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EFFECT OF CETANE ENHANCER ON SPRAY AND COMBUSTION CHARACTERISTICS OF COMPRESSED IGNITION TYPE LPG FUEL

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ABSTRACT−This research investigated the spray and combustion characteristics of compressed ignition type LPG fuel when a cetane number enhancing additive was applied to a constant volume chamber. Because LPG has a lower cetane number, DTBP and alpha olefin were added to the LPG (100% butane) to enhance the cetane number and viscosity. By adding the cetane enhancer, stable combustion over the wide range of the ambient conditions was possible as well. According to the blending rates of DTBP and alpha olefin, various proportions of LPG blended fuels were obtained. In a constant volume chamber, a high speed digital camera was also employed to visualize the combustion characteristics of LPG fuel. The combustion pressures and heat-release rates of the LPG blends were also compared at various ambient pressures. As the results of measurements of exhaust emissions, CO and HC were reduced considerably, but CO_2 was increased by blending LPG with DTBP and alpha olefin.

KEY WORDS : LPG, Compressed ignition, Cetane number, Ignition delay, Constant Volume Chamber (CVC), DTBP (Di-tert-butyl peroxide)

1. INTRODUCTION

As major fuels of internal combustion engines, gasoline and diesel have caused problems of air pollution and global warming, and their limited amounts of deposits are decreasing due to the increase in usage all over the world. Solutions to these problems have been studied in many ways. It has been reported that the share of LPG as an alternative fuel can be increased gradually for low emission vehicles with the development of alternative fuels for the domestic energy supply.

As a clean energy vehicle, an LPG vehicle hardly emits PM and SO_2 and emits 10% less CO_2 than a diesel vehicle. In addition, its charging procedure is easier than that of LNG because LPG fuel can be stored in the liquid state at a normal temperature and a lower pressure.

By direct injection of LPG inside a cylinder, it is easy to control the exact air to fuel ratio. In addition, the improved cooling effect of a combustion chamber by the latent heat for vaporization helps to increase the engine power and decrease the emissions at the exhaust (Sobiesiak *et al*., 2003; Lee and Daisho, 2004). In addition, a homogeneous mixture of air and fuel can be expected because LPG has a lower molecular weight and a higher vapor pressure, and thus uniform mixtures of fuel and air can be formed. Direct injection of LPG can improve the engine performance better than a carburetor or intake manifold injection, but there are problems in using LPG due to its low ignition quality and low cetane number. The evaluation of the relation between the cetane number and ignition delay period of LPG was made by applying three types of DTBP in a consatant volume combustion chamber (Hashimoto *et al*., 2002). Meanwhile, engine performance tests were conducted in LPG-powered DI diesel engines (displacement 1,858cc and 4,214cc) by only a single type of DTBP (Goto *et al*., 1999; Sugiyama *et al*., 2003; Alam *et al*., 2001; Goodrich *et al*., 1998; Thompson *et al*., 1997).

In this research, self-ignition was promoted by mixing cetane enhancing additives with liquid phase LPG. High compressed injection led to self-ignition, and the experimental study was done in order to obtain the optimum combustion characteristics, according to the mixing ratio of the cetane enhancing additive, in a constant volume chamber. Furthermore, a lubricating additive was applied to prevent leakage and abrasion of mechanically operating parts caused by the lower viscosity of liquid phase LPG.

2. EXPERIMENTAL APPARATUS AND METHOD

2.1. Experimental Apparatus

A constant volume chamber was applied for the visualization of the spray and combustion characteristics of a compressed ignition type liquid phase LPG direct injection engine, and its bore and width were 123 mm and 34 mm, respectively. A high speed digital camera was installed to photograph the actual shapes of fuel spray and the diffusion

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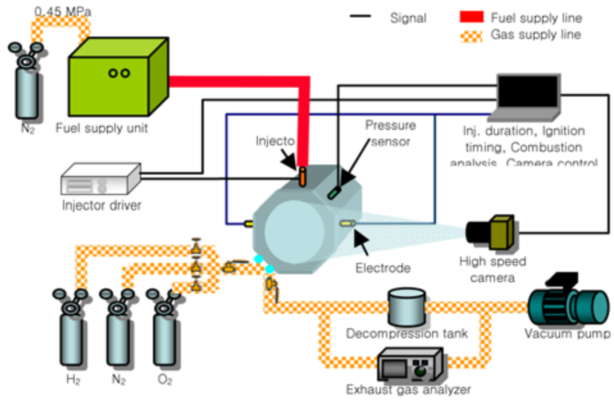

Figure 1. Schematic diagram of the experimental apparatus.

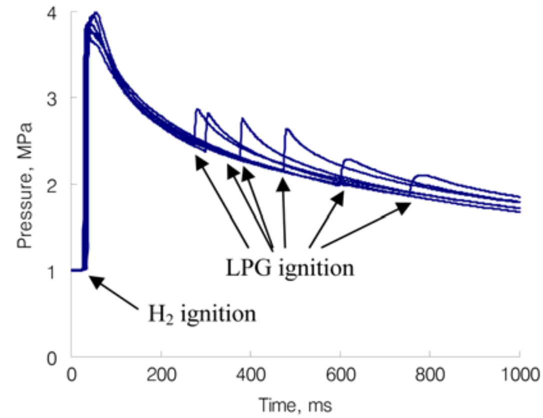

Figure 2. Pre-ignition of hydrogen and LPG injection.

of the flame. As CVC peripherals, intake and exhaust valves, a pressure sensor and a spark plug were installed, and two visual windows with a bore of 153 mm and thickness of 68 mm at both sides were used for photography. The remaining gases were removed by using a vacuum pump and a decompression tank (Figure 1).

The experimental conditions are given in Table 1. In order to investigate spray and combustion phenomena, hydrogen, oxygen and nitrogen were premixed and burned. The CVC was provided with the atmospheric conditions of high temperature and pressure similar to that of diesel engines.

The concept of hydrogen premixed combustion and liquid LPG injection is presented in Figure 2. The concentration of the premixer was controlled by the partial pressures of the gases, and the oxygen concentration was maintained at 21% by volume during the spray of liquid phased LPG, which leads to ignition.

Because the liquid phased LPG has a lower viscosity than diesel fuel and is also sensitive to heat and pressure, the cavitation phenomenon may occur and can damage the fuel pump (Munson, Okiishi, 1998). Due to this problem, the apparatus was set up to reduce the pressure drop in a fuel supplying line by pressurizing with 0.45 MPa inside a liquid phased LPG fuel tank with nitrogen.

A high speed digital camera was used to photograph the spray and flame development of the liquid phase LPG fuel, and the corresponding photographing speeds were set to 4000 and 2000 fps each. The pressure change was measured by a piezometric pressure sensor, and the combustion process was analyzed by computing the heat release rates. The ignition time delay due to various mixing rates of cetane enhancing additive were obtained. The data on the combustion pressure were collected by using DAQ (Data Acquisition: DAQ Card-6024E), and all the signals of the ignitions and photographic timings were controlled by Code Vision AVR, written in the C language. After the completion of the combustion process, a Horiba portable gas analyzer (MEXA-554JKNO$_X$) was used.

Table 1. Experimental conditions.

Bore × Stroke	123 × 34 mm
Displacement	404 cm^3
Fuel delivery	Direct Injection
Injection pressure	25 MPa
Injection duration	1 ms
Ambient O_2 concentration	21% vol
Ambient density	11.3 kg/m^3

2.2. Experimental Method

Liquid phase LPG was injected with a pressure of 25 MPa, and the spray developing process was observed at various atmospheric pressures of 0~3.0 MPa. In the combustion experiment, combustion characteristics due to the mixing ratios of a cetane enhancing additive were investigated at atmospheric pressures of 1.8~2.55 MPa. The properties of DTBP (Di-tert-butyl peroxide) are shown in Table 3.

In general, LPG fuel is used by mixing propane, n-

Table 2. Properties of LPG.

Fuel	Propane	n-Butane	i-Butane
Molecular formula	C_3H_8	C_4H_{10}	C_4H_{10}
Boiling point (°C)	–42.0	–0.5	–11.7
Lower heating value (MJ/kg)	46.36	45.70	45.55
Vapor pressure (kg/cm^2 at 25°C)	9.68	2.47	3.57
Stoichiometric A/F (kg/kg at 15.6)	15.68	15.46	15.46
Auto ignition temp. (°C)	510	490	490
Cetane number	5	10	10

Table 3. Properties of DTBP.

Molecular formula	$C_8H_{18}O_2$
Molar mass	146.23 g/mol
Density	0.8g/cm^3
Boiling point	109~110 °C

Table 4. Blending rates of LPG with DTBP at ambient conditions.

Blending rates of LPG with DTBP	Ambient conditions
LPG + 5wt% DTBP LPG + 10wt% DTBP LPG + 15wt% DTBP	1.80, 1.95, 2.10, 2.25, 2.40, 2.55 MPa (789, 829, 869, 909, 949, 989K)

butane and i-butane, and its blending ratios are varied by seasons and geographical regions; however, in this experiment, 100% butane LPG fuel was used. Table 4 represents the characteristics of LPG fuel.

The characteristics of flame diffusion and ignition delay were investigated by blending LPG with 5, 10 and 15 wt% of DTBP(di-tert-butyl peroxide) for the compression ignition type combustion because LPG has a lower cetane value. Table 3 represents the ratios of LPG and cetane enhancing additive according to ambient conditions. Small amounts of 0.5 wt% lubricant in the alpha olefin series were used to enhance the viscosity of the liquid phase LPG fuel because it has a lower viscosity.

3. RESULTS AND DISCUSSION

3.1. Spray Characteristics

The spray shape of the LPG fuel was photographed at 4000 fps by a high speed digital camera. The injected pressure was P_{inj}=25 MPa, and the ambient conditions were varied with P_{amb}=0~3.0 MPa (300~1112 K).

The shapes of the liquid LPG spray inside a constant volume chamber are shown in Figure 3. The photographs were compared in time order until the spray reached a wall

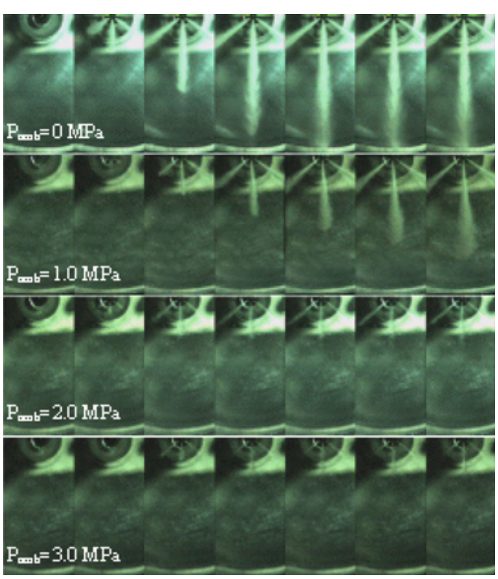

Figure 3. Spray visualization of LPG with various ambient pressures (Inj. Pressure=25 MPa, Inj. Duration=1 ms).

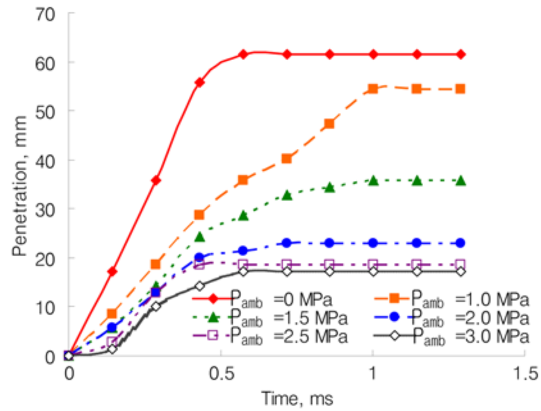

Figure 4. Spray penetration distance at various ambient pressures (Inj. Pressure=25 MPa, Inj. Duration=1 ms).

from the beginning of injection and at different ambient pressures when the injection pressure was fixed to 25 MPa.

At a room temperature and pressure, liquid LPG spray has a sufficient penetration distance to reach the wall. However, the evaporation of LPG fuel and penetration force became lower suddenly under ambient conditions of high temperature and pressure. In an actual engine, a 20-mm penetration distance is obtained under the conditions of P_{amb}=2.0 or 2.5 MPa, and thus an actual combustion chamber must be designed with these reqirements. When the ambient pressure was lower and injection pressure was increased, penetration distance of the LPG spray increased as expected. Figure 4 represents the developing progress of penetration distance with respect to time.

3.2. Combustion Characteristics

Based on the experiment on the preceding spray visualization, experiments on the combustion process were conducted by controlling the blending ratio of cetane-enhancer liquid phase LPG. Figure 5 represents progressive combustion processes when the ratio of cetane-enhancing additive was changed to 5, 10 and 15 wt% under a fixed injection pressure 25 MPa and injection duration of 1 ms.

The flame was developed in the direction of spray, and after collision with the wall it diffused throughout the whole combustion chamber. At the lower ambient pressure of 1.80 MPa, the aforementioned flame development was not observed. LPG fuel (15 wt.% DTBP) with a higher amount of cetane-enhancer had higher luminosity than LPG fuel (5, 10 wt.% DTBP), and the time in which flame diffused to the whole combustion chamber became shorter. Under different combustion conditions, the progressive combustion pressures and heat-release rates are shown in Figures 6~11. There were not many differences in the combustion pressures in accordance with DTBP ratios at higher ambient pressures, but the differences appeared at lower ambient pressures. In 5 wt% DTBP, at either P_{amb}= 1.95 MPa or 1.80 MPa, the combustion did not occur properly, and the combustion pressure increased gradually;

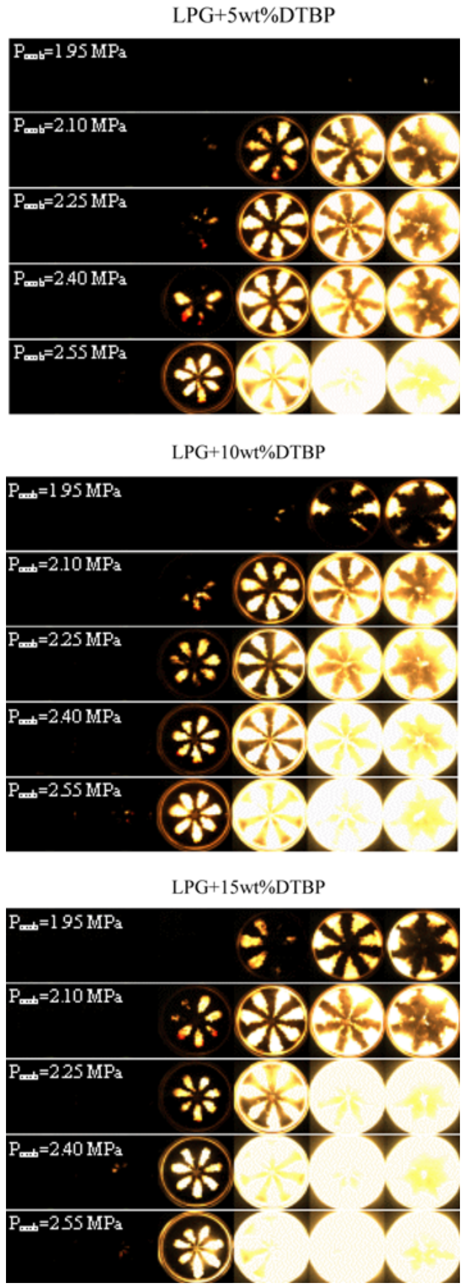

Figure 5. Combustion visualization of LPG with various ambient pressures (Inj. Pressure=25 MPa, Inj. Duration=1 ms).

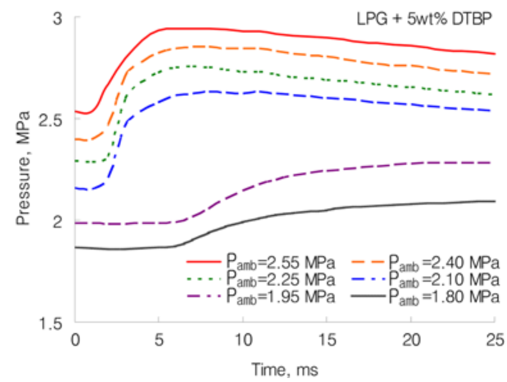

Figure 6. Development of pressures for LPG+5 wt% DTBP in various ambient pressures.

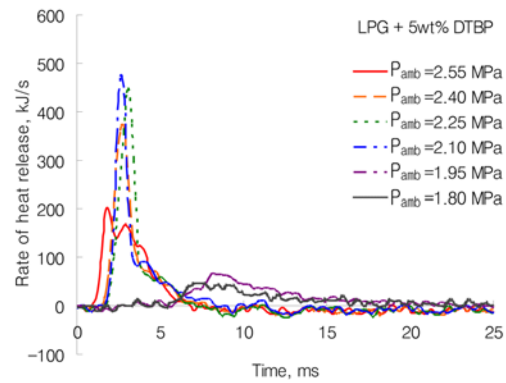

Figure 7. Development of heat release rates for LPG+5 wt% DTBP in various ambient pressures.

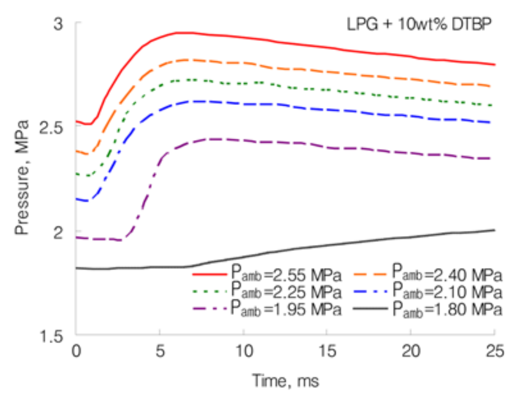

Figure 8. Development of pressures for LPG+10 wt% DTBP in various ambient pressures.

however, in 10 wt% DTBP at P_{amb}=1.95, the combustion proceeded. Even under poor ambient conditions of P_{amb}= 1.80, combustion occurred barely.

From the results of heat release rates in relation to combustion pressures, diffusitive and premixed combustions appeared at high ambient pressures, but at lower ambient pressure the portion of pressure diffusitive combustion was relatively reduced.

In addition, considering only the higher ambient condition of P_{amb}=2.55 MPa, the pattern of the heat release rates in 10 wt% DTBP was similar to that of diesel fuel, and its total heat release rate was greater than that of 5 wt% DTBP. The portion of diffusitive combustion appeared due to the improved ignition quality in 15 wt% DTBP.

Figure 12 represents the relationship between the ignition delay and the ratio of cetane-enhancing additive. The ignition delay decreased almost linearly with respect to ambient pressure as the ratio of cetane enhancer was

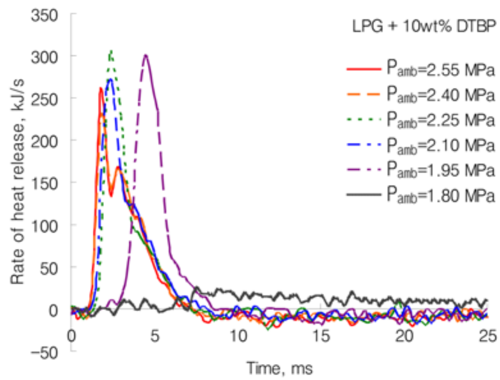

Figure 9. Development of heat release rates for LPG+10 wt% DTBP in various ambient pressures.

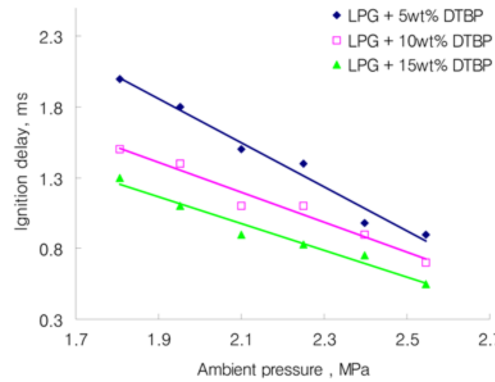

Figure 12. Effect of blending rates of LPG with DTBP on ignition delay versus ambient pressures.

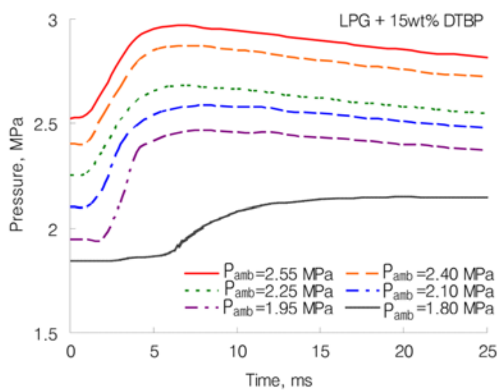

Figure 10. Development of pressures for LPG+15 wt% DTBP in various ambient pressures.

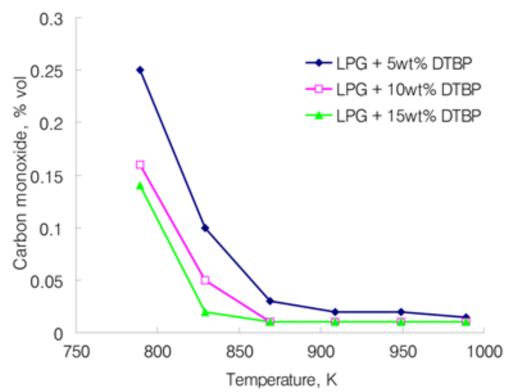

Figure 13. CO emission in LPG fuel with DTBP versus ambient temperature.

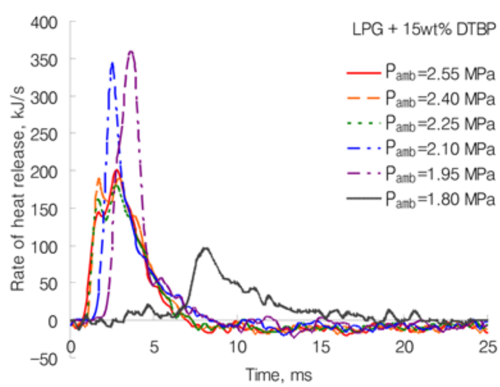

Figure 11. Development of heat release rates for LPG+15 wt% DTBP in various ambient pressures.

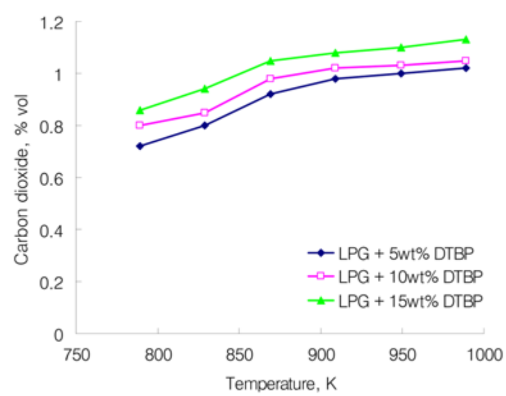

Figure 14. CO_2 emission in LPG fuel with DTBP versus ambient temperature.

increased. Longer ignition delay allows increased mixture of fuel and air.

Figures 13~15 represent emissions (CO, CO_2, HC) versus ambient temperature according to different ratios of cetane-enhancing additive. CO caused by nonhomogeneous mixing and unburned fuel decreased as the ambient temperature and ratios of cetane-enhancing additive increased, and HC emission decreased due to the reduction in unburned fuel as well. On the other hand, CO_2 increased due to the improved combustion conditions at higher ambient temperatures and higher ratios of cetane-enhancing additive.

4. CONCLUSIONS

Spray and combustion characteristics of compressed ignition type liquid phase LPG fuel were investigated under

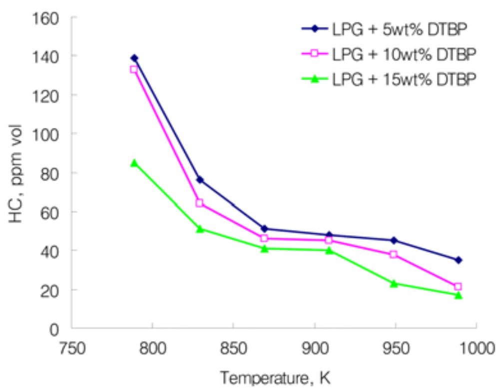

Figure 15. HC emission in LPG fuel with DTBP versus ambient temperature.

various injection and ignition conditions by changing the ratios of cetane enhancers in a constant volume chamber, and the results are summarized as follows.

(1) From the spray experiment of liquid phase LPG fuel, the penetration distance was reduced significantly as the ambient temperature and pressure increased. Similar to conventional fuels, the time in which the spray reached the wall decreased when the injection pressure increased, but an increase in ambient pressure also reduced the penetration distance.

(2) From the combustion experiment with liquid phase LPG fuel, in contrast to conventional diesel fuel, LPG started to ignite at the upper end due to the fast evaporation of the LPG fuel. The combustion pressure and heat release rate increased, and unburned fuel decreased due to the improved ignition conditions when the ambient pressure, temperature and ratio of cetane-enhancing additive were increased.

(3) From the results of the combustion pressure and heat release rate, the ignition delay was decreased by the effect of increased cetane values under the conditions of high pressure and temperature and the higher ratio of cetane-enhancing additive.

(4) CO and unburned HC decrease as the ambient temperature and ratio of cetane enhancing additives increased, but CO_2 increased due to the improved self-ignition condition.

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