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BEHAVIOR OF LIQUID LPG SPRAY INJECTING FROM A SINGLE HOLE NOZZLE

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ABSTRACT−Liquefied petroleum gas (LPG) has been used as motor fuel due to its low emissions and low cost. A liquid direct injection system into a cylinder was suggested as a next generation system to maximize a fuel economy as well as a power. This study addresses the analysis of the LPG spray injecting from single hole injector. Two different test conditions are given, which are a fully developed spray case with various injection pressures and a developing spray case with ambient pressure variation. The LPG spray photographs are compared with the sprays of gasoline and diesel fuel at the same conditions, and the spray angles and penetration lengths are also compared, and then the spray behavior is analyzed. The LPG spray photos show that the dispersion characteristic depends very sensitively on the ambient pressure soon after injection. The spray angle is very wide in a low ambient pressure condition until the saturated pressure, but the angle is quickly reduced at the condition over the pressure. However, the down stream of the LPG spray shows much wider dispersion and less penetration than those of gasoline and diesel sprays regardless ambient pressure condition.

KEY WORDS : Liquid LPG (Liquefied Petroleum Gas), Spray, Direct injection, Single hole nozzle

1. INTRODUCTION

LPG has been accepted as a low emission fuel for the engines with a little modification of current ones. However, the carburetion or gas injection system supplying the engine with LPG as gas state is not considered as low emission system any more, because the engine using gasoline fuel has been improved by a stringent requirement for exhaust emissions.

Two different methods of liquid LPG injection system are suggested as the countermeasure. One is LPG-DI injecting liquid LPG directly into cylinders, and the other is LPG-MPI injecting into intake ports. LPG-MPI system is already commonly used and developed for heavy-duty engines (Kim *et al.*, 2001; Kim *et al.*, 2001; Kim *et al.*, 2002; Kang *et al.*, 2000; Kang, 2002; Lee *et al.*, 2003; Kim *et al.*, 2002; Hwang *et al.*, 2002; Kim and Choi, 2003). The volumetric efficiency is increased up to 10% by the MPI system, however it is still considered as a constant trouble to heavy duty engines requiring much power output. Thus the liquid LPG direct injection system, in which LPG is injected directly into a chamber, has been developed as a future technology to achieve more power output and less exhaust emissions at once. The characteristic of LPG injection is distinguished from that of diesel and gasoline fuel. LPG evaporates very quickly in a low surround pressure condition. Brown and York (1962) investigated the influence of flashing phenomena on the drop breakup of the LPG spray injected in a low surround pressure. Wildgen and Straub (1989) reported boiling phenomena at the nozzle tip. Smith *et al.* (1997) reported the characteristics of LPG according to surround temperature and pressure and Fusimoto *et al.* (1997) analyzed atomizing characteristics. Other investigations for LPG spray are given with various conditions in RCEM, CVC or engines (Cho and Jeong, 1999; Lee *et al.*, 2002; Ryu *et al.*, 2001; Lim and Park, 1999; Jo *et al.*, 2002; Choi *et al.*, 2002; Choi *et al.*, 2002).

The purpose of this study is to get basic information for applying LPG direct injection system on engines with investigating and analyzing the behavior of direct injecting spray from single hole injector. The spray images are visualized and compared with diesel or gasoline sprays in a wide injection and ambient gas pressure range.

2. EXPERIMENTAL EQUIPMENT AND CONDITIONS

Figure 1 is a schematic diagram of a spray visualization system. A short arc strobo having flashing duration of 20 μs and CCD camera with a shutter speed of 1/60-1/16000

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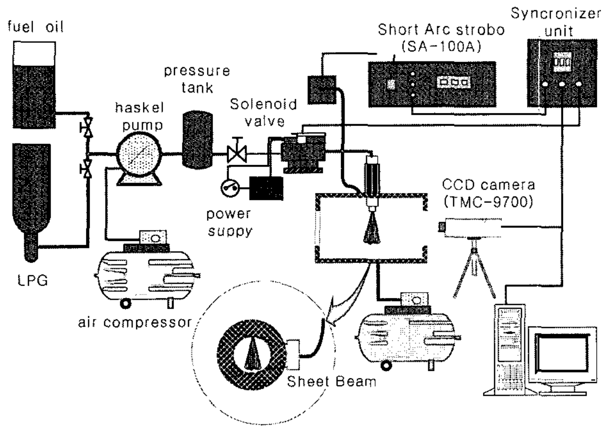

Figure 1. Experimental setup.

sec are used to take the images. The sheet beam generated by cylindrical lens irradiates the vertical section of the spray. Fuels are supplied from separated tanks to Haskel air driven pump producing pressurized fuel up to 50 MPa. The fuel is injected into constant volume chamber by a solenoid valve. The valve moving signal goes into a controller which gives 5 V signal to the strobo and the camera after a proper time delay. Therefore the sprays are captured at different times after injection start. The ambient pressure is adjusted by pumping air into constant volume chamber having 4 windows.

Table 1 shows test conditions which are largely divided into two different test conditions of a fully developed spray case with various injection pressures and a developing spray case with various ambient pressures. LPG, gasoline and diesel fuels are used and their spray behaviors are compared. The LPG fuels used in this study is a mixture of 70% butane (C_4H_{10}) and 30% propane (C_3H_8) having a saturation point of 0.252 MPa at 5°C.

3. RESULT AND DISCUSSION

3.1. The Behavior of Fully Developed Spray

Figure 2 shows spray shapes of LPG and diesel fuel at the surround pressure of 0.1 MPa and the rail pressures of 5 to 50 MPa in the fully developed spray case. In the case of LPG spray injected at injection pressure of 5 MPa, the spray near nozzle tip disperses widely and then becomes wider smoothly to the down stream. With injection pressure increased, the spray dispersion is reduced and the narrow body becomes longer, and then disperses widely in down stream. The spray behaviors are dependent on the duration of LPG vaporization from the meta stable state of liquid and vapor. The spray has enough time to evaporate in the low injection pressure case because of a low injection velocity, so the droplets near the nozzle will disperse widely with the evaporating drops, while the spray goes down quickly without enough evaporation in high injection pressure. On the contrary the diesel spray does not disperse widely and has a

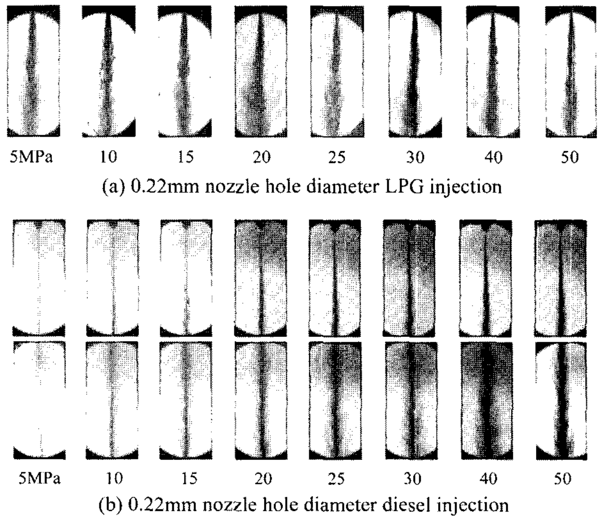

Figure 2. Spray shapes with injection pressure variation.

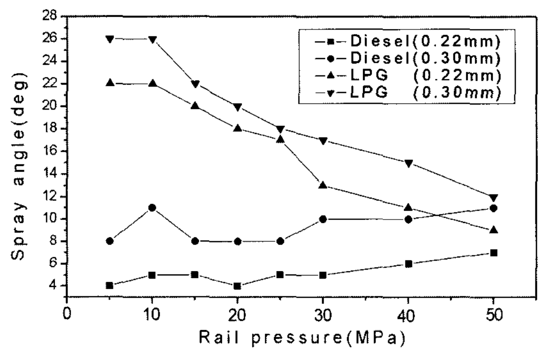

Figure 3. Spray angles measured at 35 mm from the nozzle tip.

Table 1. Test condition.

Cases	Fuel	Rail pressure (MPa)	Trap pressure (MPa)	Nozzle hole dia (mm)
Fully developed spray	LPG, Diesel	5–50	0.1	0.22, 0.30
Under developed spray	LPG, Diesel, Gasoline	10	0.1–0.7	0.22

(a) LPG spray development

(b) Diesel spray development

(c) Gasoline spray development

Figure 4. Spray developments at rail pressure of 10 MPa and trap pressure of 0.1 MPa.

narrow and long shape over all the injection pressure range. Figure 3 shows the spray angles measured at 35 mm from the nozzle tip. In the case of nozzle diameter of 0.22 mm, the spray angle of LPG is 5 times wider than that of diesel fuel. With injection pressure increase, LPG spray angle reduce quickly, while diesel spray angle increases slightly. That behavior is also appeared in the 0.30 mm nozzle diameter case.

3.2. The Behavior of Developing Spray

Figure 4 shows the spray developments in the condition of injection pressure of 10 MPa and trap pressure of 0.1 MPa for LPG, diesel and gasoline fuels. The LPG spray at 0.1 ms after injection start is just hanging on the nozzle tip and does not go further until 0.5 ms after injection. The spray is developed fast until 0.9 ms, and then slow again. The behavior seems to be the effect of fast evaporation of LPG. Diesel and gasoline sprays are developed linearly with time from injection. The comparisons are given in Figure 5 and 6 for penetration and width respectively. In the early time soon after injection, LPG spray is not developed well. The tip penetration and the width are also remained near the nozzle. But after the period, the spray penetration approaches to that of the other fuels, and the width takes over the width of diesel or gasoline. In the late time after the period the penetration rate is reduced, instead the width becomes much wider.

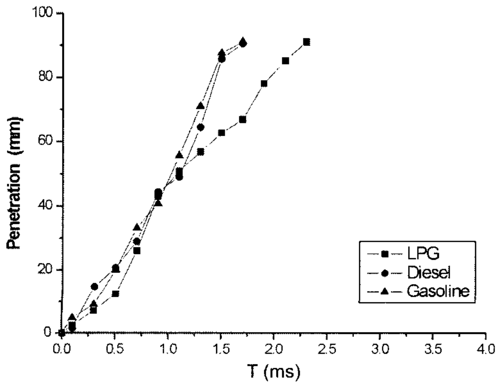

Figure 5. Comparison of spray penetration at rail pressure of 10 MPa and trap pressure of 0.1 MPa.

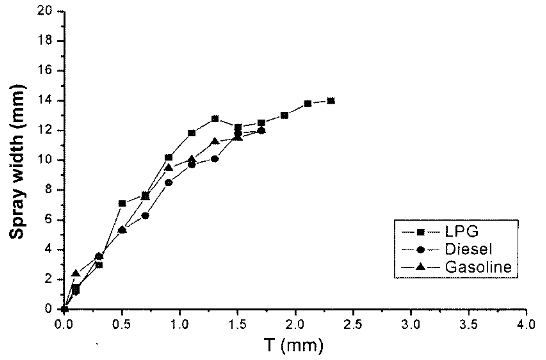

Figure 6. Comparison of spray width at rail pressure of 10 MPa and trap pressure of 0.1 MPa.

The spray shapes of LPG are very dependent upon trap pressure. The shape is very wide like a balloon in low trap pressure, instead of narrow in high trap pressure, as shown in Figure 7, while diesel and gasoline sprays are narrow. With trap pressure increase the LPG spray tip penetration becomes very similar to diesel or gasoline sprays in early stream. But the down stream of LPG is still developed slowly and much wider than diesel or gasoline sprays. Those are shown in Figures 8–11. The phenomena indicate that the early spray will be widely dispersed in the low ambient pressure until the saturated pressure of 0.252 MPa at 5°C and then the spray behavior becomes similar to diesel or gasoline over the pressure.

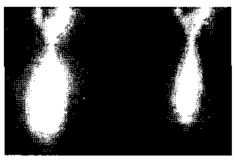

Figure 7. Comparison of early LPG sprays at trap pressures of 0.1 and 0.7 MPa.

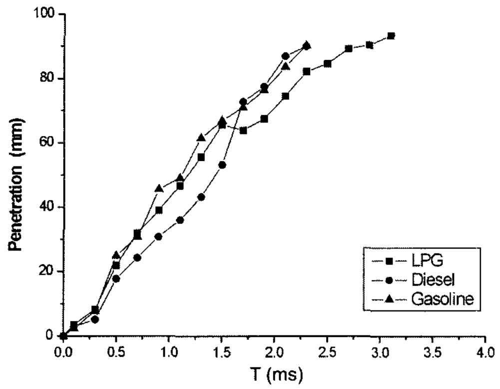

Figure 8. Comparison of spray penetration at rail pressure of 10 MPa and trap pressure of 0.4 MPa.

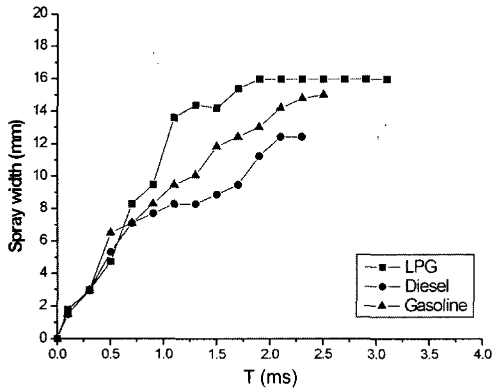

Figure 9. Comparison of spray width at rail pressure of 10MPa and trap pressure of 0.4 MPa.

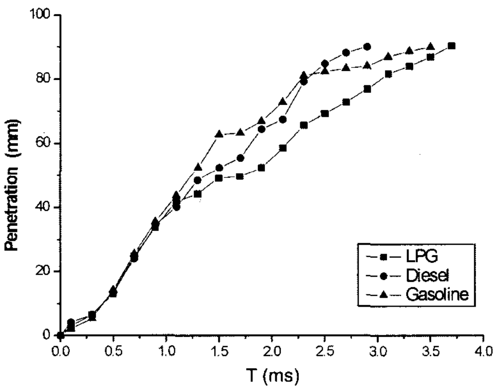

Figure 10. Comparison of spray penetration at rail pressure of 10 MPa and trap pressure of 0.7 MPa.

The down stream of the LPG spray is much wider and slower than that of diesel or gasoline sprays, although the trap pressure is over the saturated pressure.

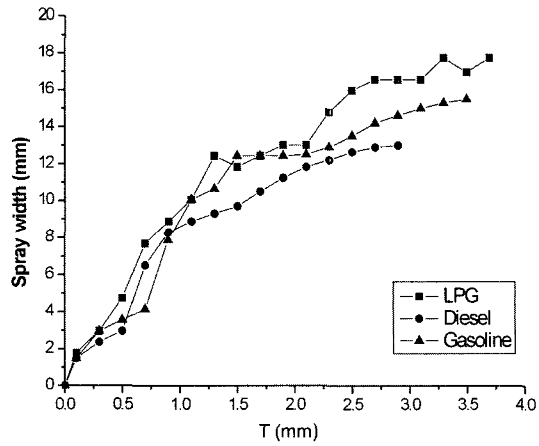

Figure 11. Comparison of spray width at rail pressure of 10MPa and trap pressure of 0.7 MPa.

4. CONCLUSIONS

From the discussion on LPG spray, the results are summarized as follows;

The LPG spray angle is much wider than that of diesel spray in near nozzle, and then reduces quickly with injection pressure increase, while diesel spray angle increases slightly.

For the early sprays near nozzle tip, LPG spray is very sensitively dependent on the trap pressure. The spray develops very widely in the low trap pressure less than saturated pressure, while that becomes similar to diesel or gasoline spray in the high trap pressure.

For the late sprays far from nozzle tip, LPG sprays are in much wider and less penetration over all the trap pressure range due to fast evaporation.

For LPG engine design, the behavior of LPG spray might be more dependent on the gas flow motion in cylinder than those of gasoline or diesel fuel, therefore the chamber should be designed carefully in order to gather the fuel vapor around the ignition site.

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