Review of the investigation of mixture formation and combustion process using rapid compression machine and direct visualization system

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Abstract. This paper reviews of some applications of optical visualization systems to compute the fuel-air mixing process during early stage of mixture formation in Diesel Combustion Engines. A number of studies have contributed to the understanding of fuel air mixing in DI diesel engine. This review has shown that the mixture formation process affects initial flame development. The review also found that injection pressure has a great effect on the mixture formation then the flame development and combustion characteristics. The method of the simulation of real phenomenon of diesel combustion with optical access rapid compression machine is also reviewed and experimental results are presented. The application of these methods to the investigation of diesel sprays highlights mechanisms which govern propagation and distribution of the formation of a combustible fuel-air mixture. A summary of the implementation of constant volume chamber and optical visualization system are shown in the accompanying tables and figures. The visualization of the formation process of diesel spray and its combustion in the diesel combustion chamber of diesel engine has been recognized as one of the best ways to understand the characteristics of the mixture formation.

1. Introduction

Nowadays diesel engines are the most important power source in the heavy transport sector and off-road machinery, and they are increasing their presence in the light and passenger transport too. In a diesel engine, combustion and emission characteristics are significantly influenced by spray atomization and fuel-air mixing processes in the combustion chamber [1-5]. The study on the mixture formation and combustion process was performed in Rapid Compression Machine (RCM) [2, 6-8]. RCM is an instrument designed to stimulate a single compression event of an engine cycle of internal combustion engine.

In diesel engine, ignition delay is a major factor determining the rapid pressure rise in the initial burning stage and the subsequent combustion stages. The ignition delay, which is defined as the time between the start of fuel injection and the start of the combustion, also influences the combustion process strongly. The ignition delay in a diesel engine is generally seen as consisting of two different which is the physical and the chemical ignition delay [9-11]. Physical ignition delay corresponds to the mixture formation, and the chemical delay to the time necessary to get an exponential increase in the chemical reaction rate. The physical processes involved such as atomization, penetration, entrainment
and vaporization and the chemical processes such as fuel decomposition and accumulation and oxidation [12-14].

Direct injection (DI) diesel engines are widely used worldwide because of their high efficiency [15]. However, the main problems associated with diesel engines are the high level of NO\textsubscript{x} and particulate emissions. According to Breda Kegl [16], NO\textsubscript{x} emissions are significantly affected by injection timing and injection pressure. High pressure fuel injection induces a higher level of dispersion of the fuel with better atomization and fuel-air mixing. The aim of the fuel injection process in a diesel engine is the preparation of a fuel-air mixing to achieve a clean and efficient combustion process [17, 18]. A comparative analysis was made by N.A.Heinan between the effects of increasing the fuel injection pressure and swirl ratio on the auto ignition reactions, cool flames and premixed combustion fractions[19]. Significant reductions in particulate matter (PM) and smoke emissions from DI diesel engines with high pressure injection have been reported [20, 21]. High pressure injection was also expected to result in improvements in exhaust odor.

The visualization of the formation process of diesel spray and its combustion in the combustion chamber of diesel engine has been recognized as one of the best ways to understand in-cylinder injection performance, spray characteristics and combustion for controlling emissions [22-24]. Flame development distribution in DI diesel engine which is an important factor of NO\textsubscript{x} and soot formation was measured by the image analysis photograph based on two color method [25].

2. Experimental Setup

The different specifications and operating conditions of the experimental are given in table 1 and table 2. A Rapid compression Machine (RCM) was used to simulate diesel combustion in a constant volume and this RCM is the same as that used in the previous report [2]. A schematic of the machine is shown in figure 1 together with outline of the fuel injection system. The main body or called cylinder liner consists of several cylinder connected in series each having an inner diameter of 50 mm and total length of 1550 mm. This machine can generate a high temperature and pressure by a method in which a piston is shot by compressed air and is rammed in to a stopper installed in front of the combustion chamber. The combustion chamber was disc type with a diameter of 60 mm and a width of 20 mm. One of the base surfaces of the chamber was composed of pyrex glass to observe spray and flame developments, and the other side surface had a injector holder.

| Base swirl velocity, \( r_s \) | 19 m/s |
|---------------------------------|--------|
| Ambient temperature, \( T_i \)  | 850 K  |
| Ambient pressure, \( p_i \)     | 4 Mpa (\( p_c = 100 \) kPa) |
|                                  | 6 Mpa (\( p_c = 150 \) kPa) |
|                                  | 8 Mpa (\( p_c = 200 \) kPa) |
| Ambient density, \( \rho \)     | 16.6 kg/m\(^3\) (\( p_c = 100 \) kPa) |
|                                  | 25.0 kg/m\(^3\) (\( p_c = 150 \) kPa) |
|                                  | 33.3 kg/m\(^3\) (\( p_c = 200 \) kPa) |
| Nozzle diameter, \( d_n \)      | 0.129 mm |
| Injection system type           | Common rail, Electronic control |
| Injection pressure              | 100 - 160 MPa |

| Ambient temperature, \( T_i \) | \( \leq 900 \) K |
|---------------------------------|-----------------|
| Ambient pressure, \( p_i \)    | 4.2 Mpa         |
|                                  | 8 Mpa           |
|                                  | 12 Mpa          |
| Nozzle diameter, \( d_n \)     | 0.25 mm         |
| Injection system type           | Electronic control |
| Injection pressure              | 30 - 150 MPa    |
The temperature and pressure at the end of the compression can be varied over a side range by changing the starting position of the piston. To control the temperature, a heater is installed around the cylinder liner. A swirler with a 14mm x 16mm-size connecting port installed at inlet of the chamber created swirl flow inside the chamber. The port inclination angle controlled swirl velocity. Swirl velocity was defined as the velocity at 2/3- location of radial direction from the chamber center. Ambient pressure $p_i$ was changes by changing initial charging pressure $p_c$ before compression by the piston. The increasing ambient pressure simulated high boost pressure condition. Injection commencement was measured from the needle lift detected by a hole sensor installed in the injector. Gas pressure inside the combustion 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.

![Figure 1. Schematic diagram of experimental set up][2]

3. Experimental Results

3.1 Combustion Characteristics in Diesel Combustion

Figure 2 shows the effect of ambient pressure on ignition delay $\tau$. According to the figure, increasing ambient gas pressure will result in shortens ignition delay because of the better mixing achievable at higher injection pressures. Beside that by increasing the fuel injection pressure, the fuel droplet size becomes finer, the entrainment of the air increases, and the injected spray becomes more uniform. As a result, the ignition delay and combustion periods become shorter, resulting combustion improvement. The ignition delay $\tau$, decreases rapidly with pressure and finally reaches a constant value above a certain pressure [8, 21].

Yamaguchi et al. [4] studied the relation between the injection pressure and heat release rate and found that the reduction in heat release results in a lower maximum pressure rise rate. Figure 3 shows the heat release obtained from the injection pressure analysis. The increased injection pressure caused an advance in the ignition timing and an increased peak rate of heat release [5]. The advance in ignition timing was due to the good atomization brought about by the high pressure injection and the short energizing duration for a given injection quantity. The high pressure fuel injection system provided a significant reduction in injection duration, a reduction in combustion delay, an increase in...
peak heat release rates and a reduction in combustion duration [26, 27]. At higher injection pressure, the better mixing formation is achievable. M. Ikegami [8] reported that net heat release due to chemical reactions might be obtained by comparing the pressure history at normal firing with the corresponding non-fired one. The mixture is heated to a considerably high temperature before the beginning of large scale heat release [28, 29]. Only a limited amount of mixture reaches the stage of net heat release and the other mixtures are still in the physical process which is vaporizing and cracking fuel. Most important for a good mixing and utilization of the complete combustion space is an intense interaction of the injected fuel jets with the combustion chamber walls and the in-cylinder flow as well as inner spray interactions [30].

3.2 Mixture Formation Effects

Effect of Mixture Formation on diesel combustion will be discussed in this section. Figure 4 shows the images of the effect of ambient density on mixture formation. At $p_c=100 \text{ kPa}$, the mixture covers wider area of combustion chamber than the other higher ambient pressure conditions. In this chamber, the condition of $p_c=100 \text{ kPa}$ seems to produce better distribution of the mixture than the cases of $p_c=150 \text{ kPa}$ and 200 kPa. The dark flame is a kind of signal that tells the position where well-mixed mixture is prepared before ignition. Combustion photograph with different injection pressures are compared in figure 5. When comparing photographs at the early stage of combustion, the first explosion and ignited flares are observed at the spray swirl downstream near the nozzle tip. But in the middle and late stage of combustion, the portions of unburned fresh air region become smaller in the case of higher injection pressure. Jiang. H. F et al. [31] observed that the initial ignition positions appear at the center of the combustion chamber. Flame extends along all injection directions of the spray and it is a typical diesel combustion process.

![Figure 2](image-url) **Figure 2.** Effect of ambient gas pressure on ignition delay [1].

![Figure 3](image-url) **Figure 3.** Heat release rate at different injection pressures [4].
3.3 The Influences of Combustion Process on Emission Production

The formation of NO\textsubscript{x} cannot be prevented in the combustion of fuel with air, as nitrogen is the main component of ambient air, unless gas temperatures are significantly reduced [32]. The increase of ignition delay period would influence the progress of combustion and the formation of emissions. Moreover, the reduction in oxygen flow rate associated with the application of EGR reduces the combustion temperature and pressure which, in turn, leads to lower NO\textsubscript{x} formation as well as lower soot oxidation [33, 34]. The measured Particulate Matter PM and NO\textsubscript{x} specific emissions are separately shown in figure 6, as a function of Start of Ignition (SOI). Three different injection pressure levels were tested to see the effect of SOI on NO\textsubscript{x} emission and PM. By comparing the emission data for a fixed SOI value, an average decrease was recorded for NO\textsubscript{x} emissions as the injection pressure was increase. On the other hand, an increase in PM emissions was detected when reducing the injection pressure [35].
Figure 7 illustrates exhaust emissions characteristics, such as soot, nitrogen dioxide NO\textsubscript{x}, hydrocarbon HC, and carbon monoxide CO. Soot emissions showed a somewhat increasing trend with advanced injection timings. The increased injection pressure resulted in low soot emissions due to the good droplet atomization and long premixed duration [36, 37]. NO\textsubscript{x} emissions increased with the advancing injection timing and it is indicated an active combustion reaction. CO and HC emissions were generally similar regardless of injection timing and injection pressure. CO and HC emissions increased were due to the incomplete combustion. Yoshio et al. [38] was compared between the 5-hole injection nozzle and 3-hole injection nozzle regarding HC, CO and NO\textsubscript{x} emissions. With the 5-hole injection nozzle HC and CO emissions are sufficiently low when a small quantity of fuel is injected, but increase as the injection quantity increases. On the contrary, with the 3-hole injection nozzle HC emissions are high overall but decrease as the injection quantity increases.

![Figure 7](image_url)

Figure 7. Effect of injection pressure and timing on the exhaust emissions characteristics [5].

4. Conclusion
The results obtained in this study are summarized as follows:

1. The rapid compression machine was used to study the fundamental of diesel combustion. Although the mechanism is looks simple, the performance and the reliability is verified to be sufficient.
2. The increased injection pressure caused an advance in ignition timing and this is due to the good atomization brought about by the high pressure injection and the short energizing duration for a given injection quantity. Also by increasing the fuel injection pressure, the fuel droplet size become finer, the entrainment of the air increases and the injected spray becomes more uniform and finally, the ignition delay and combustion periods become shorter.
3. Comparison of multi-hole injection nozzle, it’s found that HC and CO emissions are sufficiently low when a small quantity of fuel is injected, but increase due to the poor air introduction to the spray at a large quantity of fuel injection.
4. The physical and the chemical process are strongly linked with each other and their part on the ignition delay can’t be seen as independent from each other.
5. The higher injection pressure, higher oxygen content, results in lower smoke and CO emissions and in a slightly higher HC emission. The conditions in the cylinder during the first part of injection and combustion process influence to great extent the NO\textsubscript{x} formation.
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