International Journal of Automotive Technology, Vol. 8, No. 3, pp. 275–281 (2007)

1229–9138/2007/034–03

EXPERIMENTAL INVESTIGATION AND COMPARISON OF SPRAY AND COMBUSTION CHARACTERISTICS OF GTL AND DIESEL FUELS

K. S. KIM[1)*], V. BESCHIERU[1)], D. S. JEONG[2)] and Y. LEE[2)]

[1)]Department of Mechanical Design Engineering, Chonnam National University, Jeonnam 550-749, Korea
[2)]Korea Institute of Machinery and Materials, Daejeon 305-343, Korea

(Received 24 February 2006; Revised 28 February 2007)

ABSTRACT–GTL (Gas To Liquid) has the potential to be used in diesel engines as a clean alternative fuel due to advantages in emission reduction, particularly soot reduction. Since the physical properties of GTL fuel differ from those of diesel fuel to some extent, studying how this difference in characteristics of GTL and diesel fuels affects spray and combustion in diesel engines is important. In this study, visual investigation of sprays and flames from GTL and diesel fuels in a vessel simulating diesel combustion was implemented. The effects of various parameters and conditions, such as injection pressure, chamber temperature and pilot injection on liquid-phase fuel length and auto-ignition delay were investigated. It was determined that GTL has a somewhat shorter liquid-phase fuel length, which explains why there is less contact between the fuel liquid-phase and flame for GTL fuel compared to diesel fuel.

KEY WORDS : GTL, Diesel Engine, Diesel Spray, Liquid-Phase Length, Combustion, Soot

1. INTRODUCTION

Global climate changes and environmental problems are mainly caused by the rapid increase of carbon dioxide and harmful exhaust emissions from the combustion of fossil fuels. Coping with these problems requires the utilization of promising alternative clean and re-circulation of fuels, such as hydrogen, alcohol, dimethyl ether, bio-diesel, and gas to liquid (GTL). Particularly, GTL fuel seems to offer new opportunity as an alternative fuel for diesel engines due to the considerably low amount of exhaust emitted during the combustion process (Oguma *et al.*, 2004, 2002; Alleman and Eudy, 2004; Fukumoto *et al.*, 2003).

GTL is a synthetic liquefied fuel produced from natural gas or coal using the Fisher-Tropsch method. GTL fuel has a high cetane number, as well as other properties that are comparable with those of diesel fuel, and it has the potential to be utilized as an alternative fuel for compression ignition engines. Moreover, it contains little sulfur and aromatics, so that cleaner exhaust and lower emissions can be expected. If the cost of GTL fuel becomes competitive with that of fossil fuels, GTL might be used as the fuel for diesel engines in the nearest future.

However, before adapting GTL fuel for diesel engines, it is important to consider the differences in the physical properties of GTL and diesel fuels from the view point of spray, combustion and emission. For example, GTL has a higher cetane number and a lower auto-ignition temperature. It also has a distillation curve slightly different from that of diesel fuel (Alleman and Eudy, 2004). Therefore, fundamental study is necessary to understand how these different physical properties can affect spray and combustion in diesel engines utilizing GTL fuel.

Most of the work on GTL fuel that has been done in the internal combustion engine field is related to the fuel property characterization and emission testing (Oguma *et al.*, 2004, 2002; Alleman and Eudy, 2004; Fukumoto *et al.*, 2003). According to these studies, the soot emission level generally tends to decrease by about 30% compared to diesel fuel.

In the present work, the visual investigation of sprays and flames for GTL and diesel fuels was implemented for the purpose of comprehending the effects of GTL fuel's characteristics on spray and combustion. In addition, the effects of various parameters and conditions such as injection pressure, chamber temperature, and pilot injection on liquid-phase fuel length and auto-ignition delay were investigated.

2. GTL 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 (Oguma *et al.*, 2004). The liquid density and

---

**Corresponding author.* e-mail: sngkim@chonnam.ac.kr

Table 1. Characteristics of GTL and diesel fuels.

Properties	GTL	Diesel fuel
Chemical structure	$C_nH_{2.13n}$	$C_nH_{1.87n}$
Liquid density (g/cm^3)	0.78@288[K]	0.83@288[K]
Boiling point (K)	448-633	453-643
Flash point (K)	369	344
Auto-ignition temp (K)	> 493	523
Cetane index	78	57.8
Kinematic viscosity (mm^2/s)	4.352 @313[K]	3.76 @303[K]
Lower heating value (J/kg)	46533	43200
Stoichiometric A/F	14.96	14.37
Sulphur (% mass)	< 0.0050	0.034
Aromatics (% mass)	< 0.1	–
Carbon (% mass)	84.9	86
Hydrogen (% mass)	15.1	14

Table 2. Experimental conditions.

Fuel	Diesel, GTL
Chamber pressure [MPa]	4
Rail pressure [MPa]	90, 110, 135, 150
Chamber temperature [K]	300, 820, 870, 920
Injection duration	670 μs
Nozzle type	Mini-sac
Nozzle hole	d_n=0.163mm, l_n/d_n=5.52

boiling point of GTL fuel are a little different from those of diesel fuel. It was assumed that these characteristics could affect the liquid-phase fuel length of spray. Regarding auto-ignition characteristics, GTL has a higher cetane number and a lower auto-ignition temperature, compared to diesel fuel. These characteristics are supposed to lead to a shorter ignition delay and more advanced flame initiation. As for the mean drop sizes of sprays, the GTL fuel sprays might have slightly larger mean drop sizes due to a somewhat higher kinematic viscosity than that of diesel fuel.

Besides, GTL fuel has an extremely low content of polycyclic aromatic hydrocarbons (PAH) and sulfur. 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. Soot particles are formed in the region between the fuel-rich side of the reaction zone of the flame and the fuel spray. The soot formation process can be regarded as a transition from a gas phase to a solid phase with an extremely complex conversion of hydrocarbon fuel molecules, containing a few carbon atoms, to carbonaceous particles containing a few million carbon atoms.

3. EXPERIMENTAL PROCEDURE

3.1. Experimental Conditions

In order to investigate and compare spray and combustion characteristics of GTL and diesel fuels, two kinds of experiments were performed. The first one was spray visualization to measure the spray penetration at a pressure of 4 MPa and a temperature of 300 K. The second experiment was visualization of the fuel liquid-phase and flame, during the injection and combustion period, at a pressure of 4 MPa and temperatures of 820 K, 870 K and 920 K. Experimental conditions and the injector nozzle specifications are represented in Table 2.

3.2. Rapid Charging Combustion Vessel

For the purpose of investigating spray combustion phenomena in the diesel combustion chamber environment, a spray combustion simulation device named Rapid Charging Combustion Vessel (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.

Figure 1 shows the layout of the RCCV system. It consists of a 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 to about 1300°C (± 20°C) by a ceramic heater, and then

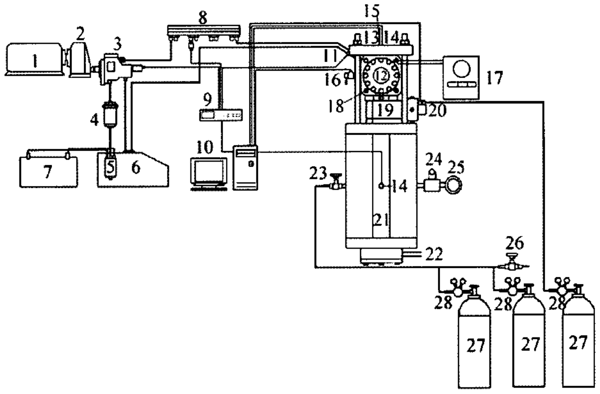


Figure 1. Schematic of the rapid charging combustion vessel (RCCV).

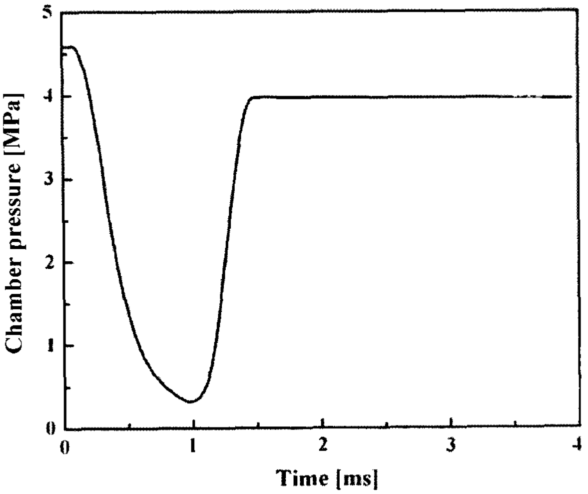


Figure 2. Pressure trace of the RCCV.

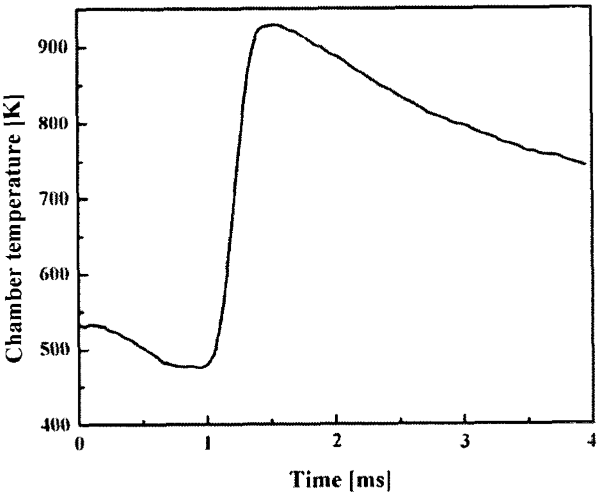


Figure 3. Temperature trace of the RCCV.

hot and pressurized gas flows into the combustion chamber when the discharge valve and FRV are opened and closed sequentially. For measuring pressure and temperature in the combustion chamber, a piezo-resistive type pressure transducer (Kistler) and a K-type thermocouple are installed in the chamber. The timing control of the RCCV, the injector and the high speed camera is performed by a programmable counter board and a delay generator (DG535; USA). When the RCCV system is operated, pressure and temperature in the combustion chamber change as shown in Figure 2 and Figure 3, respectively.

3.3. Optical System

The combustion chamber has two round quartz windows (φ70 mm) and two square windows (20 x 60 mm) to ensure optical access for imaging combustion and illuminating a laser. Figure 4 shows the optical setup for acquiring flame images and measuring the intensity of the natural incandescence of the flames. A spray axis was illuminated by a laser sheet beam from an Ar-ion laser that passes through the square windows, so that the liquid-phase fuel can be visualized with the flames simultaneously. An avalanche photo-diode (AD500) was used to measure the light intensity from the flames, which is an indication of the amount of soot. The spectral response curve of the photo-diode has a peak at 700 nm and its spectral band is very wide. A high speed color digital camera (APX) was used for taking spray and flame images. Most of the spray and flame images were acquired at the frame rate of 24,000 frames/s and the spatial resolution of 512 x 128 pixels.

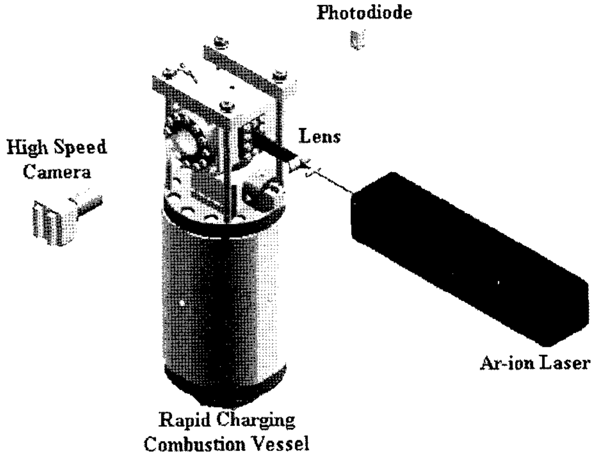


Figure 4. Schematics of the optical setup.

4. RESULTS AND DISCUSSION

4.1. Spray Characteristics

For comparing the spray penetration of both fuels, sequential images were acquired using the high-speed camera at cold and pressurized condition. As an example,

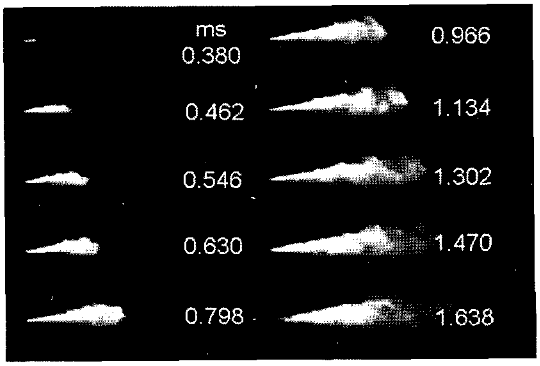


Figure 5. Temporal sequence of spray images for GTL fuel.

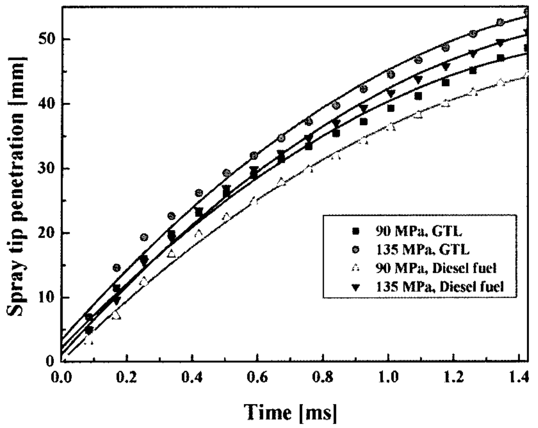


Figure 6. Spray penetration of GTL and diesel fuels at various rail pressures. Chamber pressure and temperature are 4 MPa and 300 K, respectively.

Figure 5 shows the temporal sequence of spray images for GTL fuel at a rail pressure of 135 MPa, chamber pressure of 4 MPa and chamber temperature of 300 K.

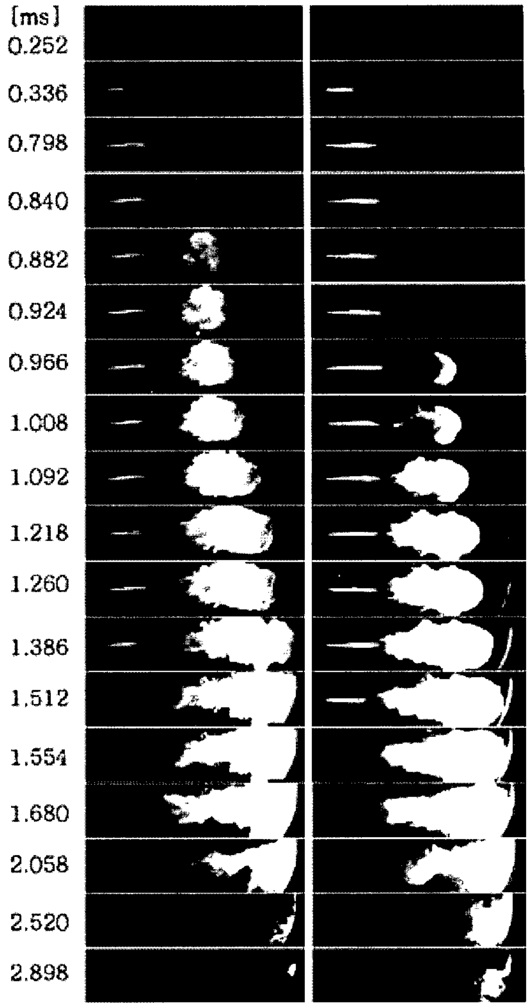
Figure 6 shows the results of the measured spray penetration. In correspondence to previous results (Park and Lee, 2003), spray penetration increases as rail pressure increases for both fuels. GTL fuel tends to have a somewhat longer penetration compared with diesel fuel at the same rail pressure. To explain this tendency, the mean drop size of the spray must be known. We estimated the mean drop size of GTL fuel relative to that of diesel fuel by using a well known experimental relation (Hiroyasu and Arai, 1990). From this estimation, it was determined that GTL fuel has a larger mean drop size (about 12%) compared to that of diesel fuel. Therefore, it might be considered that the larger mean drop size of GTL fuel causes a longer penetration due to greater momentum.

4.2. Flame Characteristics

4.2.1. Light intensity

Visualization experiments of liquid lengths and flames were performed at hot air conditions. Figures 7(a) and 7(b) show typical sequential images of GTL and diesel fuels for rail pressure at 135 MPa and air temperature at 920 K. These images were acquired in the same iris opening of the receiving lens and at the same exposure time as the high-speed camera, so that the light integrating conditions of the two experiments are the same.

In order to determine the difference in soot concentration of GTL and diesel fuels, the values of the flame intensity were measured. These measurements were done by directing the laser beam through the combustion chamber of the RCCV, as shown on Figure 4, and obtaining the attenuation of light during the combustion, caused by both the scattering of the soot particles and absorption by these particles. Figure 8 shows the results from the natural flame intensity using the photodiode. From the figure it is clear that light intensities from the flames of diesel fuel are much stronger than those of GTL fuel. This means that the soot concentration in GTL fuel during combustion is much lower than that in diesel fuel. This fact coincides with the results of previous tests performed on real engines (Alleman *et al.*, 2004; Higgins *et al.*, 2000), where the soot emission reduction was about 30%. This soot reduction can be attributed to the fact that it has very low aromatic constituents.



(a) GTL (b) Diesel fuel

Figure 7. Temporal sequence of liquid-phase fuel and natural flame images for GTL and diesel fuels. Chamber pressure, temperature and rail pressure are 4 MPa, 920 K, and 135 MPa, respectively.

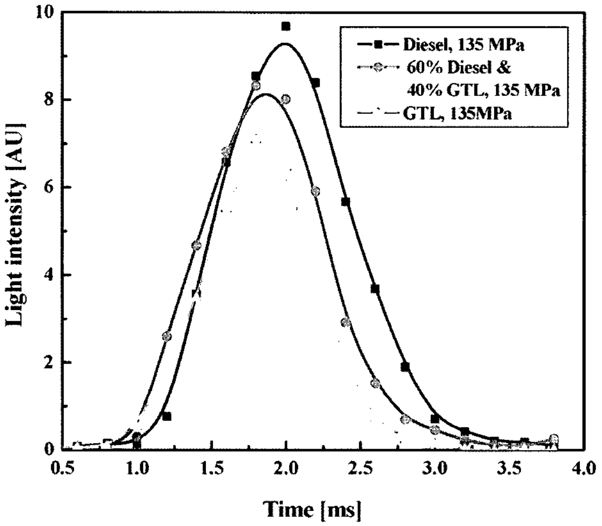


Figure 8. Natural flame intensities acquired by the photodiode.

4.2.2. Liquid-phase fuel length and auto-ignition characteristics

The images at 0.336 ms in Figure 7 show that sprays emanate from the nozzle for both fuels at nearly the same time. This means that there is a negligible difference in the needle opening instances for the two fuels. The chamber air temperature is high enough that spray evaporates very fast and liquid length is stabilized at 20~24 mm from the nozzle. The flame initiation point for GTL fuel is about 90 μs earlier than that of diesel fuel. This is caused by the facts that GTL fuel has a higher cetane number and a lower auto-ignition temperature, so it tends to auto-ignite earlier when it is exposed to the high temperature environment.

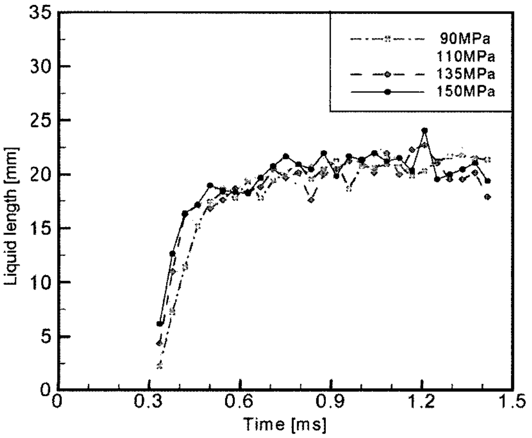


Figure 9. Liquid-phase fuel length of GTL sprays for 4 different rail pressures. Chamber pressure and temperature are 4 MPa and 920 K, respectively.

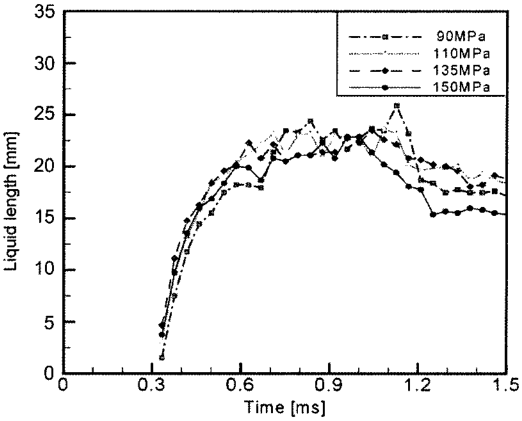


Figure 10. Liquid-phase fuel length of diesel sprays for 4 different rail pressures. Chamber pressure and temperature are 4 MPa and 920 K, respectively.

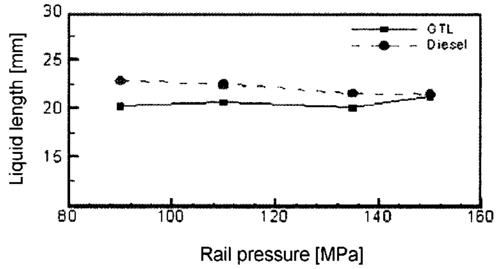


Figure 11. Comparison of the average liquid length as a function of rail pressure for GTL and diesel fuels. Chamber pressure and temperature are 4 MPa and 920K, respectively.

Figure 7 also shows that there is apparently no contact between the liquid-phase fuel and the flame for GTL fuel, however, for diesel fuel, there is some contact at the end of the liquid-phase fuel.

Figures 9 and 10 show the variations in liquid lengths for GTL and diesel fuels, respectively, during the injection. Liquid lengths for all the conditions are stabilized with some fluctuations. These fluctuations are probably caused by aerodynamic instability of a liquid jet.

Figure 11 shows averaged liquid-phase fuel lengths during the period from 0.71 ms to 1ms. From this figure, we can see that the liquid length of diesel fuel tends to be longer by about 8% and rail pressure does not have a large effect on the liquid length. This result is in fair agreement with the previous study (Siebers, 1998). After performing a number of experiments regarding the liquid length of evaporating sprays, it was concluded that injection pressure has no significant effect on the liquid length, and the lower volatility (i.e., higher boiling point) of components in a multi-component fuel controls the liquid length. As shown in Table 1, the maximum boiling

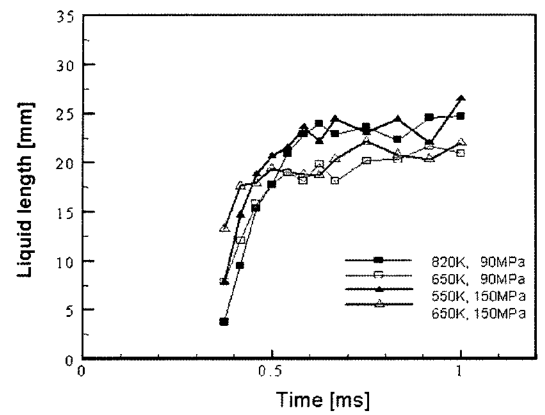
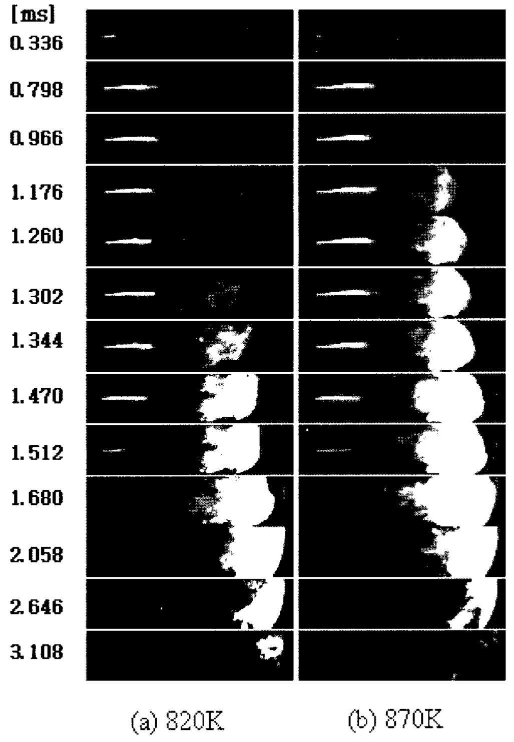


Figure 12. Effects of chamber temperature and rail pressure on the liquid length of GTL fuel for a chamber pressure of 4 MPa.

temperature of diesel fuel is slightly higher than that of GTL fuel.

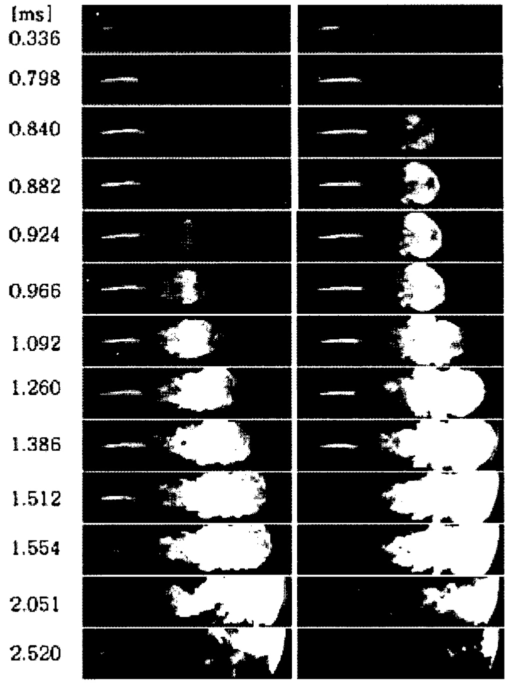
Figure 12 shows the effect of the chamber air temperature and rail pressure on the liquid-phase length.

Liquid lengths clearly decrease as air temperature in the chamber increases and as rail pressure increases: the similar trend shown in Figure 11 is confirmed.



(a) 820K (b) 870K

Figure 13. Chamber temperature effects on liquid-phase fuel and auto-ignition delay for GTL fuel. Rail and chamber pressure are 135 MPa and 4 MPa, respectively.



(a) 90MPa (b) 150MPa

Figure 14. Rail pressure effects on liquid-phase fuel and auto-ignition delay of GTL fuel. Chamber pressure and temperature are 4 MPa and 920 K, respectively.

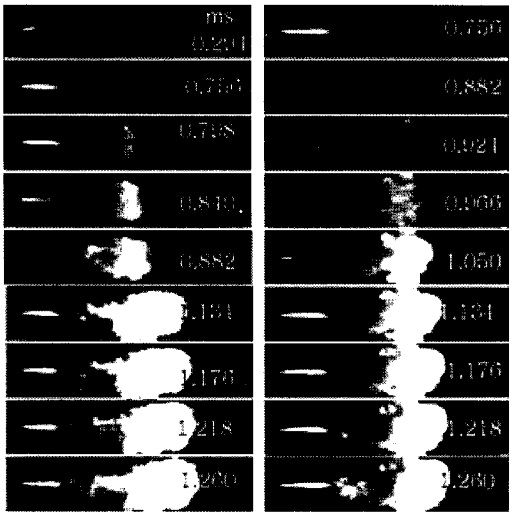
The effect of the chamber air temperature on the liquid-phase fuel and auto-ignition delay is depicted in Figure 13. As can be seen, the auto-ignition is delayed drastically with the temperature decrease.

Figure 14 shows the effect of rail pressures. When the pressure increases from 90 MPa to 150 MPa, the auto-ignition delay period decreases by about 110 μs, which is a much longer time than the needle opening advance time of about 20 μs. This may be caused by the increased heat transfer from the chamber gas to the fuel jet, due to fast penetration of the jet when the rail pressure increases.

4.2.3. Pilot injection effect

The effect of pilot injection with GTL and diesel fuels is shown in Figure 15. The pilot injection advance (PA), pilot injection (PI) duration, main injection duration, and rail pressure are 800 μs, 300 μs, 670 μs, and 135 MPa, respectively. Similar to the case with only main injection shown in Figure 7, the pilot injected GTL fuel auto-ignites earlier than diesel fuel by about 130 μs. However, looking at the main injection period, after pilot injection in Figure 15, it can be seen that this lag decreases to about 40 μs due to burning of the pilot-injected fuel.

When we compare ignition delay of injected GTL fuel during the main injection period for two cases - with pilot



(a) GTL fuel (b) Diesel fuel

Figure 15. Effect of pilot injection with GTL and diesel fuels. Rail pressure, chamber pressure and chamber temperature are 135 MPa, 4 MPa and 920 K respectively. Pilot advance, pilot injection duration, and main injection duration are 800 μs, 300 μs, and 670 μs, respectively.

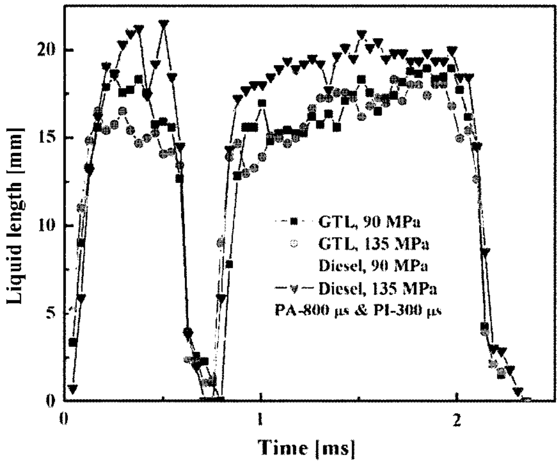


Figure 16. Effect of pilot injection on the liquid-phase fuel length for GTL and diesel fuels. Pilot advance, pilot injection duration, and main injection duration are 800 μs, 300 μs, and 670 μs, respectively.

injection and without pilot injection, the ignition delay for the former case is about 130 μs, which is much shorter than that for the latter case of 600 μs. Variation in liquid-phase fuel lengths during pilot and main injection periods is shown in Figure 16. The tendency for GTL to have a little shorter liquid length is maintained during pilot and main injections. The liquid length during the pilot injection is similar to that during the main injection.

5. CONCLUSIONS

For the purpose of comprehending the effects of GTL fuel characteristics on spray and combustion, visual investigation of sprays and flames from GTL and diesel fuels in a simulating vessel was implemented. From these experiments the following can be concluded:

(1) The liquid-phase fuel length of GTL fuel is slightly shorter than that of diesel fuel, and there is less contact between GTL liquid-phase fuel and flame compared to diesel fuel.
(2) The liquid-phase fuel length has a very weak dependency on rail pressure.
(3) GTL fuel flames have lower light intensity, which can be considered a measure of soot concentration, compared to those of diesel fuel.
(4) For the condition without pilot injection, GTL fuel auto-ignites about 90 μs earlier than diesel fuel, but for the condition with pilot injection, during the main injection period this lag decreases to about 40 μs.

ACKNOWLEDGEMENT–This work is part of the project "Development of Partial Zero Emission Technology for Future Vehicle" funded by the Ministry of Commerce, Industry and Energy and we are grateful for its financial support.

REFERENCES

Alleman, T. L. and Eudy, L. (2004). Fuel property, emission test, and operability results from a fleet of class 6 vehicles operating on gas-to-liquid fuel and catalyzed diesel particle filters. *SAE Paper No.* 2004-01-2959.

Fukumoto, M., Oguma, M. and Goto, S. (2003). Experimental investigation of lubricity improvement of gas-to-liquid (GTL) fuels with additives for low sulphur diesel fuel. *SAE Paper No.* 2003-01-1948.

Higgins, B., Siebers, D. and Aradi, A. (2000). Diesel-spray ignition and premixed-burn behavior. *SAE Paper No.* 2000-01-0940.

Hiroyasu H. and Arai, M. (1990). Structures of fuel sprays in diesel engines. *SAE Paper No.* 900475.

Oguma, M., Goto, S. and Chen, Z. (2004). Fuel characteristics evaluation of GTL for DI diesel engine. *SAE Paper No.* 2004-01-0088.

Oguma, M., Goto, S., Oyama, K., Sugiyama, K. and Mori, M. (2002). The possibility of gas to liquid (GTL) as a fuel of direct injection diesel engine. *SP–1716, SAE Int. Spring Fuels & Lubricants*, May 6-9, 2002.

Park, S. W. and Lee, C. S. (2003). Macroscopic structure and atomization characteristics of high-speed diesel spray. *Int. J. Automotive Technology* **4**, **4**, 157–164.

Siebers, D. L. (1998). Liquid-phase fuel penetration in diesel sprays. *SAE Paper No.* 980809.