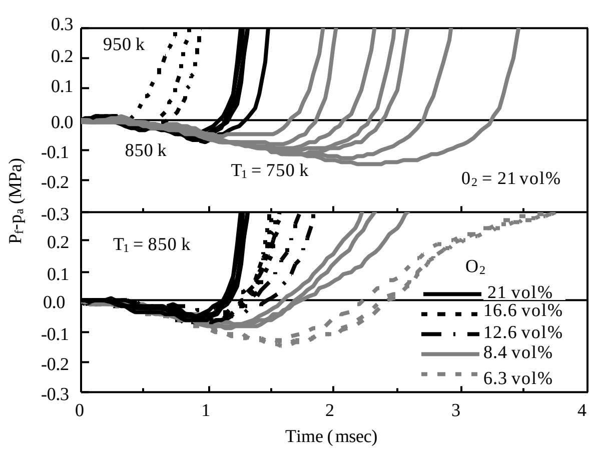

Fig. 2: Histories of pressure during ignition delay period

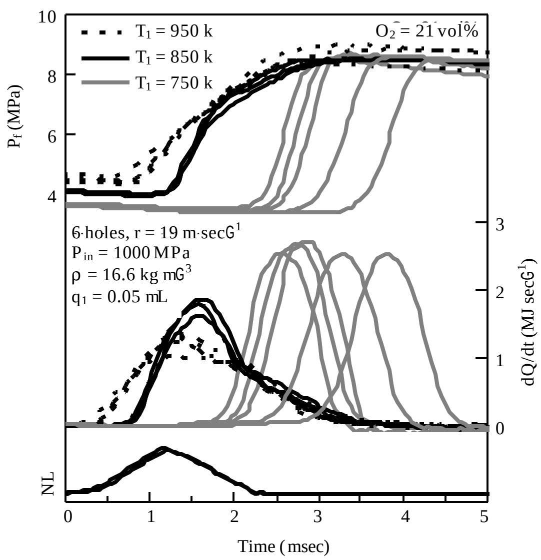

Fig. 3: Effects of ambient temperature on combustion process

initial reactant temperature simply lengthen ignition delay period. Particularly, ignition delay period also decreases with the decrease of oxygen concentrations due the lower equivalent ratio.

Figure 3 shows histories of combustion process as the ambient temperature is varied. Combustion pressure p_f and heat release rate dQ/dt are indicated together with nozzle needle lift NL against time t from start of injection. Lowering ambient temperature, increased time period from injection and initial heat release but shows to reach at higher peak heat release rate and shorten combustion duration. In addition, decrease in ambient temperature, achieves low in-cylinder temperatures extended long ignition delay, as shown in Fig. 2. The longer physical process and better combustible mixture preparation are significantly with the initial heat release rate progressively increased and reaches high peak with shorten combustion duration especially at low temperature condition of T_i = 750 K.

Figure 4 clearly demonstrates the effects of the oxygen concentration under T_i = 850 K. Lowering the oxygen concentration slightly lower the time period from injection and initial heat release. The heat release increases much more slowly and little influences on the reduction of peak heat release but shifted later in long combustion duration. Moreover, lowering oxygen concentration results in the longer ignition delay and gradually pressure recovery after ignition, same behavior as decreasing of T_i. However, the benefits of pre-mixing may not be seen due to the slower oxidizing reactions at spray boundary which later increases the heat release. As is different from the low temperature condition, the condition of low oxygen concentration causes slower increase of heat release rate after start of heat recovery even in the case of long ignition delay. The condition of low oxygen concentration provides lower amount of oxygen, resulting in this kind of heat release history.

Next, the influences of ambient temperature are investigated on the point of flame development and heat release. Figure 5 depicts the comparison of the spatial distribution of flame and schlieren

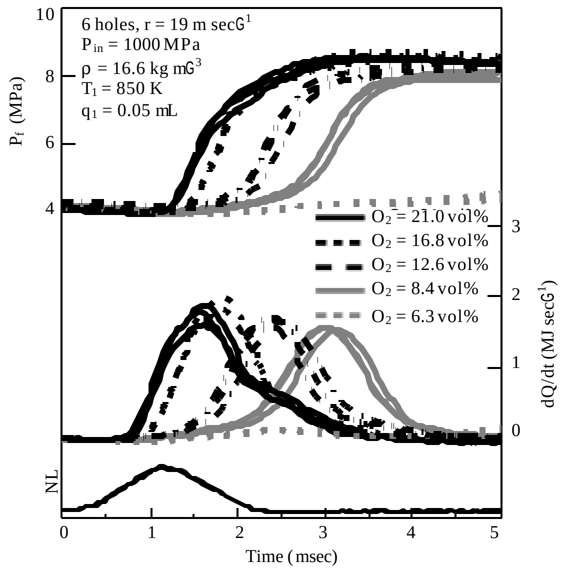

Fig. 4: Effects of oxygen concentration on combustion process

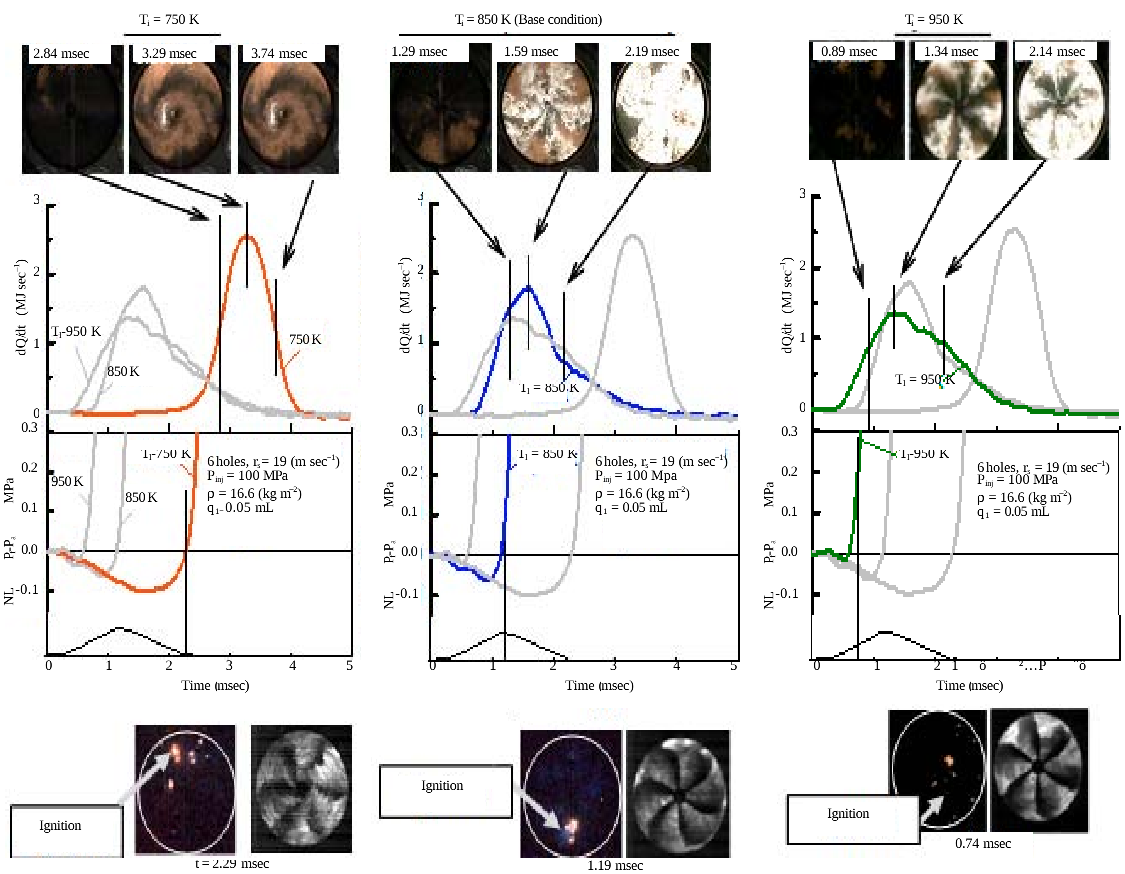

Fig. 5: Effects of ambient temperature on histories of initial flames, flame development and heat release

image, histories of heat release and ignition delay as ambient temperature T_i is varied. The optical equipments of schlieren photography are also shown in Fig. 1. The experiments with schlieren photography were conducted to observe the behavior of spray itself, thus ignition of spray were avoided by using nitrogen ambient in these series of experiment. To observe flame development after ignition, direct photography method was employed. As seen in flame images at low T_i condition, flame first becomes visible and the luminosity flame rapidly develops to the whole chamber. The rapid flame development after ignition suggests that combustible mixture is enough prepared at ignition in this case. The highest maximum heat release under low temperature condition can be explained by large amount of pre-mixture prepared during long ignition delay period.

Figure 6 depicts the comparison of the spatial distribution of flame, heat release, ignition delay period and needle lift as oxygen concentration is varied. At every presented figure, the top side showed the comparison of distribution of heat release with the high intensity direct photograph taken during burning process. The below side compared initial flame development taken just after ignition with high sensitivity photography and observed together with pressure histories. The first left diagram showed the combustion at O_2 = 21 vol% and T_i = 850 K, as a base line condition. As seen from the Fig. 6, decreased the oxygen concentration, a large blue flame area is observed at beginning of ignition process and exhibits a monotonic decrease of flame luminosity with compared the base line condition. This flame behavior could be associated with the lengthen ignition delay period and late rise of heat release distribution as previously discussed.

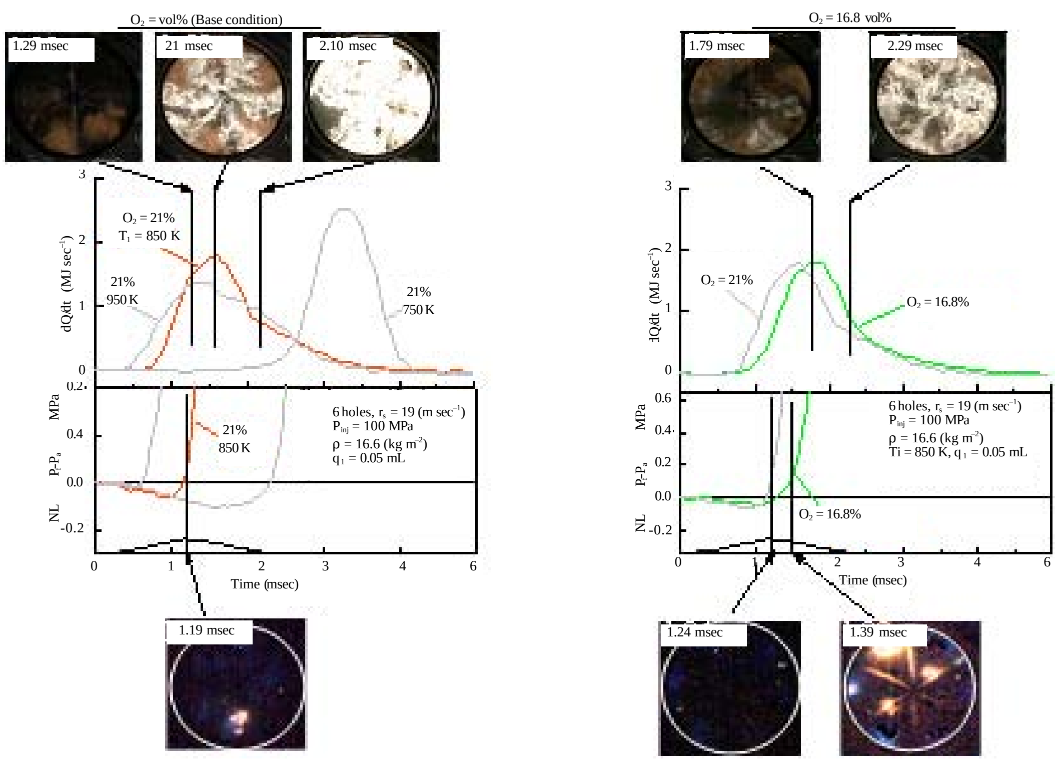

Fig. 6: Continue

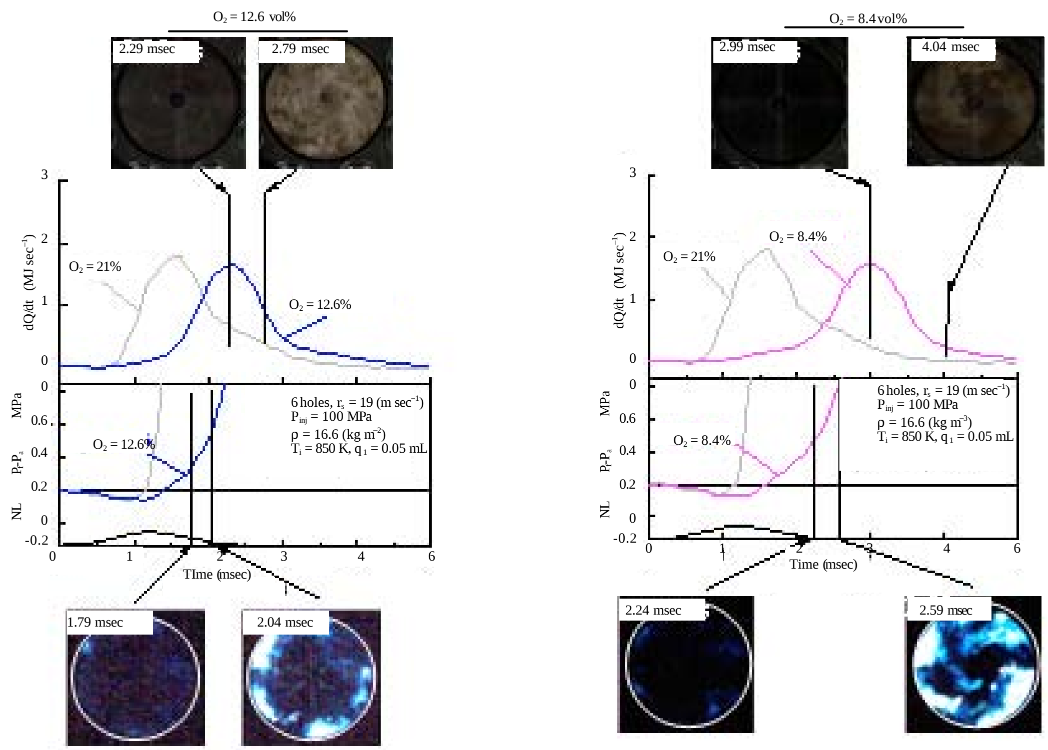

Fig. 6: Effects of oxygen concentration on histories of initial flames, flame development and heat release

It seems that the spatial distribution of the flame development, location of self ignition and heat release rate are depending on the variants in oxygen concentration. Figure 7 shows the relation between ignition delay and combustion characteristics and NOx concentration after combustion at different ambient temperature T_i and oxygen concentration. The Q_t is total heat release, Δtb the combustion duration and (dQ/dt)max the maximum heat release rate. Ignition delay τ, which is the amount of heat absorption Qab during ignition delay period and NOx emission per injected amount of fuel. As seen in Fig. 7, decreasing T_i at the base O_2 = 21 vol% lengthens ignition delay, raises $(dQ/dt)_{max}$ and shortens the combustion duration Δt_b and total heat release Q_t are hardly changed. Hence, Δt_b, Q_t and $dQ/dt)_{max}$ are not affected by ignition delay with the longer of ignition delay due to great preparation of combustible mixture. NOx deteriorates with decrease of ambient temperature. Nevertheless, lower initial reactant temperature and long endothermic duration lead to luminosity flame rapidly develops to the whole chamber, as evidenced by the reductions of NOx emissions. In contrast, lowering oxygen concentration with keeping constant T_i = 850 k, ignition delay also becomes increases similar with reduction of T_i. Reduction of $(dQ/dt)_{max}$, Q_t, NOx is remarkable as the lengthening of ignition delay. However, Due to the short endothermic duration and Slower initial heat recovery begins might be the explanation for the longer combustion duration and reductions of total heat release Q_t and heat release maxima $(dQ/dt)_{max}$ thus influences to the NOx reductions.

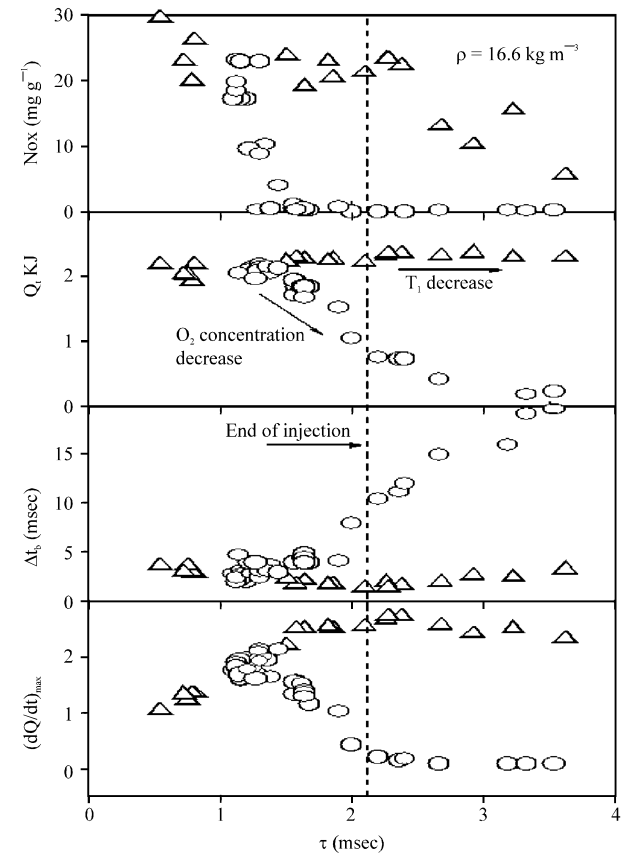

Fig. 7: Relation between ignition delay and combustion characteristics

CONCLUSION

In this study, design parameter of diesel combustion with variants in ambient temperature and oxygen concentration were investigated. Parametric studies of diesel combustion have been fundamentally investigated by using rapid compression machine and image analysis. Results are summarized as follows:

- Both low temperature and low oxygen concentration conditions lengthen ignition delay. Low temperature condition accumulates large amount of combustible mixture during ignition delay period which promotes the initial heat release; however, under the condition of low oxygen concentration, inactive chemical reaction causes slow heat generation in spite of enough time of physical mixing
- The initial heat release becomes more delayed for lowering the ambient temperatures and its peak is found to increase progressively and shorten combustion duration. The longer physical process, lower initial reactant temperature and larger amount of accumulated combustible mixture may affects this kind of heat release history especially at low temperature condition of T_i = 750 K
- Low oxygen concentration in volume generates low-luminosity flames at ignition. The flames develop very slowly to the combustion chamber. This type of flame development produces

two-stage history of heat release rate after ignition; namely firstly slow heat generation and secondly rapid generation. Further, initial heat generation after ignition is strongly dependent on oxygen mass concentration

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