Visualization of Diesel and GTL Spray Combustion and Soot Formation in a Rapid Charging Combustion Vessel with Shadowgraph Method

Ki-Seong Kim† · Ulugbek Azimov* · Yong-Ho Lee**
(Received September 2, 2008 ; Revised November 13, 2008 ; Accepted November 17, 2008)

Abstract: In this study, visual investigation of sprays and flames has been performed and soot formation in Diesel and GTL fuels has been compared in a specially designed Rapid Charging Combustion Vessel (RCCV) under various ambient gas O2 concentrations and two injection pressures. It has been concluded that soot in the mixing-controlled combustion of Diesel and GTL fuels has similar tendency to be formed in the leading portion of the jet boundaries. Auto-ignition delay for GTL fuel is shorter than that for diesel fuel. The temporal and special variation of soot concentration in the diesel flame jets at various O2 concentrations was correlated with the heat release rate. Soot concentration appears in the regions when diffusion combustion starts, and its concentration reaches maximum at the peak of heat release curve and then decreases due to oxidation. Visualization by shadowgraph method showed that soot decreases with lower O2 concentration, and higher injection pressure.

Key words: Diesel spray and combustion, GTL fuel, Soot formation, Heat release rate, Shadowgraph method

1. Introduction

Soot formed in reacting fuel jets is a major component of the particular matter emitted by DI diesel engines. Motivated by the challenge of meeting stringent emission regulations the researches investigate various alternative diesel combustion methods, as well as fuels, which can produce much lower engine emissions, while retaining high efficiency. For this reason, new technologies, like an electronically controlled high-pressure injection system and a cooled EGR system, have been developed for application in production models. Furthermore, various after-treatment systems have been studied to reduce emissions effectively. It is important to note that the best performance and the lowest levels of pollutant formation in diesel engines will depend highly on the nature of the fuel, and therefore diversified fuel sources have to be the

† Corresponding Author(Dept. of Mechanical-Automotive Engineering, Chonnam National University (Yosu Campus), E-mail: sngkim@chonnam.ac.kr, Tel: 061)659-3286)
* Dept. of Mechanical-Automotive Engineering, Graduate School, Chonnam National University (Yosu Campus)
** Dept. of Mechanical-Automotive Engineering, Chonnam National University (Yosu Campus)
focus of future research.

As one of these alternatives Gas-to-Liquid (GTL) has potential as clean alternative fuel to be used in diesel engines due to advantages in emission reduction, particularly, soot reduction. GTL has higher cetane number and lower auto-ignition temperature. It also has a different distillation curve compared with that of diesel fuel[1]. Most of the work on GTL fuel which has been done so far in IC engine field is related to the fuel property characterization and emission testing[2]-[4]. According to these studies, if GTL fuel is utilized the soot emission level generally tends to decrease by about 30%.

Since the physical properties of GTL fuel differ from those of diesel fuel to some extent, it is required to study how these differences in properties of GTL and diesel fuels affect spray and combustion as well as soot formation in diesel engines.

The current work presents experimental results of qualitative analysis on effects of ambient gas $O_2$ concentration and fuel injection pressure on soot formation in GTL fuel jets. The visualization of soot formation in GTL and diesel fuel jets was implemented using high-speed shadowgraphy method.

2. Fuel Properties

There are several types of GTL fuel produced with different properties. In this study Shell’s GTL fuel was utilized. Some properties of GTL and diesel fuels are represented in Table 1. The liquid density and boiling point of GTL fuel are a little different from those of diesel fuel[2]. Regarding auto-ignition characteristics, GTL has higher cetane number and lower auto-ignition temperature, compared to those of diesel fuel. This is supposed to lead to shorter ignition delay and more advanced flame front propagation. In addition GTL fuel spray might have slightly larger mean drop size due to a little higher kinematic viscosity than that of diesel fuel.

<table>
<thead>
<tr>
<th>Fuel properties</th>
<th>Diesel</th>
<th>GTL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density at 15 °C (kg/m³)</td>
<td>839.2</td>
<td>779.0</td>
</tr>
<tr>
<td>Cetane number</td>
<td>51.7</td>
<td>75</td>
</tr>
<tr>
<td>Sulfur (ppm)</td>
<td>403</td>
<td>3</td>
</tr>
<tr>
<td>Lower heating value (MJ/kg)</td>
<td>42.9</td>
<td>43.6</td>
</tr>
<tr>
<td>Total aromatics (wt %)</td>
<td>27.7</td>
<td>1.4</td>
</tr>
<tr>
<td>Polyaromatics (wt %)</td>
<td>6.2</td>
<td>0.4</td>
</tr>
<tr>
<td>50% distillation (°C)</td>
<td>265.3</td>
<td>275.7</td>
</tr>
<tr>
<td>90% distillation (°C)</td>
<td>330.8</td>
<td>310.1</td>
</tr>
<tr>
<td>Viscosity at 40°C (mm²)</td>
<td>2.665</td>
<td>2.74</td>
</tr>
<tr>
<td>C (wt %)</td>
<td>86.32</td>
<td>84.9</td>
</tr>
<tr>
<td>H (wt %)</td>
<td>13.32</td>
<td>15.1</td>
</tr>
</tbody>
</table>

The most importantly, GTL fuel has extremely low content of polycyclic aromatic hydrocarbons (PAH) and sulfur. The sulfur content of the GTL diesel is less than 5 ppm[5]. Therefore, when GTL fuel is used in a diesel engine, it may contribute to soot reduction, because it is generally agreed that PAHs are important precursors of soot particles.

3. Experimental Procedure

3.1 Experimental conditions

In order to investigate and compare the effect of ambient gas $O_2$ concentration and fuel injection pressure on combustion characteristics and
Visualization of Diesel and GTL Spray Combustion and Soot Formation in a Rapid Charging Combustion Vessel with Shadowgraph Method

soot formation, shadowgraph visualization experiments have been performed in Rapid Charging Combustion Vessel (RCCV).

The fuel was injected with a common-rail diesel fuel injector with a single 163 μm diameter orifice. Fuels used in the experiments were diesel fuel and Shell GTL fuel as in Table 1. The ambient gas pressure was 4MPa, ambient gas temperatures were 920K, ambient gas density 15.2kg/m³ and fuel injection pressures 90 and 135MPa. Ambient gas contained 21%, 16% and 12% of oxygen. Experimental conditions and ambient gas contents are represented in Table 2 and 3.

<table>
<thead>
<tr>
<th>Table 2 Experimental conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
</tr>
<tr>
<td>Ambient Gas Temperature [K]</td>
</tr>
<tr>
<td>Ambient Gas Density [kg/m³]</td>
</tr>
<tr>
<td>Rail Pressure [MPa]</td>
</tr>
<tr>
<td>Injection Duration</td>
</tr>
<tr>
<td>Nozzle type</td>
</tr>
<tr>
<td>Nozzle Hole</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3 Ambient gas content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular percentage</td>
</tr>
<tr>
<td>O_2</td>
</tr>
<tr>
<td>21.0</td>
</tr>
<tr>
<td>16.0</td>
</tr>
<tr>
<td>12.0</td>
</tr>
</tbody>
</table>

3.2 Rapid charging combustion vessel (RCCV)

For the purpose of investigating spray combustion phenomena in the diesel combustion chamber environment RCCV was designed and constructed. In this RCCV, highly pressurized hot air is rapidly charged to simulate the environment of the real diesel engine combustion chamber.

Fig. 1 shows the layout of RCCV system. It consists of motor (1), couple (2), high pressure fuel pump (3), fuel filter (4), fuel supply pump (5), fuel tank (6), battery (7), common rail system (8), control unit (9), DAQ and control systems (10), injector (11), combustion chamber (12), pressure sensor (13), thermocouple (14), pressure sensor’s cooling line (15), discharge valve (16), heaters controller (17), combustion chamber’s heaters (18), fast response valve (FRV) (19), FRV’s actuator (20), prechamber (21), prechamber heater (22), inlet valve (23), relief valve (24), pressure gauge (25), valve (26), pressurized air vessel (27) and pressure regulator (28).

High pressure air, controlled by the pressure regulator (28) Figure 1, is charged into the pre-chamber and heated up to about 1300°C (± 20°C) by a ceramic heater, and then hot and pressurized gas flows into the combustion chamber when
discharge valve and FRV are opened and closed sequentially. For measuring pressure and temperature in the combustion chamber, a piezo-resistive type water-cooled pressure transducer (Kistler 4075A200) and a K-type thermocouple are installed in the chamber. The timing control of the RCCV, the injector and high speed camera is performed by a programmable counter board and a delay generator (DG535; USA).

When RCCV system is operated, pressure and temperature in the combustion chamber change as shown on Fig. 2 and Fig. 3, respectively.

![Fig. 2 Pressure distribution inside RCCV's combustion chamber](image)

The quiescent ambient gas environment was checked by simulating the air flow from the pre-chamber to the main chamber using commercial CFD code. The results showed that by the time the FRV was closed, the velocity magnitude in the main chamber was negligible and the ambient gas environment considered quiescent. As it is shown in Figure 4, after the FRV is opened the air with supersonic speed fills the chamber in about 4ms. Afterwards, the ambient gas reaches the dense enough state so that there are no any vortices or flow perturbations persist inside the chamber.

![Fig. 4 Air velocity vector distribution inside RCCV's combustion chamber](image)

3.3 Optical system

The combustion chamber has two round quartz windows (Ø 70mm) and two square
windows (20×60mm) to ensure optical access for imaging combustion and illuminating a light source. Fig. 5 shows the optical setup for acquiring shadowgraph images.

![Fig. 5 Schematics of optical setup](image)

A chamber was illuminated by a flash lamp. Light passed through the pinhole that was used to make light distribution in the focal plane of the objective as a just single light spot. The diameter of pinhole which was placed in the focal point was small enough so that only the light of the inner circle, the diffractive image of zeroth order, passed through the hole, and cross section of the divergent light beam showed a totally homogeneous brightness. Sequential spray and flame images were acquired by a high speed color digital camera (APX) with the frame rate of 24000 fps.

4. Results and discussion

4.1 Auto-ignition delay

The difference in auto-ignition delay for diesel and GTL fuels is depicted on Fig. 6. The auto-ignition delay for GTL fuel is about 125μs shorter than that of diesel fuel. The increase in GTL auto-ignition delay time is due to the higher cetane number of GTL fuel. The previous work done by other researchers showed that cetane number increased linearly with the increase of a GTL fraction and auto-ignition delay reduced with about equal time increment [6].

4.2 Relation between soot formation and heat release

Comparing shadowgraph images shown in Fig. 7, 8 and 9, the relation between soot formation and heat release may be revealed. It is obvious that during the initial combustion period, no soot was detected in the flame for all conditions with different $\phi$ concentrations in ambient gas. Soot is observed for the first time immediately after the

![Fig. 6 Auto-ignition of diesel and GTL fuels](image)
start of diffusion combustion period, and the sooting zone rapidly expands its volume toward the flame tip. When the rate of heat release reaches its peak, the magnitude of sooting zone reaches its maximum. As the heat release rate decreases the soot is subsequently oxidized as flame is extinguished. It can be noticed that with 16% oxygen content the sooting zone is increased, but for 12% oxygen content sooting zone is gradually decreased in magnitude. This soot reduction is due to the longer ignition delay which provides the better air–fuel mixing. The observed trend is in agreement with previous studies which experimentally proved that when $O_2$ concentration reduced from 21% to 15% soot concentration tended to increase, and soot decreased from 15% to 12% of ambient gas oxygen concentration$^7$.

---

**Fig. 7** Heat release for diesel fuel at $O_2$-21%, $T_{amb}$ -920K and injection pressure 90MPa

**Fig. 8** Heat release for diesel fuel at $O_2$-16%, $T_{amb}$ -920K and injection pressure 90MPa

**Fig. 9** Heat release for diesel fuel at $O_2$-12%, $T_{amb}$ -920K and injection pressure 90MPa

4.3 Soot formation

As was mentioned earlier, soot formation in Diesel-GTL blends was studied based on the shadowgraph method using high speed photography. The shadowgraph method implies that the individual light rays, when passing through the combustion chamber, are refracted and bend from their original paths. If the gradient of the refractive
index is constant along the length of the chamber, then the deflection angles of all rays are the same, and the rays that passed through the chamber illuminate it uniformly. However, if a density variation is present in the chamber, then the sensitive shadow method visualizes fields in which the second derivative of the density is not uniform, and hence represents the density variation on the camera’s objective.

Soot formation and oxidation processes in the combustion chamber of DI diesel engine were investigated by various researchers. The time histories of soot concentration measured by these researchers revealed that soot formation starts simultaneously with the onset of diffusion combustion, and that its concentration increases rapidly with time during the injection period. The soot concentration reaches a maximum at about the end of injection. Thereafter, the magnitude of sooting zone remains constant for a while, soot is subsequently oxidized at a rapid rate and its concentration gradually reduced due to high temperature.

In Fig. 10 shadowgraph images of soot formation regions in the diesel fuel jet show distinct density gradients formed in the leading portion of the jet boundaries. These results are in close agreement with the conceptual model of soot formation in diesel fuel jets. It was found that soot concentration is gradually reduced in GTL fuel jets. The results show that with the higher fuel injection pressure soot formation intensity is reduced in diesel fuel jets. In case of GTL fuel, the concentration of soot was barely visualized for both injection pressures.

![Sequential shadowgraph images of soot formation comparison at 21% O2 concentration](image)
This trend in reducing soot with increased injection pressure was also observed for the conditions with reduced ambient gas O₂ concentrations, 16% and 12%. With the reduction of oxygen mass fraction in the ambient gas, it was more difficult to visualize soot for both, diesel and GTL. It is because in the diluted ambient gas the chemical reactions slow down causing the increased ignition delay, and it takes more time for the fuel to evaporate and reach the combustible limit. It is confirmed that injection pressure has a low scale effect on the soot formation in diesel combustion. However, reducing O₂ concentration of ambient gas can...
greatly influence the soot formation. In Figure 11 it can be seen that at 16% of ambient gas $O_2$ concentration and 90MPa injection pressure for diesel fuel soot has a tendency to increase, however with the increase of injection pressure to 135MPa soot is noticeably reduced. In GTL fuel jets very low density gradients were observed indicating very low soot formation. In Figure 12, at 12% of ambient gas $O_2$ concentration, some dark zones can be visualized in the diesel and GTL fuel jets along the entire spray and combustion process. However, these dark zones are believed to be not yet evaporated fuel due to the reduced oxygen in the ambient gas, which caused the increase of ignition delay period as well as the decrease of combustion temperature. Nevertheless soot concentra- tion at the tip of the jets for both fuels was significantly low, compared with the conditions at 21% and 16% of oxygen concentration.

It has been a concern that in diesel fuel combustion the soot emission level may increase due to the decrease in the ignition delay period. However, it is different for GTL fuel. Although the GTL cetane number is higher than that of diesel fuel, meaning that ignition delay period is shorter, the soot emission level of GTL tends to decrease. This happens because GTL has very low content of sulfur and aromatics. The fuel sulfur is believed to be a source for Polycyclic Aromatic Hydrocarbons (PAH), and PAH are the soot precursors. Thus, the effect of the negligibly small aromatics and sulfur content of GTL outweighs the effect of the increased diffusion combustion fraction due to the shorter ignition delay.

5. Conclusion

The results of this research provide a comprehensive picture of the parameters affecting the soot formation in Diesel and GTL fuel jets. The specific major findings are summarized as follows:

- Auto-ignition delay time is shorter for GTL fuel compared with diesel. This is because cetane number of GTL is considerably higher than that of diesel fuel.
- Soot formation in the diesel fuel jet is initiated when the diffusion combustion starts. When the heat release rate reaches its peak the soot concentration reaches the maximum. The maximum peak of heat release decreases with the decrease of $O_2$ concentration in the ambient gas.
- Injection pressure has a minor impact on soot formation; however, lowering ambient gas $O_2$ concentration below 16% shows potential for the major soot reduction.
- It was observed that the soot formation in GTL fuel jets is considerably lower than that in diesel fuel jets. It was confirmed that very low content of sulfur in GTL fuel highly contributes to significant soot reduction. Although the ignition delay period for GTL fuel is much shorter than that of diesel, soot tends to decrease for all the conditions with different oxygen concentrations in the ambient gas. It is believed that the low sulphur content of GTL fuel has a greater influence on soot reduction than a longer ignition delay of diesel fuel.

References


Author Profile

Ki-Seong Kim
Professor, College of Engineering Science, Chonnam National Univ. (Yosu Campus). Ph.D. and M.S. in Dept. of Mechanical Eng., KAIST. B.E. in School of Mechanical Eng., Pusan National University

Yong-Ho Lee

Ulugbek Azimov
He received his MS degree in 2002 from Texas A&M University, USA. 2005–present PhD candidate, Dept. of Mechanical Design Eng., Chonnam National University. His research interests include low-temperature diesel combustion, non-intrusive analysis of diesel soot formation, spray combustion of alternative fuels, modeling of diesel spray combustion.