JSAE 20119102
SAE 2011-01-1834

Effect of Air Entrainment and Oxygen Concentration on Endothermic and Heat Recovery Process of Diesel Ignition

Amir Khalid, Keisuke Hayashi, Yoshiyuki Kidoguchi
The University of Tokushima

Tomoaki Yatsufusa
Hiroshima Institute of Technology

ABSTRACT

The mixture formation prior to the ignition process is a key element in the diesel combustion because it significantly influences throughout the combustion process and exhaust emissions. Purpose of this study is to clarify the effects of ambient temperature, oxygen concentration and air entrainment into the spray on the heat release process during ignition delay periods.

This study investigated diesel combustion fundamentally using a rapid compression machine and high speed digital video camera. The detail behavior of spray evaporation, spray interference and mixture formation during ignition delay period was investigated using the schlieren photography system. Ignition process, flame development and images of the spray ignition with extremely dark flame were investigated by light sensitivity direct photography method. Heat release processes were analyzed by pressure measurement in the chamber. Results show that short endothermic process produces slow heat recovery, leading to gentle increase of initial heat release rate. Low oxygen concentration produces slow heat recovery process rather than long endothermic period, which suggests fuel-air mixing is required to promote chemical reaction for the case of low oxygen-concentration atmosphere. Initial heat release is activated to some extent by increase of air entrainment into spray during ignition delay period. However, excessive air entrainment increases initial heat release little and rather affects diffusion combustion.

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.

The major problem in diesel combustion chamber design is achieving sufficient rapid mixing between the injected fuel and the air in cylinder. In the diesel ignition and initial combustion process, heat absorption process first occurs due to fuel evaporation and fuel thermal-decomposition just after start of injection. Subsequently, heat recovery process starts when fuel-oxidation generates heat. Spray ignites at this process.

There were many studies on the fuel-air premixing that responsible to the ignition of diesel spray which linked to the improvement of exhaust emission[1-6]. Ishiyama et al.[7] 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. 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[8]. 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. The endothermic period discussed here represents the time from beginning of injection to the attainment of heat recovery by chemical reaction. However, it is complicated to clarify the effects of endothermic duration on ignition and initial heat recovery as it is affected by air entrainment into the spray. Moreover, thermal effect of the entrained air on ignition is dependent on the ambient temperature and oxygen concentration.

The oxidation reactions at the end of endothermic period depends on the physical process such as air entrainment, the breakup of the jet spray, and droplets evaporation[9]. Air entrainment caused by fuel injection and air motion is considered to be predominantly influences on chemical process such as pyrolysis and oxidization. However, it is complicated to achieve the best preparation of fuel-air mixing at first stage of mixture formation due to the dependency of the design parameter and air entrainment rate.

There have been many findings regarding the interaction between fuel spray and surrounding air toward the improvement of emissions [8-10]. Authors also investigated effects of the ambient density, ambient temperature and oxygen concentration, injection pressure and nozzle specifications on combustion process fundamentally by using rapid compression machine and image analysis[11, 12]. It is suggested that the interaction between fuel spray and surrounding gas is important for the combustion efficiency and exhaust emissions. Ignition is important as it is first stage of combustion and emission formation.

In this research, the characteristics of diesel ignition and combustion are investigated focusing on fuel-air mixing with changing ambient condition, injection parameters and air flow. Experiment used a rapid compression machine together with the schlieren photography and direct photography methods. The detail behavior of mixture formation during ignition delay period was investigated using the schlieren photography system with a high speed digital video camera. This method can capture spray evaporation, spray interference and mixture formation 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 could clearly capture spray ignition with extremely dark flame. Then, tried to make clear the influence of the operating parameters on entrainment rate, continuously investigate the effect of entrainment on endothermic and heat recovery process, ignition and combustion characteristic.

Effect of Air Entrainment on Ignition and Initial Heat Release

Next, effect of air entrainment into the spray on the specific time-characteristics and combustion will be investigated.

This study calculated air entrainment based on the momentum theory[12] , where the spray is treated as a quasi-steady gas jet. For an injector with a hole number n_0 and a hole-diameter d_0, injection rate M_j can be calculated as follows using fuel density ρ_f and constant fuel velocity u_j at nozzle outlet.

$$M_j = \rho_f \frac{\pi}{4} n_0 d_0{}^2 u_j \tag{1}$$

The mass ratio, e of entrained air flow M_a to the fuel flow M_j is calculated by[12]

$$e = \frac{M_a}{M_j} = \left(\frac{c_0 s}{d_0} - 1 \right) L \tag{2}$$

where L is the constant which expresses the effect of swirl, c_0 the constant given by the momentum theory, and s the spray tip penetration. L is calculated by[12]

$$L = 1 + \frac{c_s r_s}{u_j} \tag{3}$$

where r_s is the swirl velocity, c_s is the constant as 2.3[13]. Oxygen entrain rate into the spray per unit length, dm_{02}/ds can be computed by

$$\begin{aligned} \frac{dm_{O2}}{ds} &= \rho \frac{V_{O2}}{21} \frac{dM_a}{ds} = \rho \frac{V_{O2}}{21} M_j \frac{de}{ds} \\ &= \rho \frac{V_{O2}}{21} M_j \frac{c_0 L}{d_0} \\ &= \rho \frac{V_{O2}}{21} \rho_f \frac{\pi}{4} n_0 d_0{}^2 u_j \frac{c_0}{d_0} \left(1 + \frac{c_s r_s}{u_j} \right) \end{aligned} \tag{4}$$

$$\frac{dm_{O2}}{ds} \propto \rho \frac{V_{O2}}{21} n_0 d_0 u_j \left(1 + \frac{c_s r_s}{u_j} \right) \tag{5}$$

where ρ is ambient density, V_{O2} the volumetric ratio of oxygen in the atmosphere. Accordingly, we define oxygen entrain ratio Ent as

$$Ent = \rho \frac{V_{O2}}{21} n_0 d_0 u_j \left(1 + \frac{c_s r_s}{u_j} \right) \tag{6}$$

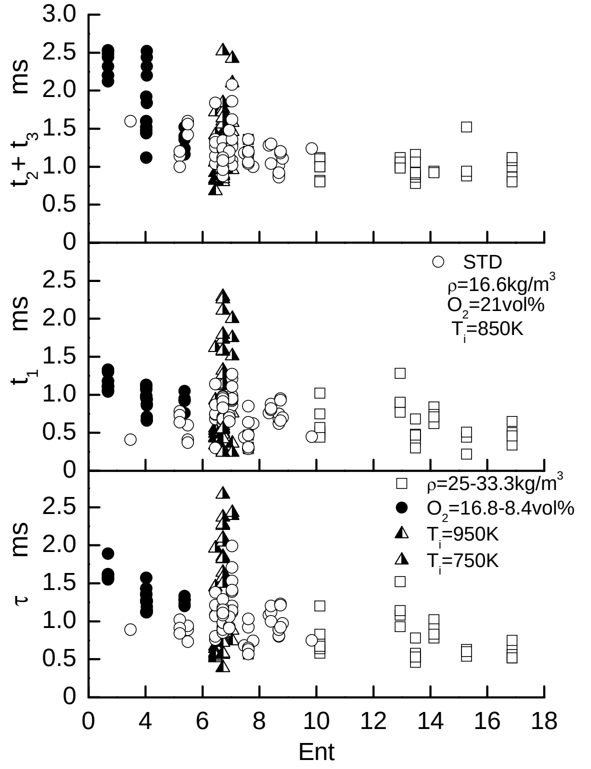


Fig.12 Effect of air entrainment on time characteristics

Figure 12 shows the effect of air entrainment on specific time-characteristics. As shown in the figure, increasing entrainment Ent tends to shorten ignition delay τ and endothermic period t_1. However, when Ent is larger than 10, increasing entrainment has little effect on shortening of τ and t_1. Ignition delay and endothermic period cannot be decreased shorter than about τ=0.5ms and t_1=0.2ms. The t_2+t_3, namely total heat generation period at initial burning, shows almost same trend as τ and t_1. At Ent <10, the t_2+t_3 is more sensitive to Ent than τ and t_1.

These results suggest that endothermic period and ignition delay can be shortened to some extent by promoting air entrainment into the spray; however, excess entrainment can change initial heat release little.

Table 2 summarizes the series of representative experiment conditions, their ignition delay period and calculated Ent. Figure 13 compares images of the schlieren photograph and direct photograph obtained under the conditions in Table 2.

Figure 14 compares the heat release rate dQ/dt and pressure histories at ignition delay close ranges between 0.8ms to 0.9ms. The entrainment rate is varied at ranges 5.21 to 14.13, as listed in Table 2. As seen in Fig 14, increasing rates of heat release rate and pressure are different despite of same ignition delay. No.2 (Ent=6.72), No.3 (8.68) and No.4 (10.12) show greater rise of dQ/dt. No.1 (5.49) and No.6 (5.21) show slower heat generation. The air entrainment promotes initial combustion. Nevertheless, No.5 is high density condition and high entrain ratio of Ent=14.13; however, rising rate of initial heat release rate is lower than No.2 (base condition). As seen from the images in Fig.13 that high density and high swirl (No.5) tends to form heterogeneous mixture. Spray interaction, which is not modeled in Ent calculation, may affect history of initial heat release. In addition, high density has high heat capacity, which is effective to shorten endothermic period and ignition delay but high heat capacity has disadvantage against heat recovery.

Table 2 Ignition delay and air entrainment

Data No.		No.1	No.2	No.3	No.4	No.5	No.6	No.7	No.8
Injection nozzle		4×0.158	6×0.129	10×0.1	6×0.129	6×0.129	6×0.1	10×0.1	6×0.129
Injection pressure	MPa	100	100	100	100	100	100	100	160
Swirl velocity	m/s	19	19	19	19	30	19	10	19
Ambient density	kg/m^3	16.6	16.6	16.6	25	33.3	16.6	16.6	16.6
Ambient temperature	K	850K	850K	850K	850K	850K	850K	850K	850K
Oxygen concentration	vol%	21	21	21	21	21	21	21	21
τ	ms	0.89	0.89	0.81	0.83	0.83	0.84	1.08	1
Ent		5.49	6.72	8.68	10.12	14.13	5.21	8.34	8.41

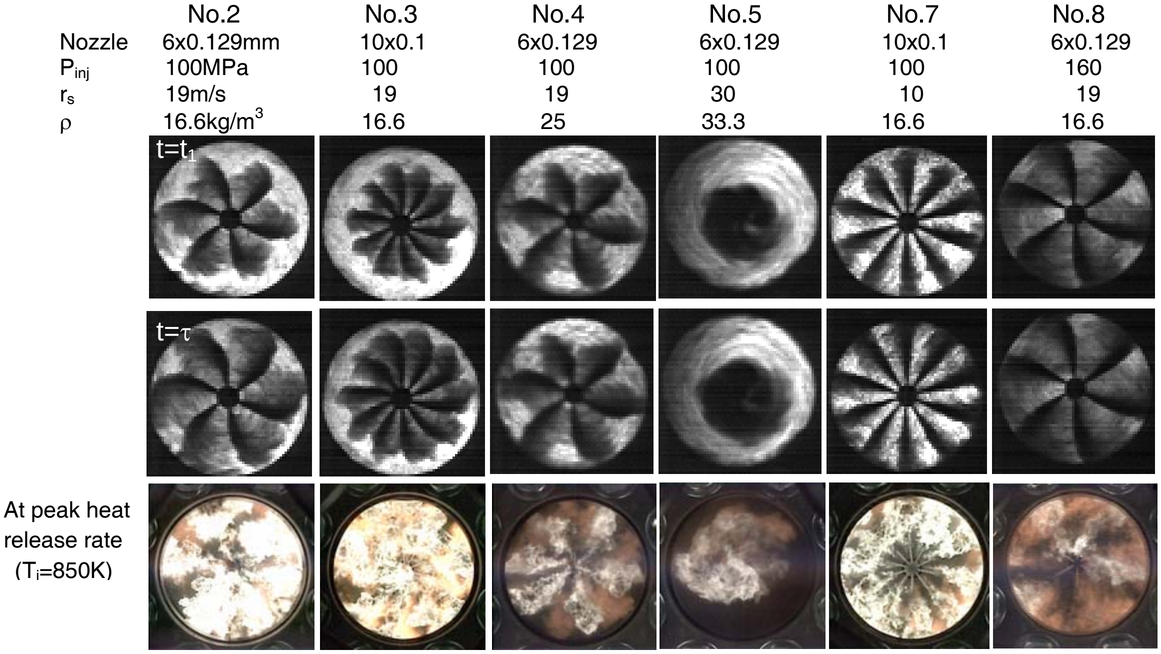
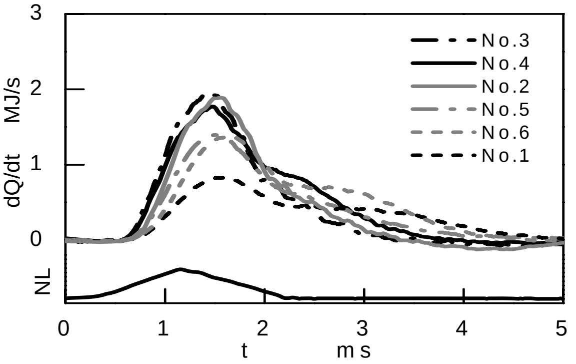
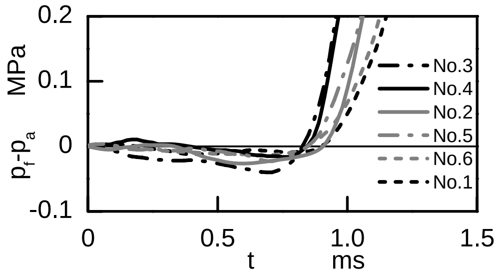


Fig.13 Comparison of mixture formation and flame development

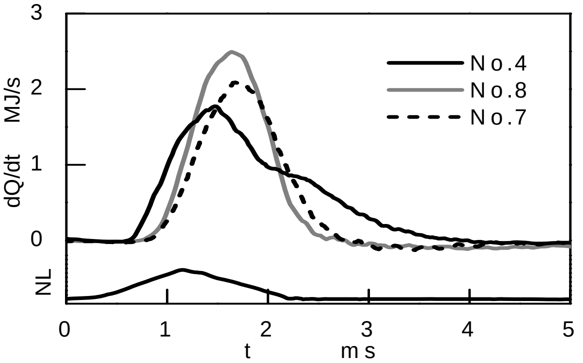


(a) Heat release rate

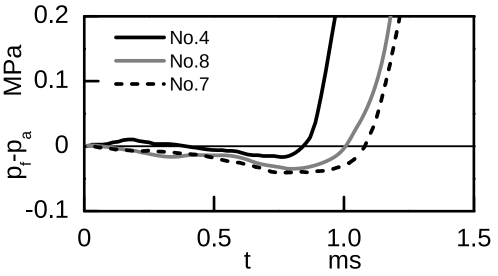


(b) Pressure during ignition delay period

Fig.14 Comparison of heat release rate and pressure histories (τ=0.8-0.9ms)



(a) Heat release rate



(b) Pressure during ignition delay period

Fig.15 Comparison of heat release rate and pressure histories (Ent=8.34-10.12)

Figure 15 is the same comparison as Fig.14. This figure compares conditions No.4 (Ent=10.12), No.7 (8.34) and No. 8 (8.41) at close ranges of high entrainment. High entrainment ratios are obtained by high density with No.4, multi-hole and low swirl with No. 7, and high-pressure injection with No.8. As shown in the figure, ignition delays of No.7 and No.8 are longer than No.4. All conditions have high rising rate of heat release as compared with Fig.14. Improving air entrainment certainly has an effect on rapid heat recovery.

CONCLUSION

In this research, a fundamental study on the characteristics of diesel combustion was carried out using a rapid compression machine by changing ambient temperature and oxygen concentration, swirl velocity and fuel injection parameters. Discussions were made on relation between air entrainment into the spray and heat release history during endothermic and heat recovery period before ignition. Results are summarized as follows;

1. 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.

2. Flame observation shows that, under lower oxygen concentration and high ambient density condition, the low-luminosity flame hardly develops toward the upstream of the spray due to the longer flame lift-off length.

3. Extremely short endothermic duration after start of injection rather lengthens heat recovery period before ignition. Heat recovery period is shortest when endothermic duration is about 0.5ms.

4. Increasing air entrainment into the spray generally produces short endothermic period and rapid heat recovery, leading to short ignition delay; however, according to estimation of air entrainment, excess entrainment can no longer control these durations.

REFERENCE

1. Goda, E., Kidoguchi, Y., Nitta, M. and Miwa, K., "An Appraisal of High-Pressure Injection and High Squish Combustion Chamber for Reduction of Diesel Particulate ", Trans. of JSAE, Vol. 34, No.3, pp.49-54, 2003.
2. Aoyagi, Y., Kunishima, E., Asauimi, Y., Aihara, Y., Odaka, M. and Goto, Y., "Diesel Combustion and Emission Using High Boost and High Injection Pressure in a Single Cylinder Engine", JSME International Journal, Series B, Vol. 48, No.4, pp.648-655, 2005.
3. Choi, D., Miles, P.C., Yun, H. and D.Reitz, R., "A Parametric Study of Low-Temperature, Late-Injection Combustion in a HSDI Diesel Engine", JSME International Journal, Series B, Vol.48, No.4, pp.656-664, 2005.
4. Ogawa, H., Li, T., Miyamoto, N., Kido, S. and Shimizu, H., "Dependence of Ultra-High EGR and Low Temperature Diesel Combustion on Fuel

Injection Conditions and Compression Ratio", SAE Paper 2006-01-3386, 2006.

5. Horibe, N., Takahashi, K., Kee, S.-S., Ishiyama, T. and Shioji, M., "The Effects of Injection Conditions and Combustion Chamber Geometry on Performance and Emissions of DI-PCCI Operation in a Diesel Engine", SAE Paper 2007-01-1874, 2007.
6. Horibe, N., Annen, T., Miyazaki, Y. and Ishiyama, T., "Heat Release Rate and NOx Formation Process in Two-Stage Injection Diesel PCCI Combustion in a Constant-Volume Vessel", SAE paper 2010-01-0608,, 2010.
7. Ishiyama, T., Miwa, K. and Horikoshi, O., "A Study on Ignition Process of Diesel Spray", JSME International Journal, Series B, Vol.38, No.3, pp.483-489, 1995.
8. Khalid, A., Yatsufusa, T., Miyamoto, T., Kawakami, J. and Kidoguchi, Y., "Analysis of Relation between Mixture Formation during Ignition Delay Period and Burning Process in Diesel Combustion", SAE Paper 2009-32-0018, pp.1-10, 2009.
9. Ikegami, M., Nakatani, K., Tanaka, S. and Yamane, K., "Fuel Injection Rate Shaping and Its Effects on Exhaust Emissions in a Direct-Injection Diesel Engine Using a Spool Acceleration Type Injection System ", SAE Paper 970347, 1997.
10. Horibe, N., Harada, S., Ishiyama, T. and Shioji, M., "Improvement of Low-Temperature Combustion by Two-Stage Injection", COMODIA 2008, pp.159-166, 2008.
11. Yatsufusa, T., Kawakami, J., Kidoguchi, Y., Khalid, A., Fujita, Y. and Omae, K., "Effects of Supercharging, Swirl Strength and Fuel Injection Pressure on Development and Combustion of Diesel Spray", Trans. of JSAE, Vol.40, No.3, pp.755-761, 2009.
12. Ishiguro, J.i., Kidoguchi, Y. and Ikegami, M., "Three-Dimensional Simulation of the Diesel Combustion Process", JSME International Journal, Series II, Vol. 31, No.1, pp.158-165, 1988.
13. Ikegami, M., Shioji, M. and Koike, M., Proc. 20th Symp. (Int.) Combustion, p.217, The Combustion Institute, 1984.