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SPRAY CHARACTERISTICS OF DIRECTLY INJECTED LPG

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ABSTRACT–It has been recognized that alternative fuels such as Liquid Petroleum Gas (LPG) show less polluting combustion characteristics than diesel fuel. Furthermore, engine performance is expected to be nearly equal to that of the diesel engine if direct-injection stratified-charge combustion of the LPG can be adopted in the spark-ignition engine. However, spray characteristics of LPG are quite different from those of diesel fuel. Understanding the spray characteristics of LPG and evaporating processes are very important for developing efficient and low emission LPG engines optimized in fuel injection control and combustion processes. In this study, the LPG spray characteristics and evaporating processes were investigated using the Schlieren and Mie scattering optical system and single-hole injectors in a constant volume chamber. The results show that the mixture moves along the impingement wall that reproduced the piston bowl and reaches in ignition spark plug. LPG spray receives more influence of ambient pressure and temperature significantly than that of n-dodecane spray.

KEY WORDS : LPG, Visualization, Spray, Impingement spray, Common rail, OH radical

1. INTRODUCTION

LPG is used widely as the fuel for the taxi with convenience because there are almost 2000 LPG refueling stations in Japan (LP Gas Center, 2000). Therefore, the development and research on using LPG is actively carried out by Goto *et al.* (1999), Stavinoha *et al.* (2000) and Hyun *et al.* (2001). From these studies, it was reported that diesel fuel could be replaced with LPG as a high-performance and clean fuel. Also, Choi *et al.* (2002) investigated that the LPG spray width got bigger and SMD of the spray was smaller with higher injection pressure same to diesel fuel.

Studies mentioned above are intended for mixer or multi-point injection type. However, it has a potential to achieve less polluting and more efficient combustion characteristics than diesel fuel if direct-injection stratified-charge combustion of the LPG can be adopted in the spark-ignition engine. However, there are many unknown phenomena in the behavior of spray, mixture formation and combustion of LPG in the cylinder. These points are making the development of high-efficiency LPG engine difficult.

In this work, visualization of LPG sprays was, Thus, carried out to investigate stratified charge combustion having the higher efficiency than that of the conventional pre-mixed spark ignition combustion. By applying the Schlieren and Mie scattering method, LPG liquid and gas phase were visualized. In addition, the influence by fuel temperature and fuel components was also investigated.

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2. RESEARCH METHOD

2.1. Experimental Apparatus

The experimental apparatus is composed of the constant volume chamber, fuel injection system, optical systems, and control measuring systems as shown in Figure 1. A constant volume chamber was used to duplicate high temperature and pressure conditions appearing in real engines. Quartz windows were attached on both sides of the chamber for visualizing of the fuel spray by means of laser methods. A prism to reflect the laser sheet, a fan to stir the initial chamber mixture, and a spark plug to ignite this mixture were installed around the chamber. The chamber pressure was measured using a piezo-electric transducer and acquired by a computer with an A/D board. A computer was used to control the fuel injector and the spark plug. A common-rail fuel supply system was used in this experiment. LPG was pressurized by a pump, and injected using an electromagnetic injector.

Figures 2 and 3 illustrate the schematic diagrams of the optical systems. Argon laser was used as a light source in

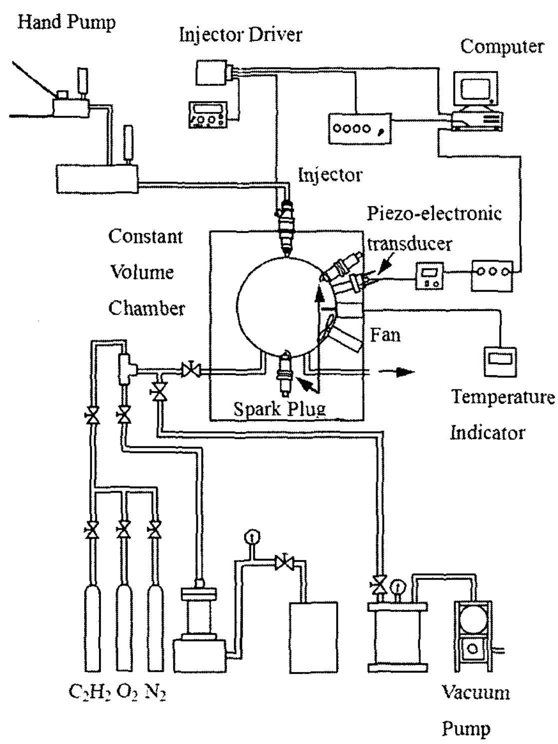

Figure 1. The experimental system.

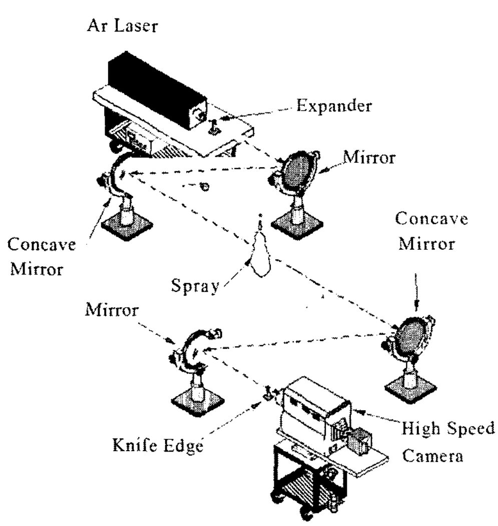

Figure 2. Schlieren optical system.

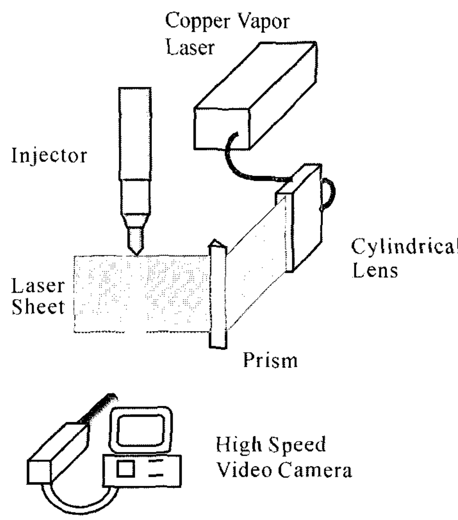

Figure 3. Mie scattering optical system.

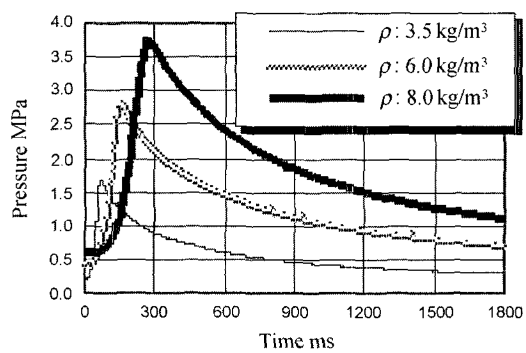

Figure 4. Pressure history of ethylene combustion.

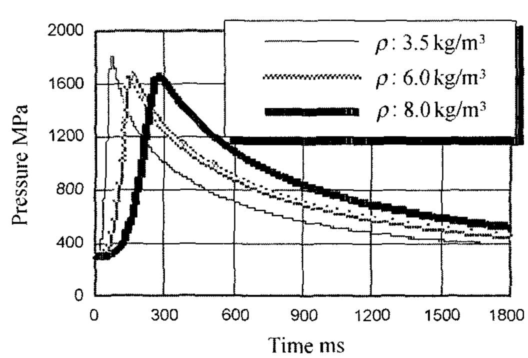

Figure 5. Temperature history of ethylene combustion.

the Schlieren optical system. The laser beam was enlarged by an expander and the rays made parallel by the concave mirror. After passing through the chamber, the light is reflected by a mirror, and then focused by another concave mirror. A high-speed video camera was placed behind the knife-edge to take images of the spray. Liquid-phase images were also taken based on the Mie scattering of the wavelength with 532 nm emitted from copper vapor laser as shown in Figure 3.

2.2. Experiment Methods

To reproduce the high pressure and temperature conditions prior to fuel injection in a chamber, the chamber was filled with ethylene, oxygen, and nitrogen gases. Concentration of each gas was adjusted by measuring the partial pressure of each gas using a pressure gauge attached to the chamber. The gases were mixed by a fan and ignited by the spark plug. For spray visualization

Table 1. Experimental conditions.

Items	Conditions
Ethylene concentration %vol.	4.0
Nozzle	Single hole, ϕ 0.5 mm
Component of LPG fuel	n-C_4H_{10}, C_3H_8 (7:3)
Ambient O_2 concentration vol.%	3 (spray)
Ambient temperature K	300, 600, 800
Ambient density kg/m^3	3.5, 6.0, 8.0

without combustion, the oxygen amount was adjusted to attain 3% concentration after ethylene combustion. Gas temperatures in the chamber were calculated as a function of time based on the measured pressure histories as shown in Figures 4 and 5. Specific fuel injection timing was selected for a given combination of pressure and temperature after ignition of the ethylene mixture. The experimental conditions are shown in Table 1.

3. LPG SPRAY CHARACTERISTICS

3.1. Free and Impingement Spray

The experiments were conducted at room temperature under different chamber pressures. LPG was injected into the chamber filled with quiescent nitrogen gas. The fuel injection pressure was 10 MPa. The single-hole nozzle with an orifice diameter of 0.5 mm was used. The injection quantity was 20 mg. The images were taken at a camera speed of 9000 frames/sec.

Figures 6 and 7 show the photographs and curves of the spray area with time at different chamber pressures. LPG spray tip penetrations decreased and spray angles increased with the increase in chamber pressure, which were similar to the diesel spray. In spite of the room temperature, the evaporating process of LPG could be found actively due to its low boiling point and low viscosity (Li and Saito, 2001). Under ambient pressure of 0.7 MPa, while the gas area is narrow, liquid phase is remaining a lot yet.

Figures 8 and 9 show impinging spray images and the area histories of the free and the impinging spray respectively, where the Schlieren methods were applied.

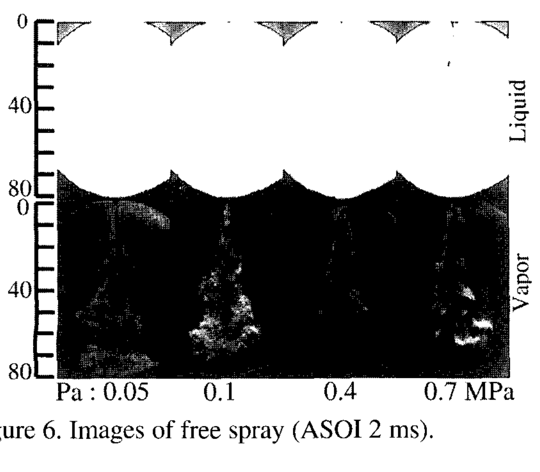

Figure 6. Images of free spray (ASOI 2 ms).

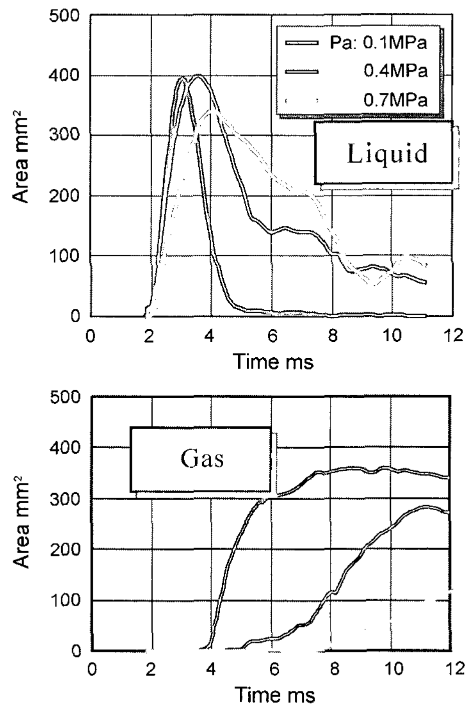

Figure 7. Comparison of spray area.

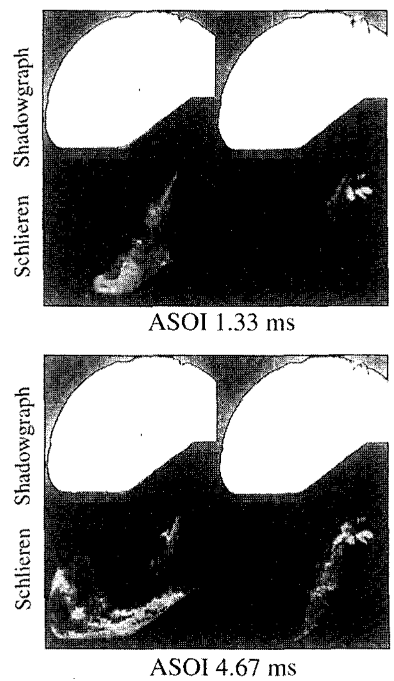

Figure 8. Images of impingement spray.

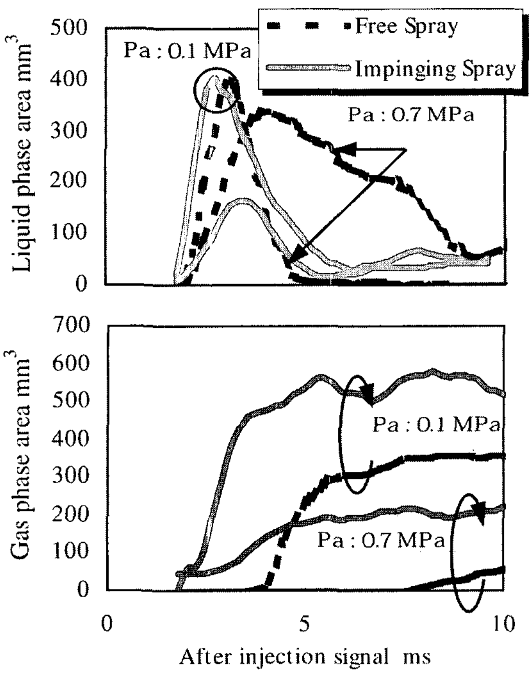

Figure 9. Comparison of free & impingement spray.

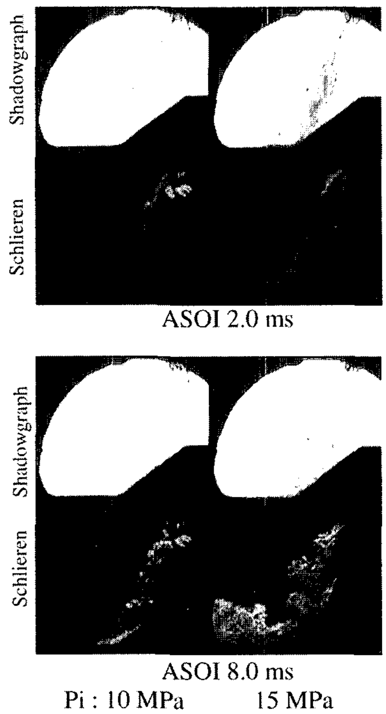

Figure 10. Spray images of each injection pressure.

With impinging action, the mixture retained enough momentum to reach the spark plug location. And, flash boiling characteristics appear at the LPG spray injected into the ambience whose pressure is under 0.6 MPa, because the saturated vapor pressure of LPG at 293K is 0.6 MPa approximately. By the impinging injection, it is clear that evaporation is promoted in comparison with free spray. And the higher the ambient pressure becomes, the less the spray diffuses.

3.2. Influence of Injection Pressure

Since LPG evaporates very quickly and tip penetration short than that of diesel fuel, it is thought that the high injection pressure of LPG is required. In this experiment, the LPG sprays at injection pressures of 10 and 15 MPa were compared as shown in Figure 10.

From these results, the spray tip penetrations increased with the increase of the injection pressure. In the later stage of the spray development, the higher the injection pressure, the wider the area of the spray. The reason was that with the increase of injection pressure, the jet velocity increased, which caused the penetration of spray to increase and the drop size to decrease. Thereby, the surface area of the spray and of the total fuel drops increased, which promoted the more rapid spray evaporation (Hiroyasu and Arai, 1980).

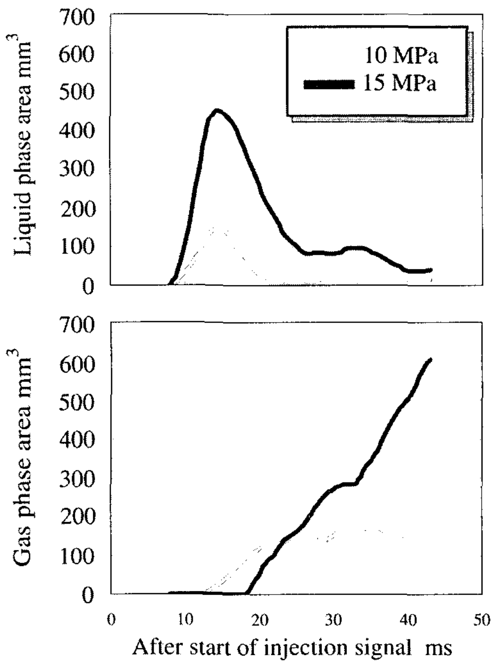

Figure 11. Comparison of each injection pressure.

3.3. Influence of LPG Fuel Temperature

When LPG in the liquid phase is injected into atmospheric conditions, the icing phenomenon occurs around injector tip in an MPI type. This hinders injection and makes air-fuel control difficult. Furthermore, in the case of directly injected LPG type engines, performance deteriorates at high load conditions because of the rise in fuel temperature.

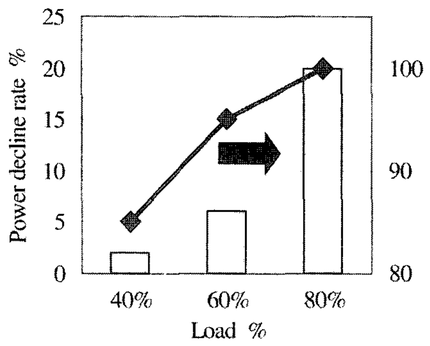

Figure 12. Power decline rate.

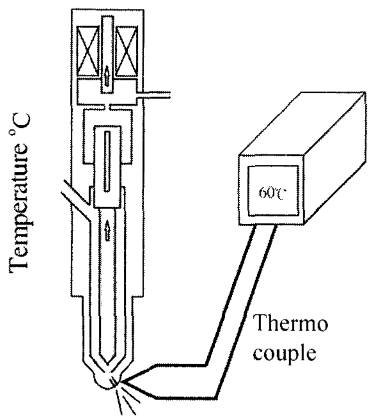

Figure 13. Measuring method.

To investigate the influence of fuel temperature, the spray was measured at different fuel temperatures using the shadowgraph method. Figure 12 shows the power decline rate, which is base on engine test and shows the temperature change on injector body. Figure 13 shows the fuel temperature measuring method.

Figure 14 shows that spray penetration is proportional to time for the relatively low fuel temperatures of -15 to 60°C. However, when the fuel temperature exceeds 80°C, the proportionality ceases to exist as the spray angle becomes bigger. These results suggest that fuel temperature needs to be regulated and cooled sufficiently for direct injection LPG engines.

3.4. Influence of LPG Fuel Component

LPG that is composed of propane (30 wt.%) and n-butane (70 wt.%) was used as fuel. According to Figure 15 and 16, the penetration of butane is slightly longer than that of propane. The reason is that the density of butane is bigger and boiling point is higher than that of propane. Although the initial velocity of propane was higher than that of butane with the same injection pressure, the momentum of butane was preserved more than that of propane.

As mentioned above, the short spray penetrations of LPG will result in poor air utilization since the air on the

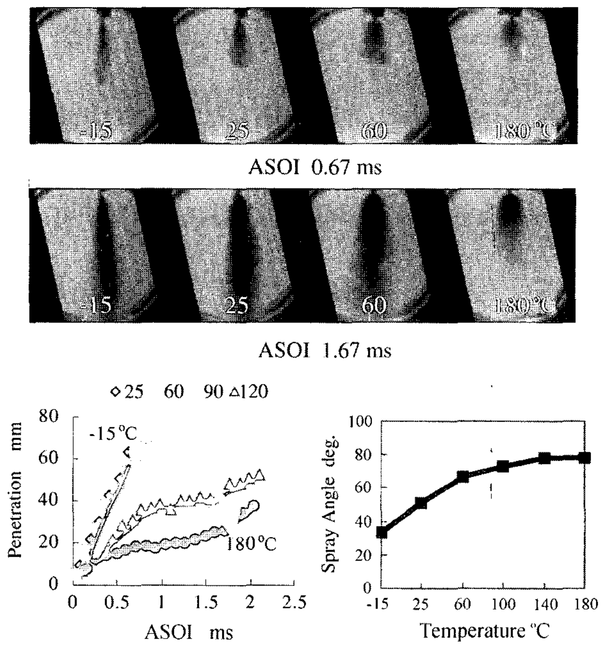

Figure 14. Spray images, penetration & spray angle.

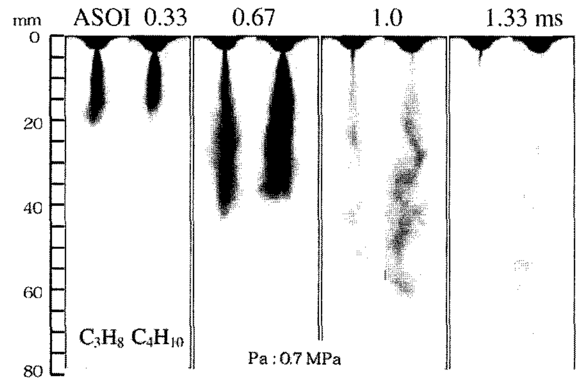

Figure 15. Spray images of each fuel.

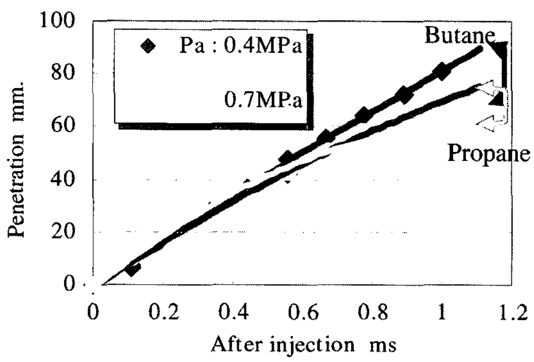

Figure 16. Penetration of each fuel.

periphery of the chamber does not contact the fuel. Although LPG evaporates very quickly, short penetration will neutralize the advantages. For this reason, it is

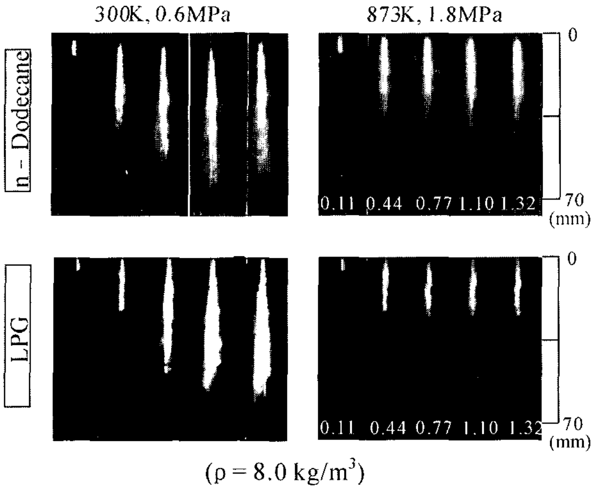

Figure 17. Images of n-dodecane & LPG fuel spay.

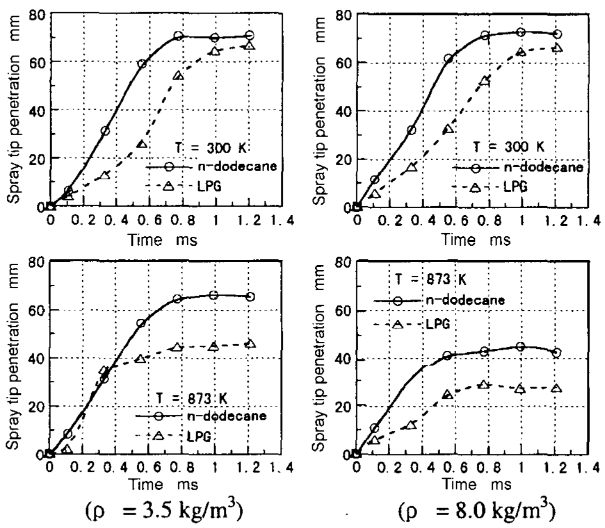

Figure 18. Penetration of each fuel.

important to optimize the injection pressure and shape of the combustion chamber and components of LPG fuel.

3.5. Influence of Ambient Condition

Figure 17 shows the liquid phase images taken by the high-speed video camera of n-dodecane and LPG fuel sprays under high pressure and temperature ambient conditions. In the case of n-dodecane sprays, the liquid phase tends to become shorter and narrower with increasing ambient temperature and pressure due to enhanced resistance with the surrounding air and evaporation of the spray. For the LPG sprays, the liquid phase also decreased with increasing ambient temperature and pressure in the same manner.

However, greater reduction in LPG spray is seen compared to that of n-dodecane at higher temperatures and pressures. The penetration of n-dodecane and LPG sprays as measured from the images are shown in Figure 18. As seen from these figures, the LPG spray is significantly influenced by both ambient temperature and pressure (Hwang *et al.*, 2003). The maximum penetration of LPG is only 30 mm at an ambient density of 8.0 kg/m³ and temperature of 873 K.

4. CONCLUSION

The transient characteristics of LPG sprays are investigated under variable temperature and pressure conditions in the constant volume chamber. The following conclusions are drawn.

(1) LPG spray has similar behavior with the diesel spray with the variation of chamber pressure and injection pressure. However, the spray tip penetration of LPG is shorter and spray angle is wider than that of diesel spray.
(2) LPG mixture was observed to move along the impingement wall that reproduces a real combustion chamber in the engine and favorably reaches the spark-plug location.
(3) LPG fuel temperature needs to be regulated and cooled sufficiently for direct injection LPG engines because spray receives an influence largely by fuel temperature.
(4) Penetration of n-butane is longer than that of propane clearly because of the difference of physical properties such as density, viscosity, and vapor pressure.
(5) The LPG spray receives the influence of ambient pressure and temperature significantly more than that of n-dodecane spray. Therefore injector location and combustion shape should be carefully determined for LPG fuel, taking into account the evaporation distance.

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