Effect of High Injection Pressure on Mixture Formation, Burning Process and Combustion Characteristics in Diesel Combustion

Amir Khalid, and B. Manshoor

Abstract**—**The mixture formation prior to the ignition process plays as a key element in the diesel combustion. Parametric studies of mixture formation and ignition process in various injection parameter has received considerable attention in potential for reducing emissions. Purpose of this study is to clarify the effects of injection pressure on mixture formation and ignition especially during ignition delay period, which have to be significantly influences throughout the combustion process and exhaust emissions. This study investigated the effects of injection pressure 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 injection pressure and air motion are important variable that strongly affect to the fuel evaporation, endothermic and prolysis process during ignition delay. An increased injection pressure makes spray tip penetration longer and promotes a greater amount of fuel-air mixing occurs during ignition delay. A greater quantity of fuel prepared during ignition delay period thus predominantly promotes more rapid heat release.

Keywords**—**Mixture Formation, Diesel Combustion, Ignition Process, Spray, Rapid Compression Machine.

I. Introduction

THE diesel engine has excellent thermal efficiency but a major concern with the diesel combustion is to tackle the two major emissions; nitrogen oxides (NOx) and particulate matter (PM). The improvement of diesel combustion regimes with controlling the combustion process has received considerable attention due to their potential for reducing NOx and PM to levels commensurate with the future emission standard[1-4]. The alternative combustion strategies with systematic control of mixture formation have provided new opportunities and considerable improvement in the combustion process and exhaust emissions reduction [5-6]. Therefore, the latest diesel combustion concepts based on the application of modern engine technologies are employed especially in controlling the combustion process.

The major problem in diesel combustion chamber design is to understand the important of phenomenon of the interaction between fuel spray and surrounding gas prior to ignition. There are many studies on the fuel-air premixing that responsible to the ignition of diesel spray which linked to the improvement of exhaust emission [7-10]. In particular, mixture formation during ignition delay period is important process because ignition is controlled by physical process caused by multi-hole injection, air motion, and chemical process of fuel decomposition and oxidation. Ishiyama et al [11] has reported that, in diesel combustion, fuel gasification, thermal cracking and oxidation process begin at early time during ignition delay period. The authors reported the concepts of the evaporation of spray droplets and atomization of a spray. In the report, it was suggested that mixture is first formed at spray boundary at middle stream of the spray[11]. It is complicated to understand ignition because above two processes are progress simultaneously during ignition delay period; moreover, there are a lot of design parameters related to mixture formation. High injection pressures decreases the injection duration thus maximizing the time available for fuel-air mixing prior to ignition. It was reported that the implementation of swirl velocity and injection pressure has a great effect on the mixture formation, ignition delay, flame pattern, turbulence, then affects to the flame development, combustion characteristics and emissions elements[12-13].

In this paper, experiment used a rapid compression machine together with the schlieren photography and direct photography methods with a high speed digital video camera. The new combustion concept based on the characteristics of diesel ignition and combustion is investigated focusing on fuel-air mixing especially during ignition delay period. The effects of mixture formation behavior, heat release rate, exhaust emission and combustion process have been examined under various design injection parameters.

II. Experimental Setup

Measurements were made in an optically-accessible rapid compression machine (RCM) with intended for diesel engines application, as shown in Fig. 1. The RCM is equipped with the Denso single-shot common-rail fuel injection system, capable of a maximum injection pressure up to 160MPa. A constant volume chamber with displacement of 1701.4cm^3, RCM was used to simulate the actual diesel combustion related phenomena. The RCM has a portable swirler at intake ports

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which allow the amount of swirl to be varied at 10-60m/s by changing the port inclination angle controlled swirl velocity. The RCM is equipped with an air compressor and vacuum pump, capable to increase ambient pressure and discharge ambient gas through exhaust valve, respectively.

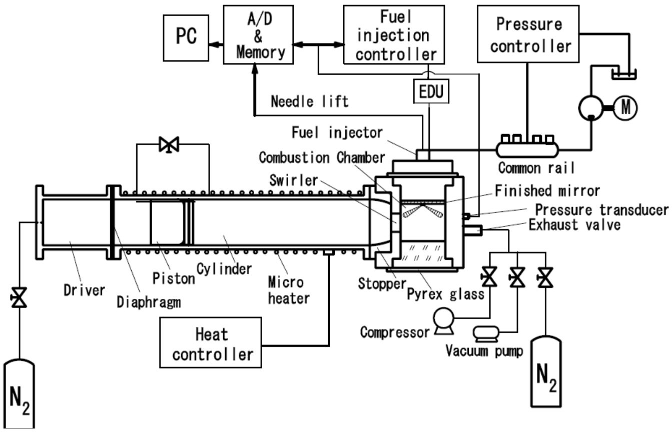


Fig. 1 Schematic diagram of experimental apparatus

Table I 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 836kg/m^3 and lower heating value of 42.7MJ/kg) into the spray chamber. The effect of P_{inj} on the combustion development was investigated at the base swirl velocity r_s=19m/s for P_{inj} of 100MPa, 130MPa, and 160MPa. The investigated initial charging pressure was kept to maintain the same at p_i=4MPa that corresponds to ambient density of ρ=16.6kg/m^3 and the equivalence ratio ϕ was ϕ=0.37. The injection period was controlled to kept fuel quantity at q_i=0.05 ml. In conducting this research, a parametric study of combustion process were investigated as comparing every condition with base condition as equivalence ratio was ϕ=0.37, ambient density of ρ=16.6kg/m^3 (ambient pressure of p_i=4MPa), ambient temperature of T_i=850K, swirl velocity r_s=19m/s and oxygen concentration of 21vol%. Moreover, nozzle parameter was held fixed at 0.129mm hole-diameter with 6 holes, respectively. 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). The heat release rate dQ/dt was calculated from the combustion pressure. NOx concentration was measured by a chemiluminescence analyzer (Yanako, ECL-77A).

The temperature of ambient gas in the chamber at the time of fuel injection can be widely varied using an electric heater. The ribbon heater was placed at the surface liner and heater rod installed in the chamber, and controlled by heat controller (Toho-BX-303). This study changed ambient pressure by changing initial charging pressure p_c before compression by the piston. The ambient gas oxygen concentration was varied by changing the composition of the oxygen inside chamber with inducing the nitrogen gas. The variant in oxygen concentration was used to simulate the combustion process with the different equivalent ratio associated with the application of exhaust gas recirculation (EGR) in the real diesel engine. This study kept injection quantity at q=0.05 ml. The injection durations were 2ms for P_{inj}=100MPa and 1.5ms for P_{inj}=160MPa.

TABLE I
EXPERIMENTAL CONDITIONS AS INJECTION PRESSURE WAS VARIED

Fuel	Injector type	***6holes , d = 0.129mm***		
	q_i	***0.05ml***		
	P_{inj} MPa	***100***	130	160
	ϕ	***0.37***		
Ambient gas	T_i K	***850***		
	r_s m/s	***19***		
	ρ kg/m^3	***16.6***		
	O_2 vol%	***21***		

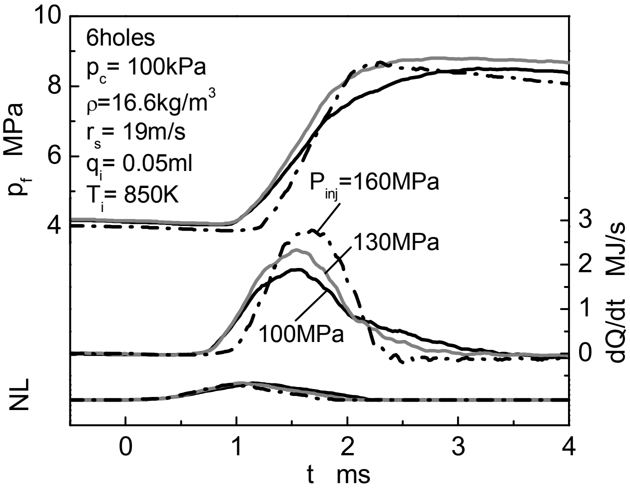
Italic bold : baseline

III. RESULT AND DISCUSSION

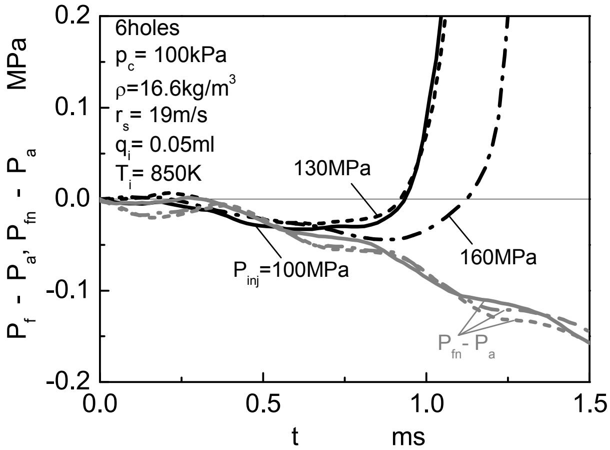
A. Effect of Injection Pressure on Combustion Process and Ignition

Injection systems demonstrate varying potential in terms of the flexibility of injection pressure parameter for improving mixture formation and combustion. In this section, the potential of different injection pressure are evaluated to improve the exhaust emissions. Aim of this study is to clarify the combustion development under different of injection pressure P_{inj}.

Fig. 2 show the histories of combustion pressure p_f and heat release rate dQ/dt during ignition delay period together with nozzle needle lift NL against time, t from start of injection were obtained at the Table I. Fig. 1(a) clearly demonstrates that the higher injection pressure promotes the more rapid heat release and shifted later the initial heat release rate in shorten combustion duration. The peak heat release rate rise with increases injection pressure, more markedly so for the P_{inj}=160MPa. Moreover, as seen in Fig. 2(b) increasing P_{inj} extended ignition delay and longer the physical process.



(a) Combustion process



(b) Histories of pressure during ignition delay period

Fig. 2 Effects of injection pressure on pressure history in combustion chamber during ignition delay

B. Effect of Injection Pressure on Mixture Formation and Combustion Characteristics

Next, the influences of injection pressure on combustion are investigated on the point of mixture formation. Fig. 3 compares images of schlieren photographs and direct photographs. Both images depict the influences of mixture formation behavior in combustion development as injection pressure is varied.

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 as mentioned before. The schlieren images shown at the upper row are at the time of ignition. The second rows are images of direct photograph taken during the peak of heat release. In all images, swirl flow is counterclockwise. As seen in schlieren images, lower injection pressure weakens the spray penetration. The spray path is bended by the swirl motion; fuel is mainly distributed at the center of the combustion chamber. In particular, at higher injection pressure P_{inj}=160MPa, fuel spreads out between each spray. Some fuel evaporates between the sprays and large amount combustible mixture is formed at the time of ignition. It seems that higher injection pressures make spray tip penetration longer and promotes a greater amount of fuel-air mixing occurs during ignition delay as compared at P_{inj}=100MPa. A greater quantity of fuel prepared during ignition delay period and could explain the increased peak heat release as seen in Fig.2 (a). In addition, large amount of combustible mixture is formed under high injection pressure could be associated with the initial flame develops widely at spray tip region and between sprays before appearance of high luminosity flame. Furthermore, high luminosity flame less intensity due to well mixing.

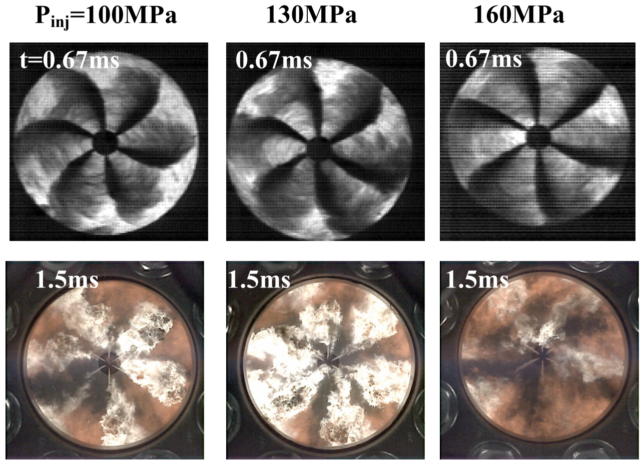


Fig. 3 Images of evaporation, mixture of diesel sprays as a function of injection pressure

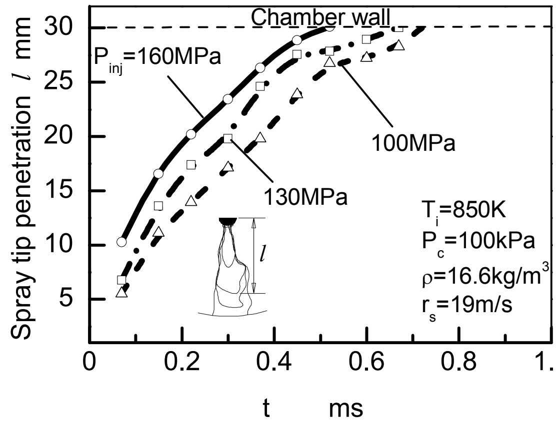


Fig. 4 Comparison of spray tip penetration as injection pressure is varied

Fig. 4 shows spray tip penetration as injection pressure is varied. It is clearly shown that the increasing P_{inj} promotes spray tip penetration near the wall region. In addition, this fuel-air mixing condition is influenced by both spray behavior and air movement in the combustion chamber as presented in Fig. 5. At higher injection pressure distributes larger amount of fuel-air premixing thus predominantly influences the good spray atomization and improvement of combustible mixture.

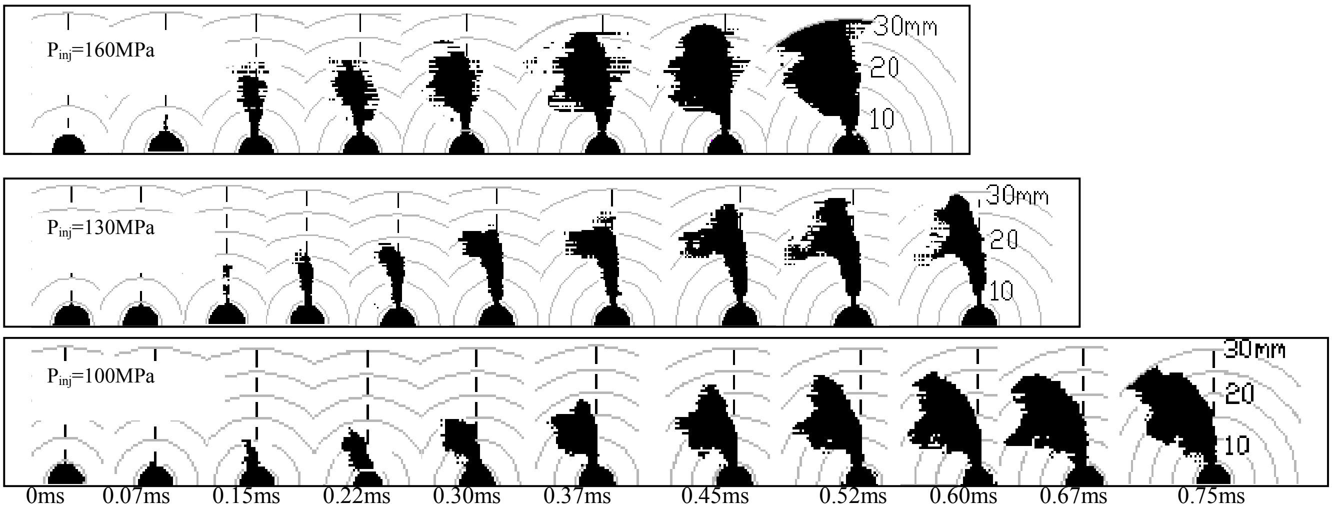


Fig. 5 Images of spray development during injection

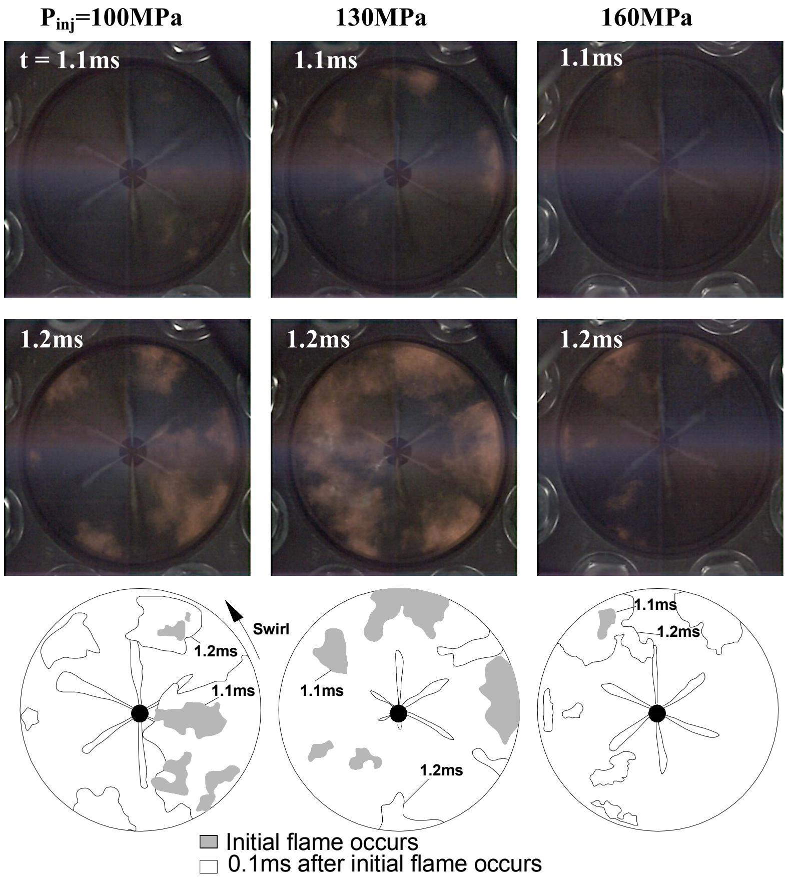


Fig. 6 Effects of injection pressure on mixture formation and initial flame development

Images of the spatial distribution of initial flame development obtained at the different injection pressure are presented in Fig. 6. The second and third rows are images of direct photograph taken just after ignition. The diagrams at lowest row show development of flame outline drawn by the above direct photographs. In all images, swirl flow is counterclockwise and compared with the same time start of injection. As seen from the first flame images, at P_{inj}=100MPa and P_{inj}=130MPa, initial flame is firstly observed near the chamber wall and between the sprays. Then, the luminosity flame develops to the entire chamber. On the other hand, at P_{inj}=160MPa, initial flame increase much more slowly, covered the whole chamber later than that seen at the P_{inj}=100MPa and P_{inj}=130MPa. This behavior could be associated with a difference in the ignition delay period and injection penetration. It seems that higher injection pressure the ignition delay is extended and enhanced fuel-air premixing will occur. These tendencies of initial flame distribution well correspond to the distribution of combustible mixture where well-mixed mixture is prepared before ignition.

Fig. 7 shows combustion characteristics with changed injection pressure. Ignition delay τ, which is the amount of heat absorption Q_{ab} during ignition delay period, combustion duration ΔQ_b, total heat release Q_t, and maximum heat release rate $(dQ/dt)_{max}$ are shown as combustion characteristics including NOx emission per injected amount of fuel. The variation in mixture formation could be associated with the different in combustion characteristics presented in Fig. 7 The decay variation in the mixture formation and luminosity of flame suggests that the less NOx is formed with reductions of $(dQ/dt)_{max}$ at the higher injection pressures, while having great impact on shorten combustion duration Δt_b.

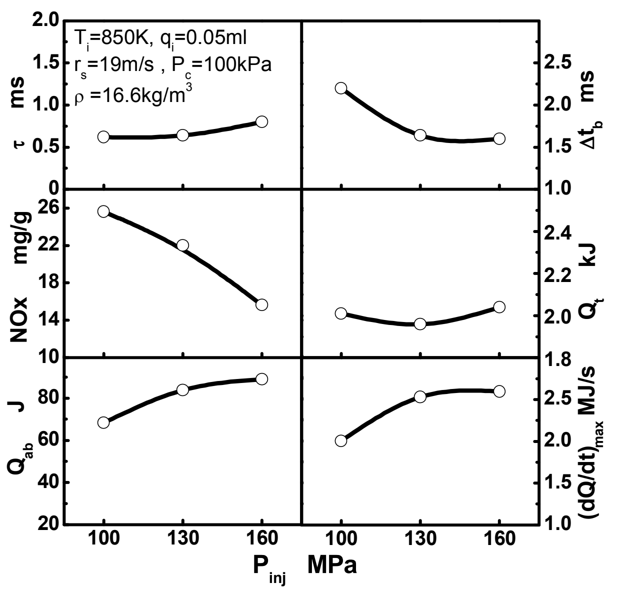


Fig. 7 Effects of injection pressure on combustion characteristics

IV. Conclusion

In this research, the effects of mixture formation on ignition and combustion of a multi-hole diesel spray were investigated in detail. Experiment was carried out using rapid compression machine. Flame development was analyzed in detail using optical flame-visualizing system with digital video cameras. The results are summarized as follows. Discussions were made on relation between mixture formation and injection pressure during heat recovery period before ignition. Results are summarized as follows;

1. Increased injection pressures makes spray tip penetration longer and promotes a greater amount of fuel-air mixing occurs during ignition delay as compared at P_{inj}=100MPa. A greater quantity of fuel prepared during ignition delay period could explain the increased peak heat release.
2. High-pressure injection promotes mixture formation during ignition delay period and large amount of combustible mixture is formed; therefore, after ignition, the initial flame develops widely at spray tip region and between sprays before appearance of high luminosity flame. Furthermore, high luminosity flame less intensity due to well mixing.

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