Spray Characteristics of Dimethyl Ether(DME) Fuel Compared to Various Diesel Fuels

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Key Words: Dimethyl Ether(DME), Diesel, LPG, Spray, Visualization

Abstract

It is recognized that alternative fuel such as dimethyl ether (DME) has better combustion polluting characteristics than diesel fuel, even though the cetane number of DME is almost the same as that of diesel. Characteristics of DME spray were observed experimentally under various ambient conditions using a constant volume chamber and a common-rail injection system. N-dodecane and LPG fuel sprays were also observed under same conditions of DME spray. Using spray images from backlight scattering and Mie scattering, characteristics of fuel sprays such as penetration and spray volume were visualized and quantitatively measured. The measurements showed that the penetration of early period decreased remarkably, because evaporation of alternative fuels became prosperous by the influence of flash boiling phenomenon under the condition of the low temperature and pressure compared with n-dodecane. The penetration of DME and LPG spray received the influence of temperature more largely in comparison with low density, because the specific surface area increased by atomizing in high density.

1. Introduction

These days, many diesel studies have investigated alternative fuels to improve fuel consumption and to reduce NOx and particulate matters (PM) emissions. Among these alternative fuels, di-methyl ether (DME) has regarded as an effective alternative fuel to diesel. DME, as a good candidate of diesel, has physical properties including cetane number close to those of diesel fuel so that it is easily adopted to conventional diesel system. Furthermore, an innovative chemical process has been developed to produce DME efficiently from natural gas(1).

DME is an oxygenate fuel having a molecular carbon-oxygen bond, which leads the DME to a smoke-free fuel. DME is expected to be a good fuel solution of diesel engines, as a less-polluting replacement of diesel fuel.

Inasmuch as DME fuels have several merits such as lower molecular weight, higher volatility and evaporative properties than those of diesel, DME is also able to reduce particulate matters of diesel combustion by virtue of faster mixture formation. The purpose of this work is to provide detailed information on mixing and spray characteristics of directly injected DME. This work investigates spray characteristics of several fuels like n-dodecane as a representative diesel molecule, LPG and DME under various conditions in a constant-volume combustion chamber.

2. Experimental apparatus and methods

2.1 Experimental apparatus

A constant-volume chamber was employed to show spray characteristics of DME under high-temperature and high-pressure conditions of diesel engines.

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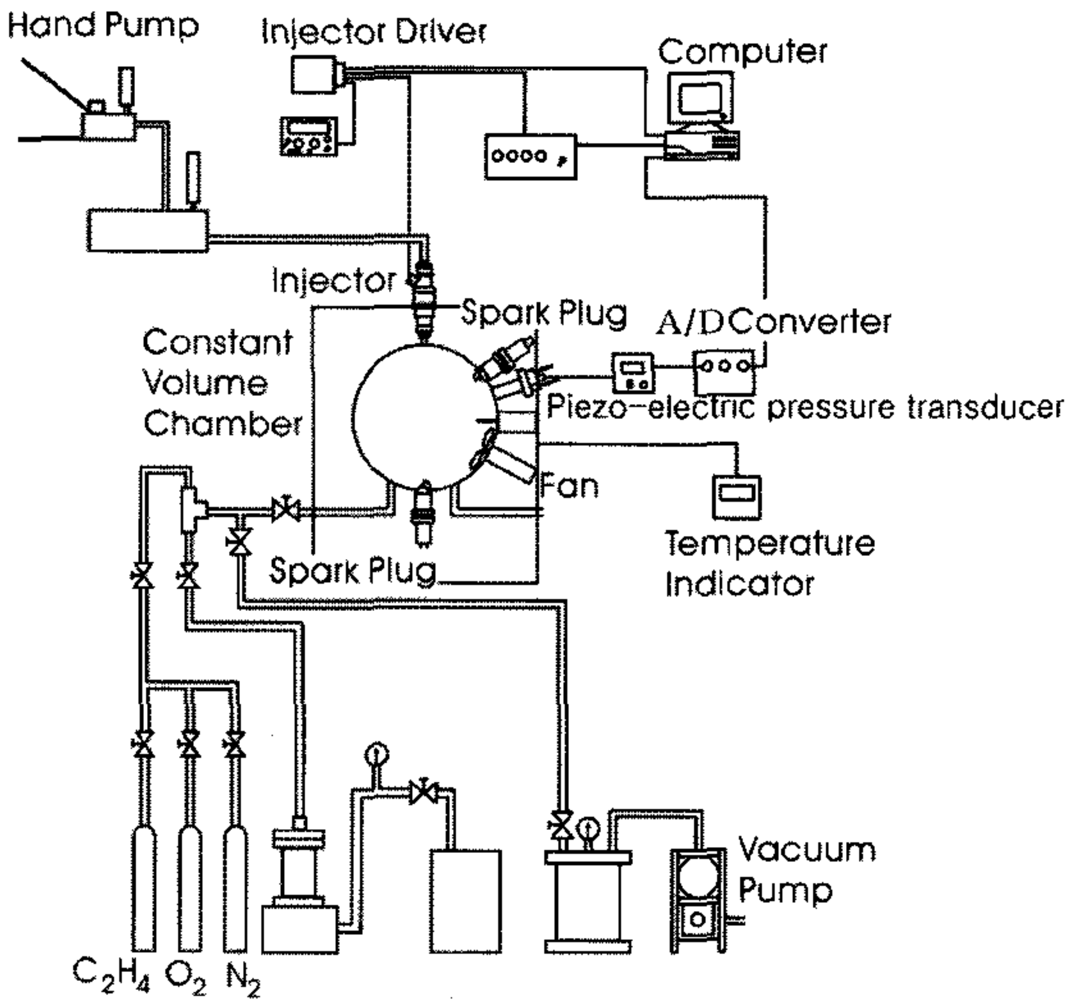


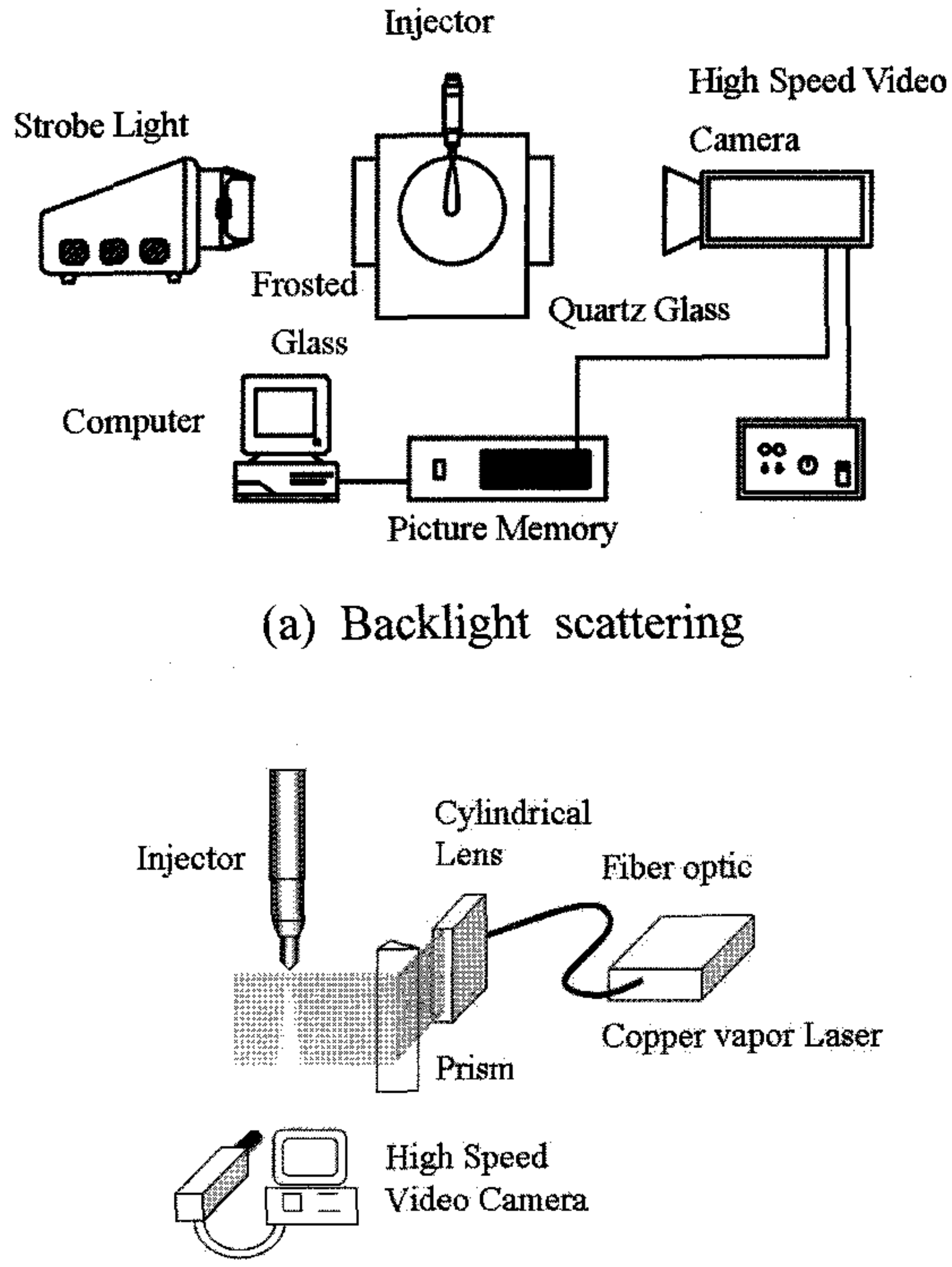
Fig. 1 Schematic diagram of experimental setup

A common-rail fuel injection system (BOSCH) was used to provide an in-chamber evaporating spray. A single-nozzle injector that had 0.3 mm hole diameter was applied to all the experiments. Injection and optical systems were electronically controlled as shown in Figure 1. Hold current of the injector driver was 6A, and peak current 15A. By virtue of quartz windows installed laterally on both sides of the chamber, it was possible to observe the spray phenomena through simultaneous optical measurements.

Figure 2(a) presents schematic diagram of the optical system. The spray is illuminated by parallel strobe light and recorded on digital high-speed camera with 9000 frames/second. Spray images were taken using the backlight scattering and these images are used to measure penetration, spray angle and volume of the spray. Exposure and gain of the image-intensifier applied in these tests were 200 ns and 8, respectively. Mie scattering was also applied to the various fuel spray to investigate liquid spray characteristics. The schematic diagram is depicted in Figure 2(b).

2.2 Experimental methods

Table 1 represents injection conditions of each fuel. Three fuels, n-dodecane, DME and LPG are tested at 40 MPa of injection pressure, under various



(a) Backlight scattering

(b) Mie scattering

Fig. 2 Schematic diagram of optical image-taking system

Table 1 Experimental conditions - fuel and injection

Items	Conditions
Concentration of ethylene %	4.0
Nozzle	Single hole, ϕ0.30 mm
Injection pressure MPa	40
Quantity of injection mg	15
Fuels	n-dodecane, DME, LPG
Ambient temperature K	300, 573, 873
Ambient density kg/m^3	3.5, 6.0, 8.0

ambient temperature and pressure conditions. Table 2 shows fuel properties applied in these tests. Compared to n-dodecane which is a representative of diesel fuel, DME shows similar or a little higher cetane value. Lower boiling point and density cause DME to an enhanced fuel candidate. The fact that oxygen atom is present in the fuel molecule is one of other noticeable characteristic of DME as mentioned in the introduction.

In preliminary tests, DME spray was injected to the chamber under room conditions to investigate basic characteristics of DME in addition to verify test

Table 2 Fuel properties

Fuel property	n-dodecane	DME	LPG	
			n-Butane (50%)	Propane (50%)
Chemical formula	$C_{12}H_{26}$	$(CH_3)_2O$	C_4H_{10}	C_3H_8
Molecular weight	170.34	46.07	58.12	44.1
B.P. °C	216.5	- 25.5	- 0.45	- 42.05
$T_{Critical}$ °C	358.15	126.85	152.01	96.67
ρ_l g/ml	0.75	0.66	0.50	0.67
$H_{combustion}$ MJ/kg	42.5	28.84	45.76	46.4
$H_{vaporization}$ kJ/g	256.19	466.80	385.52	426.0
Cetane value	38~43	55~60	-	-
Octane value	-	-	94	112

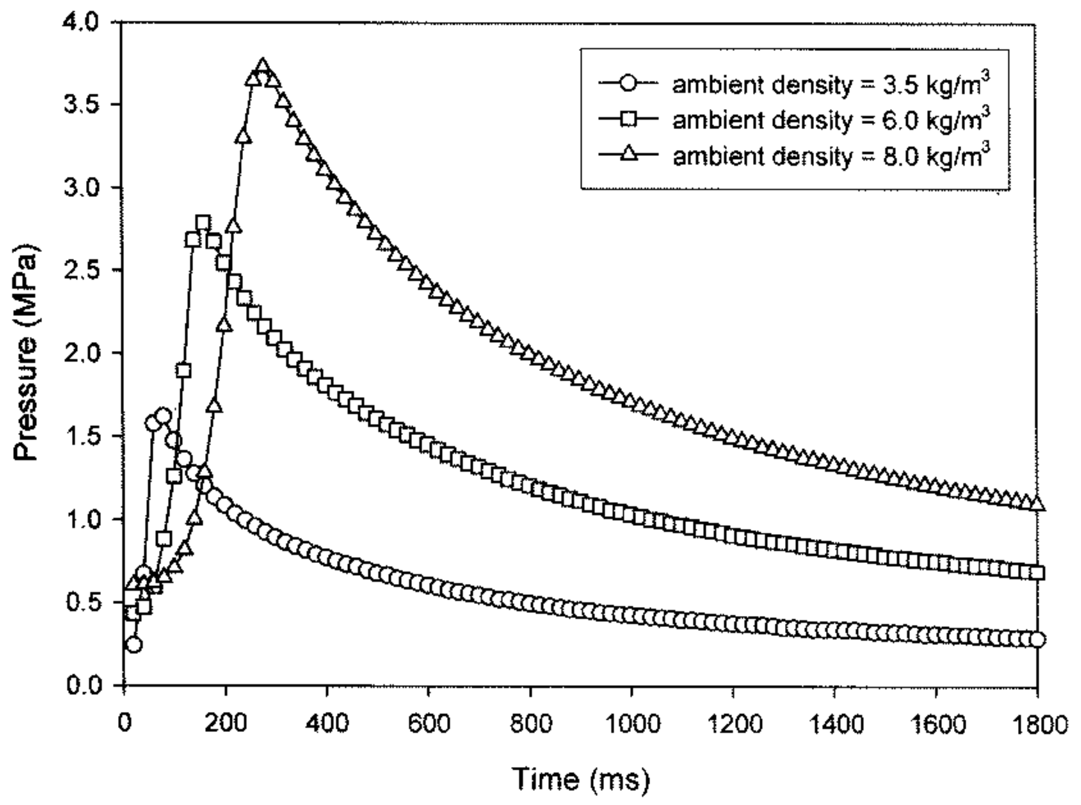


Fig. 3 Pressure history after the combustion of ethylene

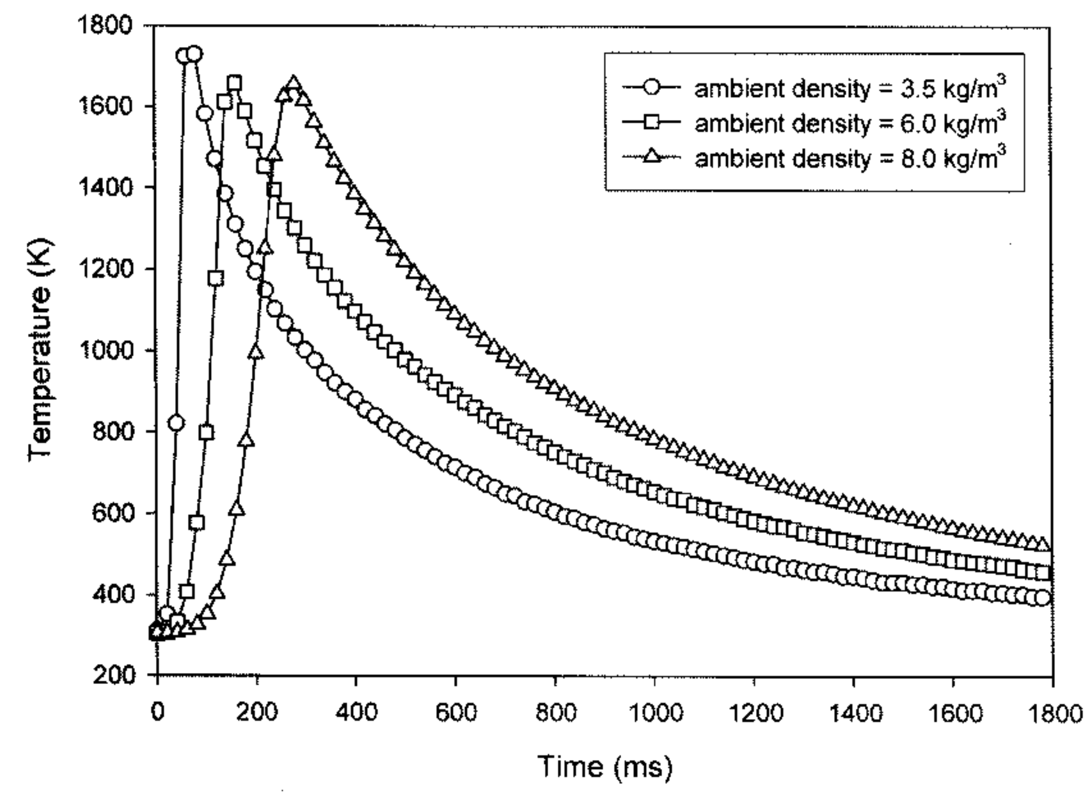


Fig. 4 Temperature history after the combustion of ethylene

facilities. These preliminary tests have two injection pressure (35/50 MPa) under ambient temperature (300K) and high pressure (ρair =16 kg/m^3 and 28 kg/m^3) conditions.

Table 3 Test conditions - injection timings

Ambient density kg/m^3	Injection timing after ethylene combustion ms	
	573K	873K
3.5	870	410
6.0	1230	620
8.0	1560	850

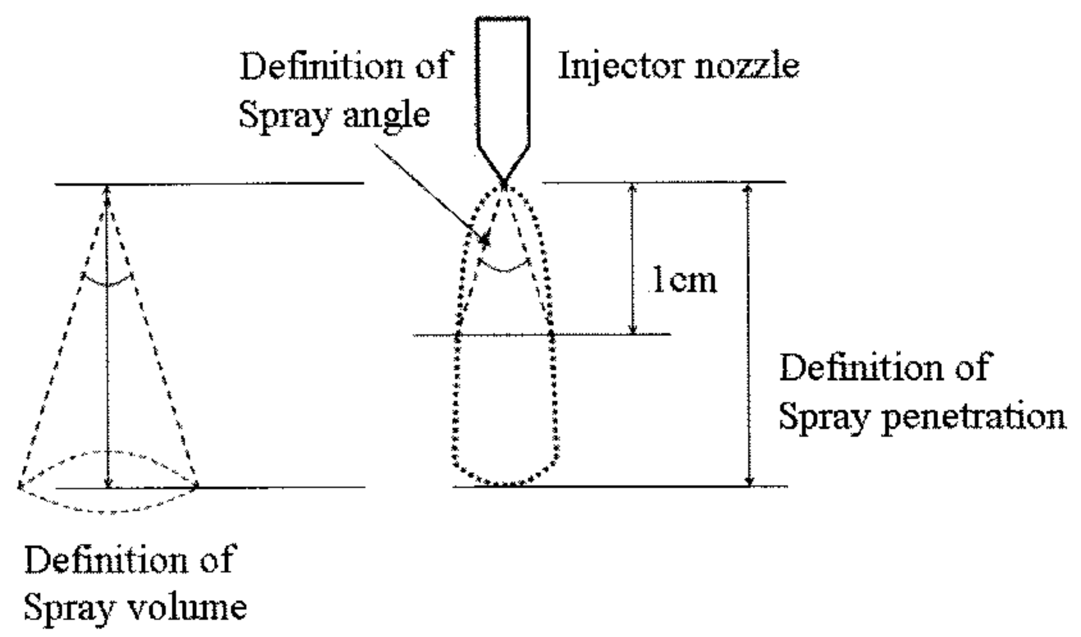


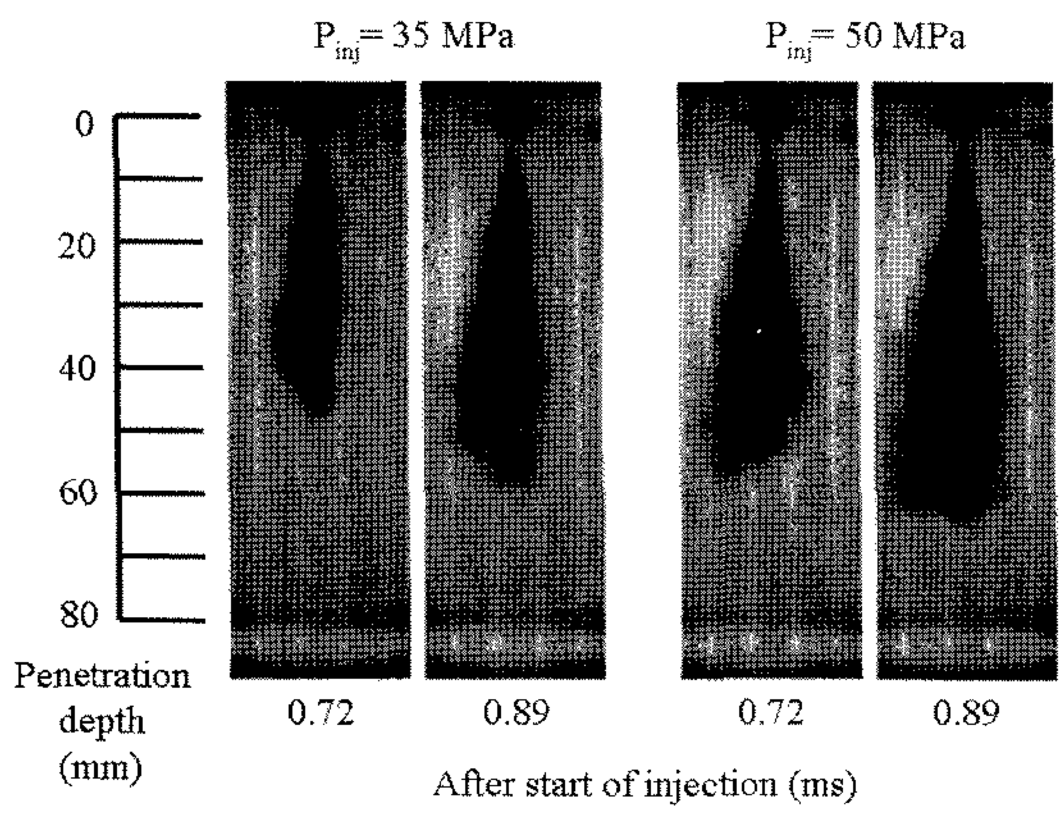
Fig. 5 Definitions of spray characteristics extracted from DME spray images

To prepare high-pressure and temperature conditions prior to fuel injection in the chamber, the chamber was filled with ethylene, oxygen and nitrogen mixture. Concentration of each gas was adjusted by measuring the partial pressure of each gas using a pressure gauge attached to the chamber. Before injections, ethylene is ignited and burned so that ambient conditions of combustion chamber change into high pressure and temperature. The measured pressure history after the combustion of ethylene and temperature calculated using state equation(2) are shown in Figure 3 and 4. From these figures, injection timings under various conditions are determined as shown in Table 3. Also, from the images of preliminary tests, spray characteristics such as penetration, spray angle and spray volume are measured and calculated followed by the definitions in Figure 5.

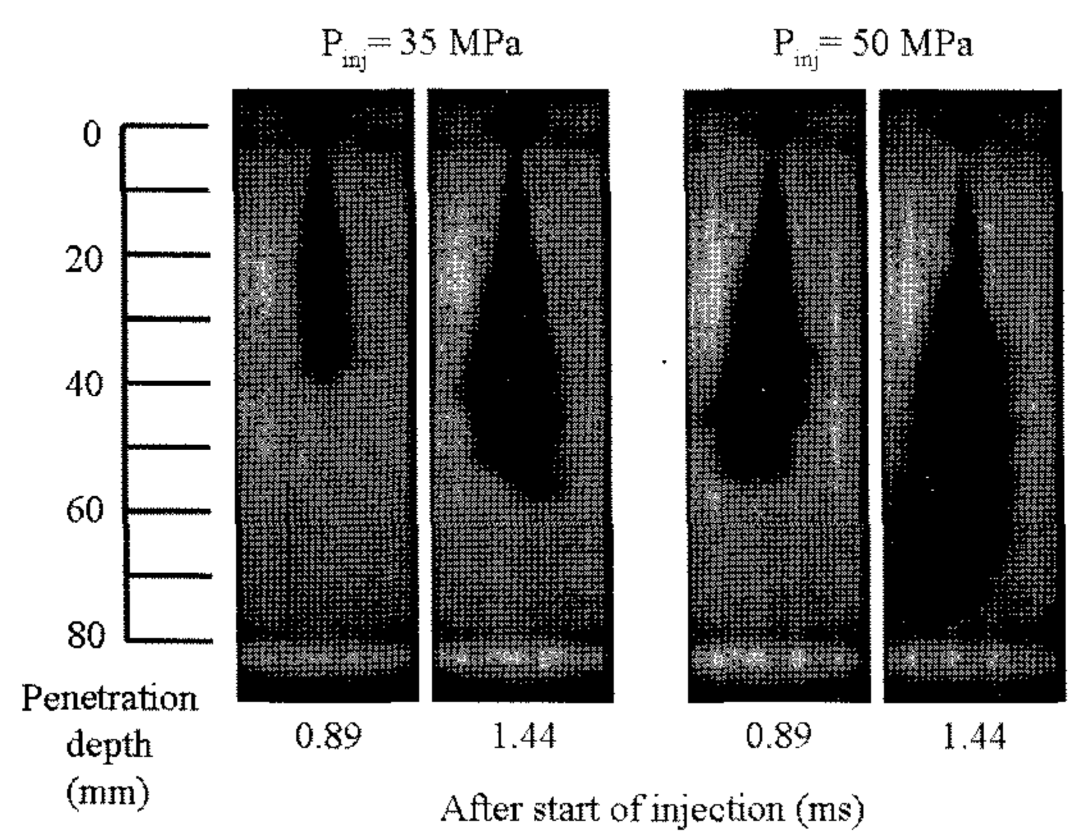
3. Results and discussion

3.1 DME spray under room conditions

Figures 6 shows DME spray images captured by backlight scattering for various densities and spray pressures. Through these figures, it is easily observed



(a) T = 300K, ρ_a = 16 kg/m^3



(b) T = 300K, ρ_a = 28 kg/m^3

Fig. 6 Spray images of DME (backlight scattering)

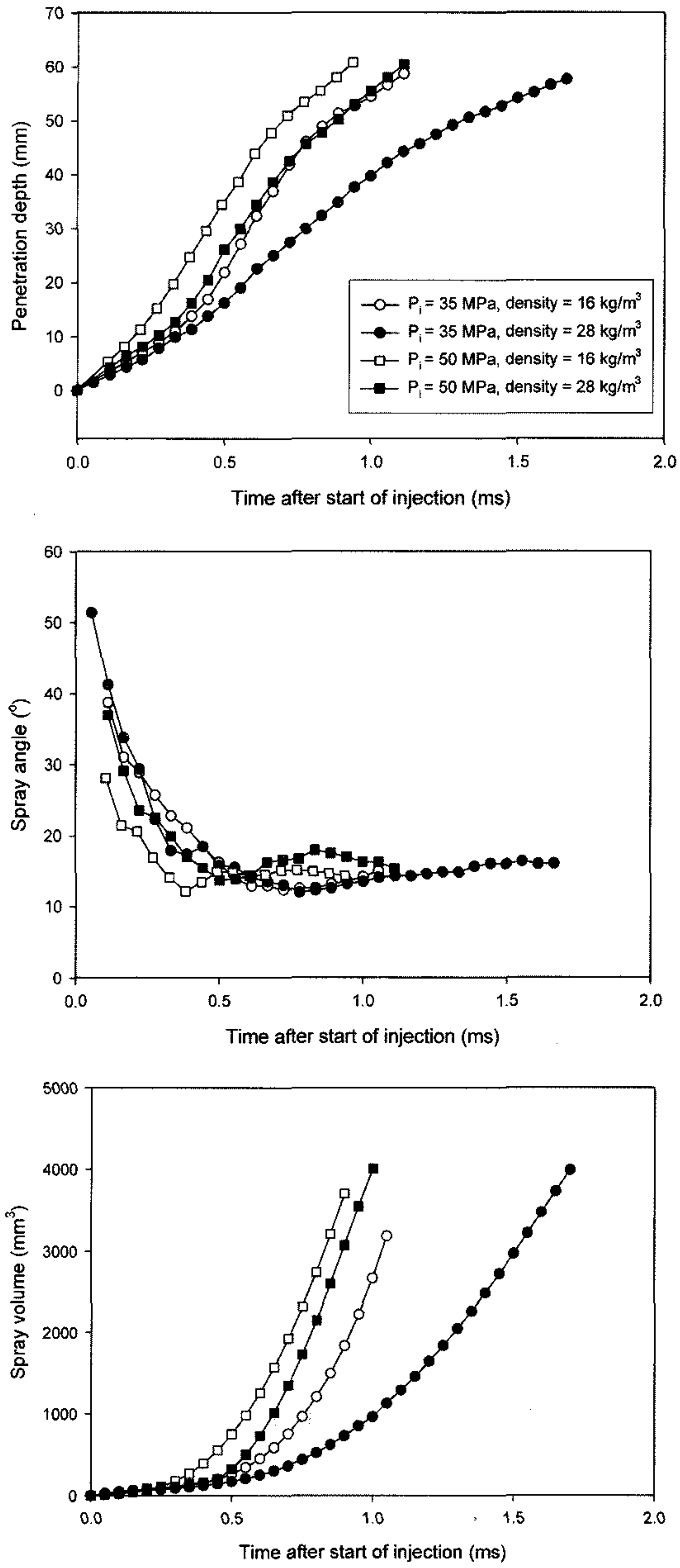


Fig. 7 Characteristics of DME spray under various injection pressure and ambient density conditions

that the spray has weaker penetration and larger spray angle as the ambient density increases. This is due to the increase in shear force by the ambient gases. Furthermore, higher spray pressure leads to stronger penetration response of the spray by increasing momentum of spray.

Figure 7 depicts the calculated results of DME spray tests. Spray angle is measured at a point 1cm downstream of the nozzle exit and the measurement is started from the time of issuance of the first fuel droplet. Spray volume is calculated under the assumption that spray is conic shape with the height same as the penetration depth of liquid spray as defined in Figure 5.

From the penetration depth measurements, it is clear that the penetration depth becomes longer under higher injection pressure and lower ambient density. It is also noticeable that the slope of penetration depth sharply increases at 5 ms ASOI (After Start Of Injection). The liquid spray angle is wide at the early period, but gradually decreases and settles down to a constant value regardless of the injection pressure nor ambient density. The flash boiling phenomenon will be a major reason to explain such characteristics on spray angle because DME has very similar boiling characteristics with LPG[3]. The flash boiling phenomenon occurs when the ambient pressure is sufficiently lower than saturated pressure of the injected fuel so that there is a rapid decrease in the portion of liquid fuel near the interface between fuel and air. The example of flash boiling is easily found in the case of injection of lower boiling point fuel such as LPG[4].

However, the penetration and spray angle differ from physical properties of fuel as well as ambient conditions. Furthermore, the maximum value of the spray angle at the initial stage is greater at pressure of 35 MPa - a lower spray pressure condition - compared with 50 MPa of injection pressure. This means that the flash boiling phenomenon occurs more easily under the lower spray pressure[5].

From these figures, it is also clear that the spray volume rapidly increases after 0.5 ms of injection, as the increase in penetration depth at the same time ASOI. As the spray pressure increases, effects of ambient pressure on spray volume become weaker so that the difference in spray volume is small under higher injection pressure condition. Therefore, it is suggested that higher injection pressure is more crucial to improve fuel-air mixing by virtue of increased spray volume rather than spray angle when DME fuel is applied.

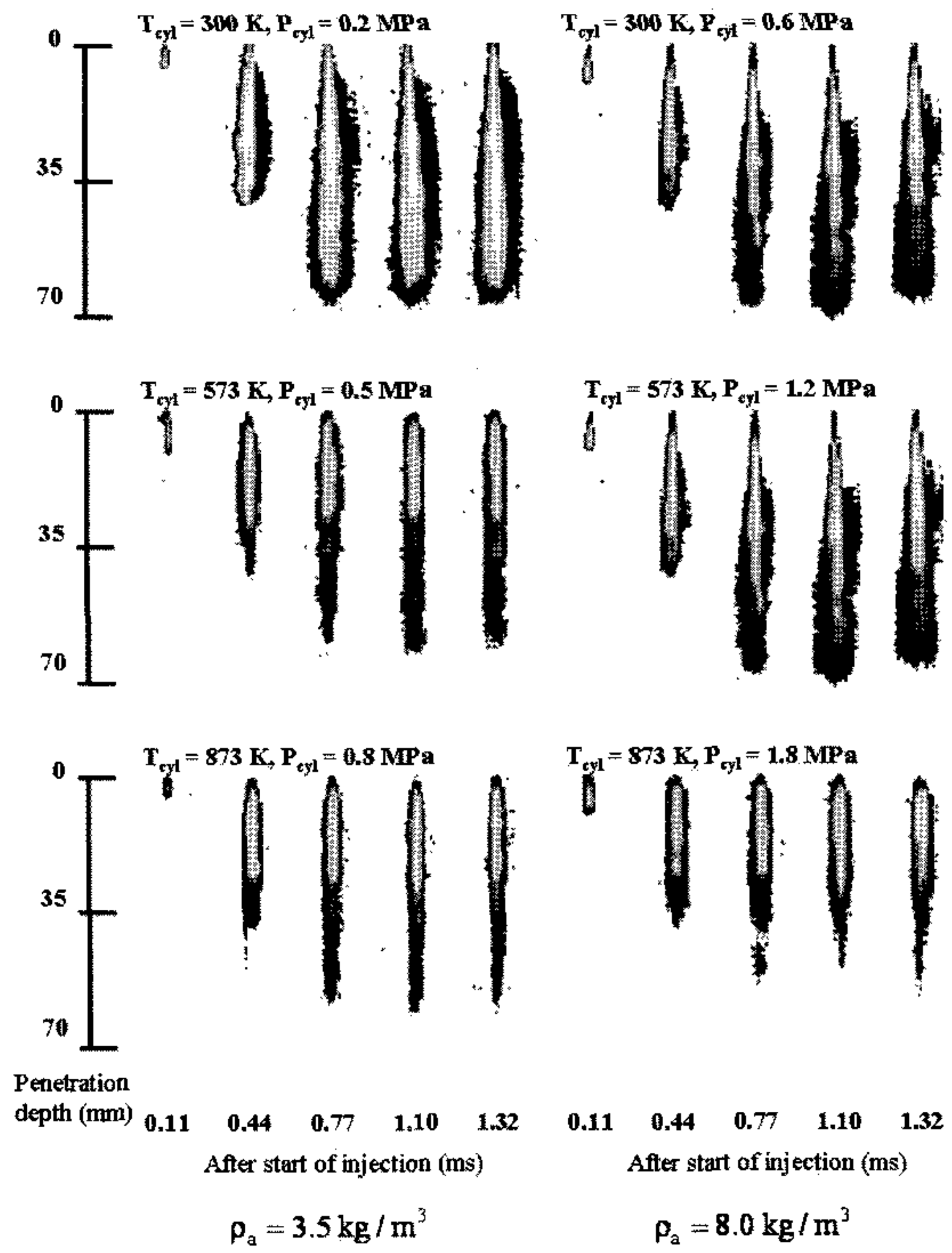


Fig. 8 Spray images of n-dodecane (diesel) fuel

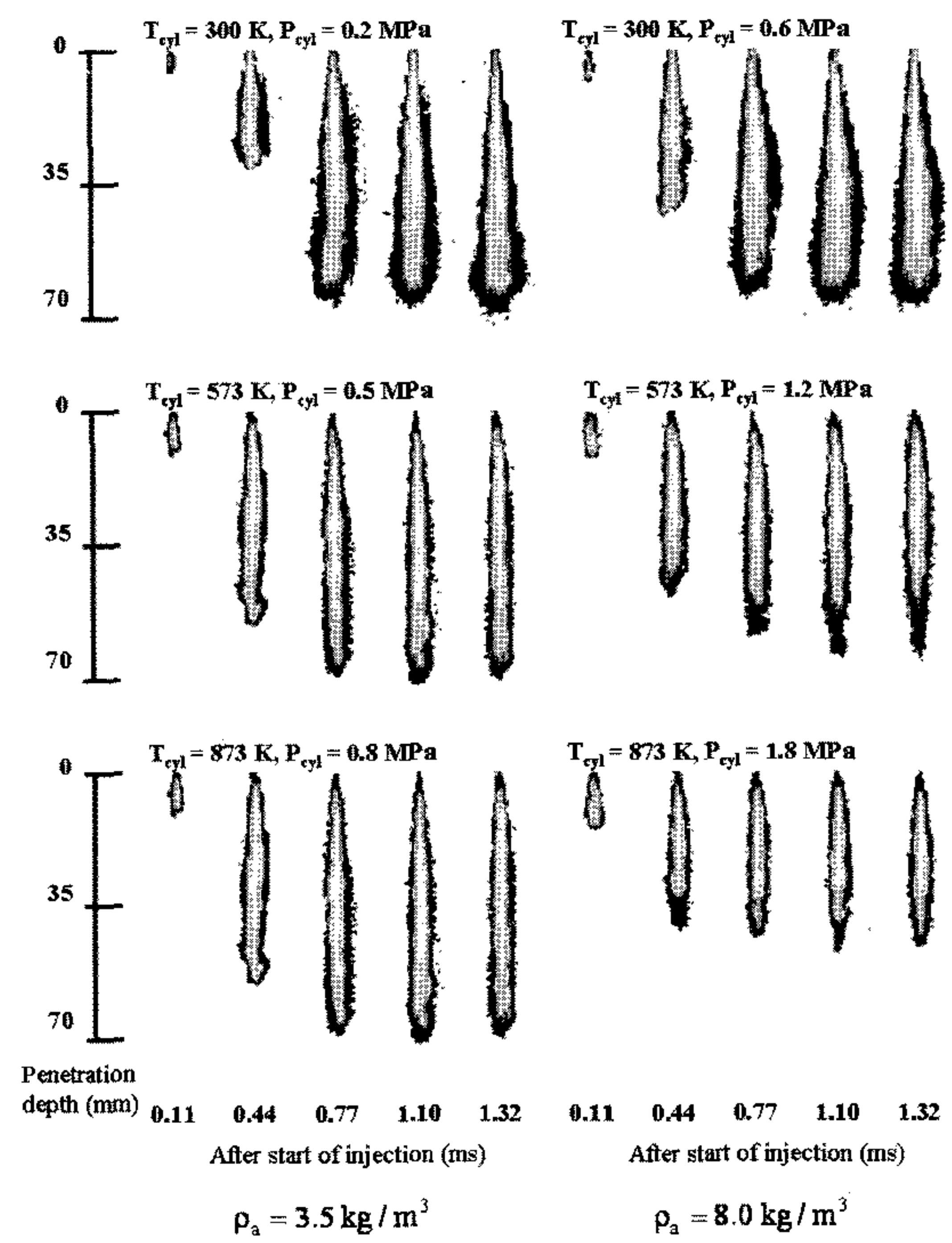
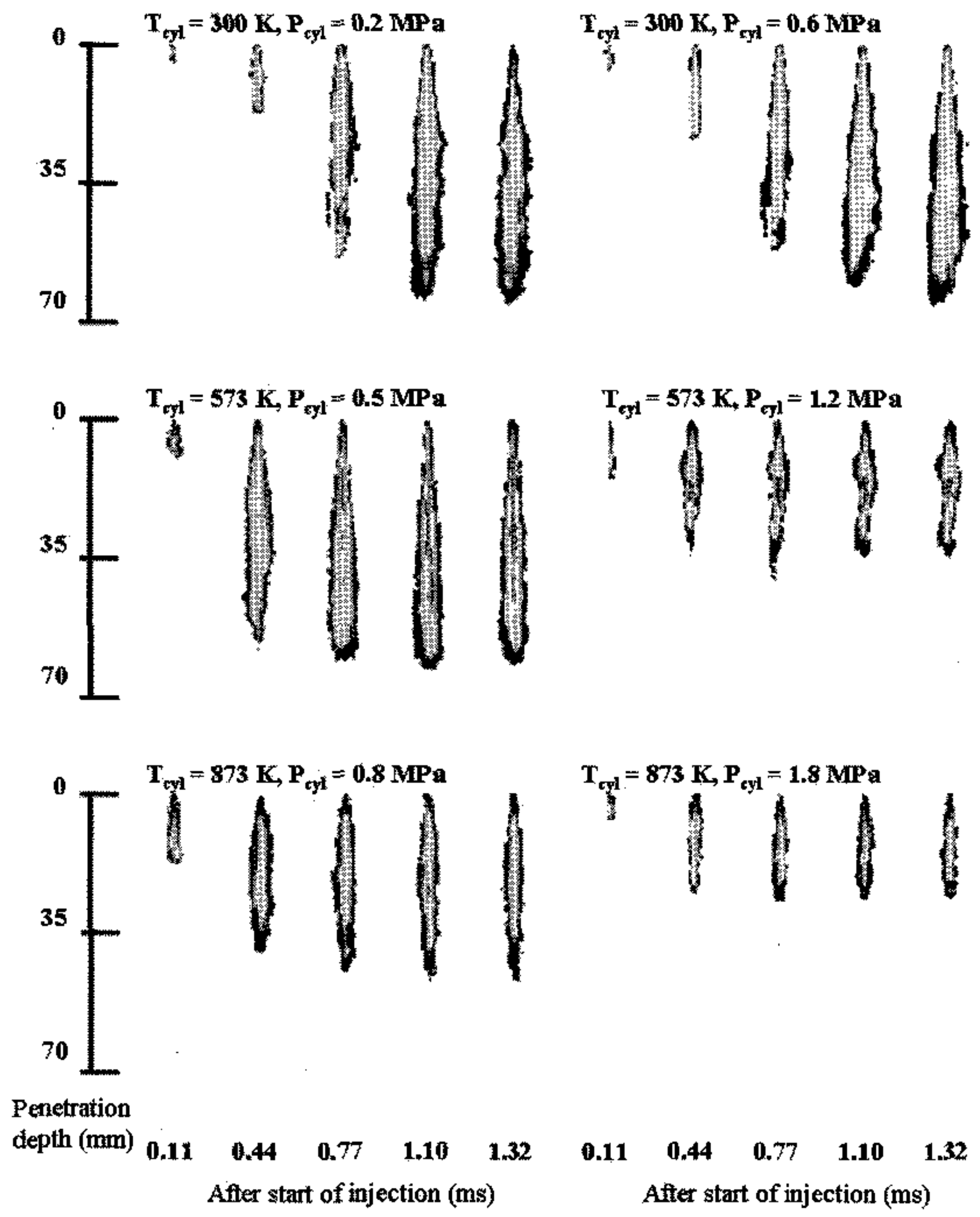


Fig. 9 Spray images of DME fuel



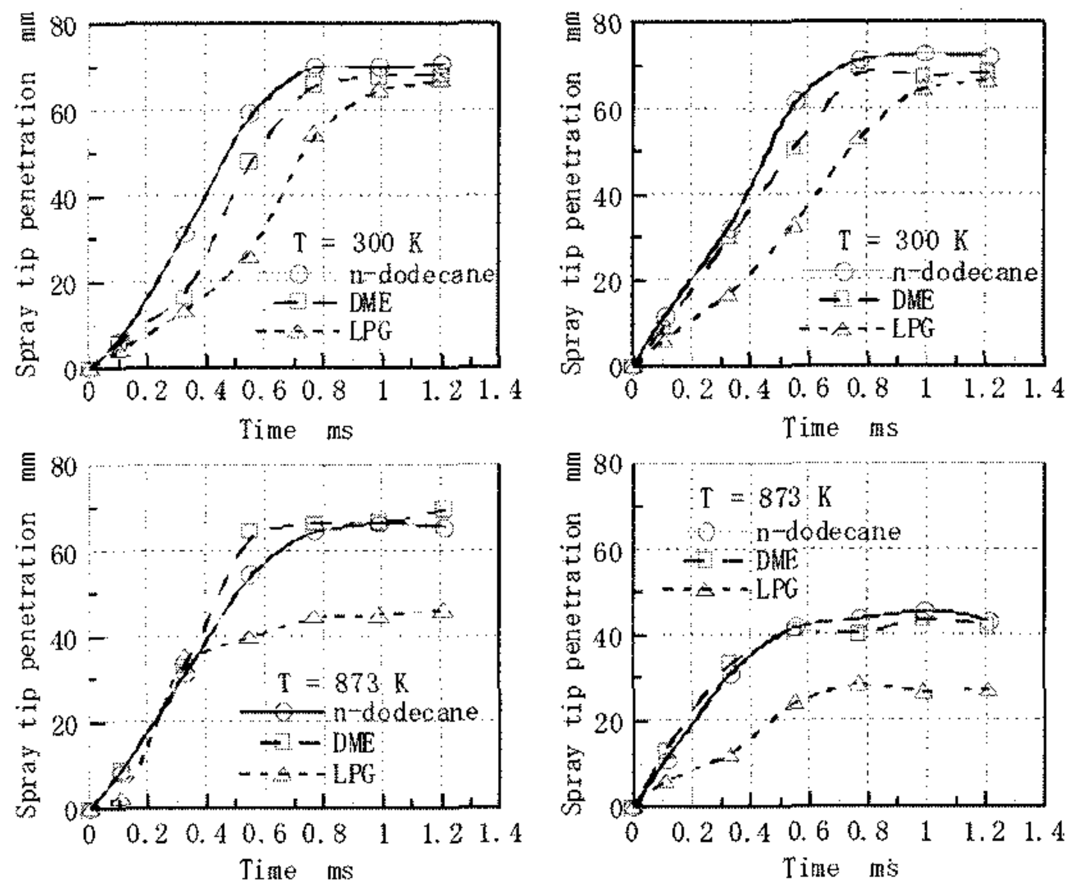
$\rho_a = 3.5 kg/m^3$ $\rho_a = 8.0 kg/m^3$

Fig. 10 Spray images of LPG fuel

3.2 Various fuel spray under high temperature and pressure conditions

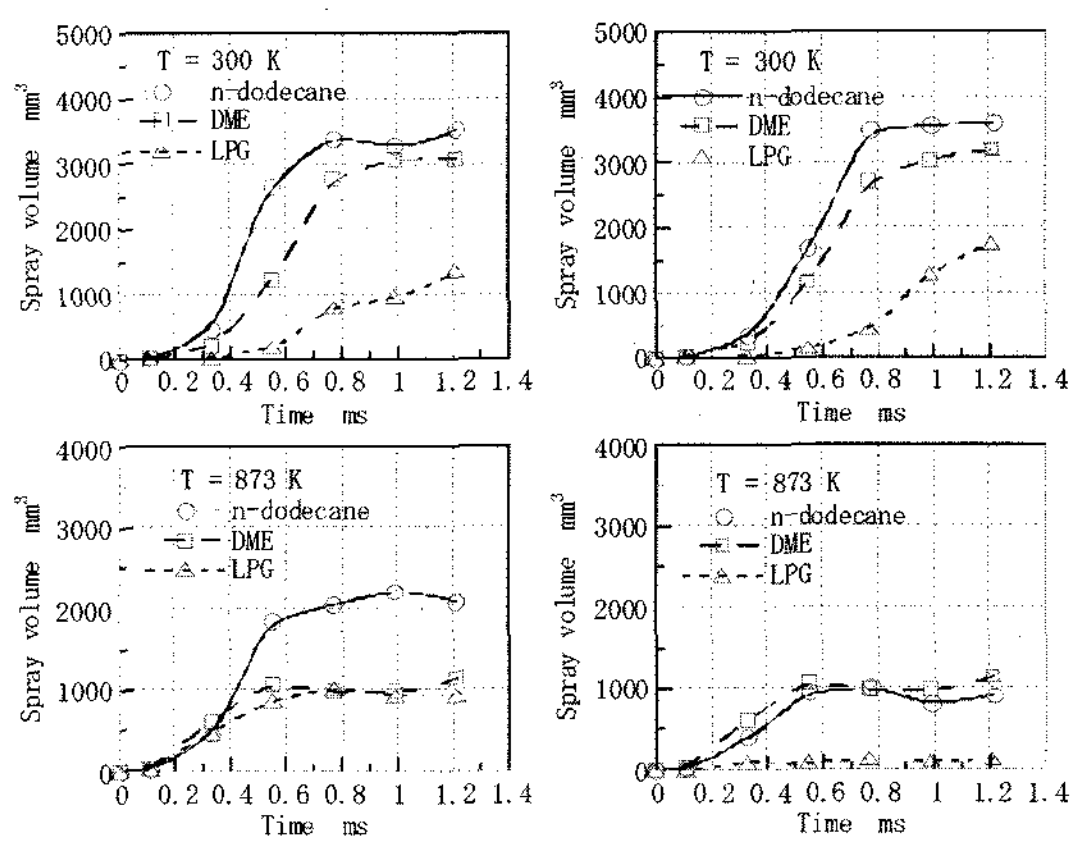
Figure 8, 9 and 10 show Mie-scattered liquid spray images from a high speed video camera grabbed for n-dodecane, DME and LPG fuels. In n-dodecane spray, images become short and thin with increased ambient density. It is easily understood that the breakup and evaporation of the spray is promoted when ambient density is higher. On the other hand, at the same ambient density, the breakup process is rarely influenced by temperature and pressure, because changes in shear force between fuel and air are dominant in fuel breakup. However, under same density with higher ambient temperature condition, evaporation process is promoted and liquid phase fuel decreases. In both DME and LPG sprays, the same tendency was observed that the liquid phase decreases with higher ambient temperature even ambient density was constant.

In other words, the penetration and the width of the spray become longer and wider, respectively as the ambient density become lower. It is noticeable



(ρ = 3.5 kg/m³) (ρ = 8.0 kg/m³)

Fig. 11 Penetration characteristics of various fuel spray



(ρ = 3.5 kg/m³) (ρ = 8.0 kg/m³)

Fig. 12 Volume characteristics of various fuel spray

that, under high temperature and pressure conditions, the reduction of liquid phase region of both alternative fuels is larger than that of n-dodecane, reference fuels to diesel.

Through these figures, it can be seen that LPG spray is strongly influenced on ambient temperature and pressure. The maximum penetration of DME and LPG are short with 45, 30 mm respectively under the condition of 8.0 kg/m³ density and 873 K ambient temperature. The fact that propane, one of the major species of LPG, has lower boiling point is a major reason to explain the characteristics. Evaporation of LPG becomes faster due to the higher concentration of easily boiling species, resulting in the shorter penetration compared with n-dodecane and

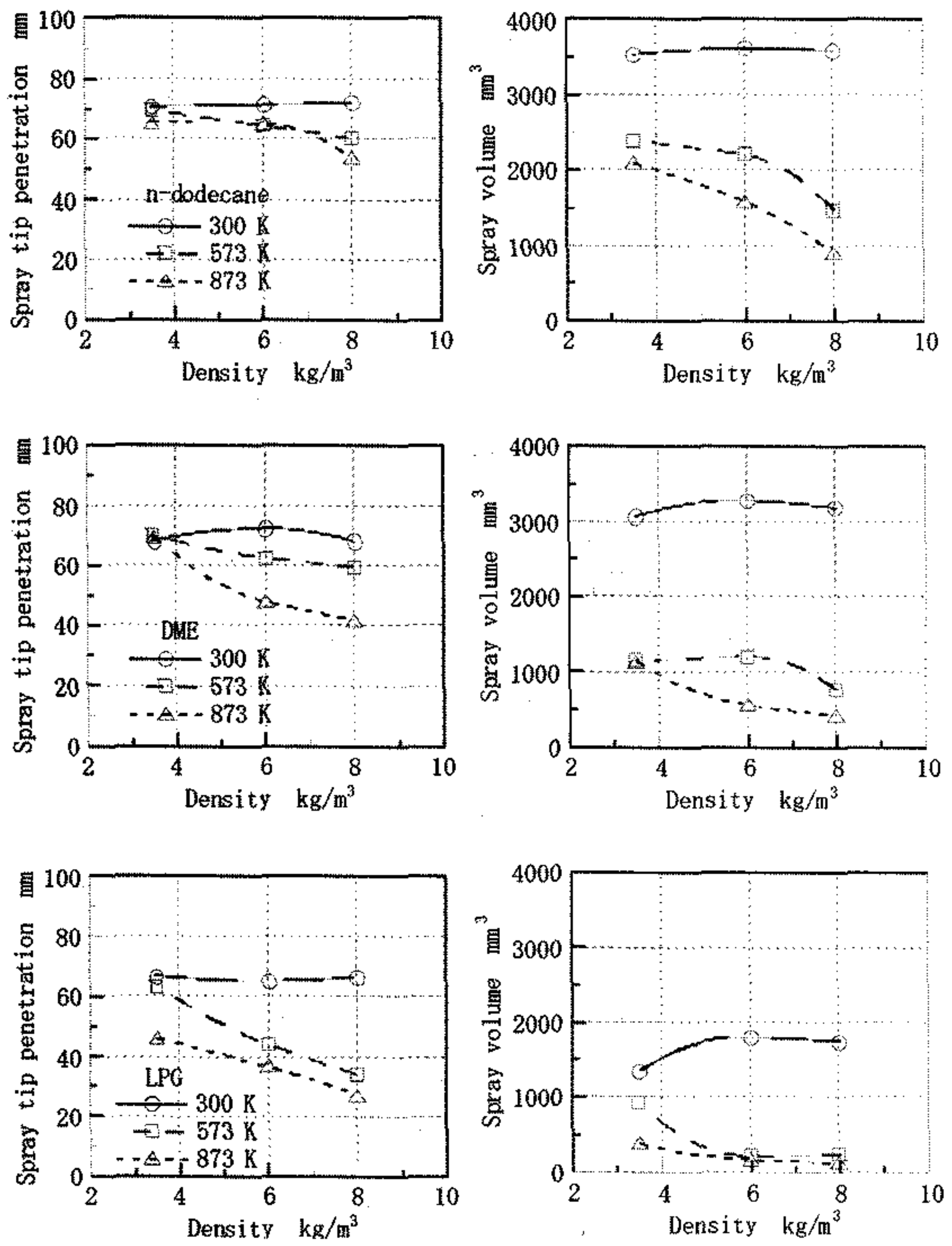


Fig. 13 Effect of ambient density on penetration and volume of spray (at 1.32 ms after start of injection)

DME. It is necessary to research the evaporation process of the spray of two-component fuel such as LPG in detail hereafter.

The maximum penetration and spray volume of fuels under each ambient condition are shown in Figure 11 and 12, respectively. It is clear to show the trend that the liquid phase of the early period spray decreases more remarkably when boiling point of the fuel is lower in comparison with n-dodecane fuel in low density and temperature. It is explained that atomization and evaporation are carried out actively by flash boiling characteristic in such a low-temperature and low-pressure condition. However, the characteristic of alternative fuels spray is similar to that of diesel spray under the high-temperature and high-pressure conditions such as near top dead center of an engine.

Figure 13 indicates the effect of ambient density on penetration and volume of spray. The more ambient density is increases, the more shear force between spray and ambient air is exerted that atomization is promoted and penetration becomes shorter. However, near room temperature, changes in penetration and volume of the DME and LPG spray is not so strong as n-dodecane. Furthermore, decrease in penetration and spray volume of LPG is more remarkable in comparison of DME under high density condition. This phenomenon also supports that evaporation of LPG is more promoted. As mentioned above, the formation of the mixture and the spray structure of alternative fuels are influenced strongly by the ambient temperature. Therefore, it is suggested that the injection timing and duration become an important factor in an engine design when alternative fuel is applied to direct injection strategy.

4. Conclusion

A constant-volume chamber was used to reconstruct the high-temperature and high-pressure conditions of diesel engines. Under various conditions, spray characteristics of some representative fuels and DME were tested. These results will be helpful to understand spray phenomena of DME and to design DME-dedicated combustion chamber. The following results were obtained.

1) At the nozzle exit, the injected DME spray expands rapidly in the early stage of the spray because a flash-boiling phenomenon is created by reduced pressure.

2) Injected DME fuel is atomized and evaporated actively because of its physical properties even the evaporation is markedly affected by ambient conditions. Higher injection pressure is more crucial to improve fuel-air mixing by virtue of increased spray volume rather than spray angle when DME fuel is applied.

3) Penetration of early period decreases remarkably because evaporation of DME becomes prosperous by the influence of flash boiling phenomenon under the condition of the low temperature and pressure compared with n-dodecane. The spray of LPG receives the influence of ambient pressure and temperature largely more that of DME.

4) The penetration of DME and LPG spray receive the influence of temperature more largely in comparison under lower density condition because of the higher amount of easily boiling species in those fuels.

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