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# An Analysis on Structure of Impinging and Free Diesel Spray with Exciplex Fluorescence Method in High Temperature and Pressure Field

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Because an injected spray development process consists of impinging and free spray in the diesel engine, it is needed to analyze the impinging spray and free spray, simultaneously, in order to study the diesel spray behavior. To dominate combustion characteristics in diesel engine is interaction between injected fuel and ambient gas, that is, process of mixture formation. Also it is very important to analyze liquid and vapor phases of injected fuel on the investigation of mixing process, respectively and simultaneously. Therefore, in this study, the behavior characteristics of the liquid phase and the vapor phase of diesel spray was studied by using exciplex fluorescence method in high temperature and injection pressure field. Finally, it can be confirmed that the distribution of vapor concentration is more uniform in the case of the high injection than in that of the low injection pressure.

**Key Words :** Diesel Engine, Impinging and Free Diesel Spray, Exciplex Fluorescence Method, ECD-U2

## Nomenclature

$H$ : Spray Height
$L$ : Liquid-phase length
$R$ : Spray Radius
$U$ : Velocity

**Greek symbols**

$\rho$ : Density of Ambient Gas

**Subscripts**

$a$ : Ambient gas
$f$ : Fuel
$liq$ : Liquid Phase
$vap$ : Vapor Phase
$w$ : Wall

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## 1. Introduction

Diesel engine is widely used in transport field and industrial power plant, because the diesel engine has high economical efficiency, thermal efficiency, generating power compared with other internal combustion engines. However, the diesel engine has a few problems, that is, emissions especially $NO_X$ and PM (particulate matter) exhausted from diesel engine. Then diesel engine has facing with crisis of emission reduction. Hence, in order to reduce the harmful emission from diesel engine, it is must need to analyze organized structure and mixture formation process of diesel spray, because the process is controlled by the interaction of injected fuel and ambient gas, which dominates emission generation mechanism from the diesel engine. Numerous research of diesel spray behavior have been studied, however, it is few to research simultaneously the spray structure and mixture formation process in the free and impinging spray with phase change. Injected fuel from an injector is turned liquid to vapor phase by the heat transfer of ambient without regard to impinging and free spray in actual diesel engine. Therefore aim of this study is making clear the structure and mixture formation process of diesel spray by visualization technique of exciplex fluorescence that can take liquid and vapor phase images of impinging and free spray simultaneously and respectively in high temperature and pressure field. The study results concerned with impinging and free spray in diesel engine have already reported (Katsura et al., 1989 ; Melton et al., 1993 ; Choi et al., 2002 ; Lee et al, 2003). However the study of Katsura et al.(1989) was non-reaction diesel spray which is diesel impinging spray on experimental conditions of a flat and cold wall and the laser light extinction method was used in the study as visualization method. Also the evaporative diesel spray study using with the exciplex fluorescence method was executed by Melton et al.(1983) in conditions of a flat and hot wall. The injection pressure of Melton et al.(1983) was 17.8 MPa. In the study of the Dan et al.(1997), the structure analysis of diesel spray had investigated by means of laser light scattering and transmission method in non-reaction free spray. In this study, the quenching effect of high density and temperature on intensity of excited fluorescent beam is corrected by Lambert-Beer's law. This study using a constant volume chamber was carried out in the quiescent atmosphere of nitrogen gas. As the reference fuel of the gas oil, the n-tridecane was used.

## 2. Experimental Apparatus and Procedure

The experimental apparatus and the procedure are described here. The n-tridecane as the reference fuel oil of JIS second class gas oil was injected into the quiescent atmosphere of nitrogen gas through a single hole injector. 9% in mass of naphthalene and 1% in that of TMPD (N, N,N',N' tetramethyl-p-phenylene diamine) were mixed in n-tridecane to obtain the fluorescent emissions of the liquid and vapor phases. The mixing of TMPD with n-tridecane was carried out in the nitrogen atmosphere to prevent the oxidation of TMPD. The ambient temperature and the ambient pressure were kept constant at 700 K and 2.55 MPa. Such temperature and the pressure are the limit of generation of the normal combustion observed in a small sized high-speed CI engine. The high pressure injection system proposed by Denso Co., Ltd. (ECD-U2 system). The system was consisted of the three main sections, namely, high pressure supply pump, common rail and electric control circuit (ECU) for control injector and them. The diameter and the length of nozzle were 0.2 mm and 1.0 mm, respectively. The injection pressure was changed in the range from 22 MPa to 112 MPa. The injection duration was varied in the range from 2.82 msec. to 1.24 msec. related to the change in the injection pressure, because the quantity of the fuel injected was kept as constant at 12.0 mg.

Table1 shows the summarized experimental conditions.

Figure 1 is a schematic diagram of the optical system used in this study. The light source was the third harmonic of an Nd : YAG laser at 355 nm (power 60 mJ/pulse, pulse width : 8 nsec., maximum frequency : 10 Hz, beam diameter : 6.4 mm, beam shape : doughnut type). A thin sheet of laser light is formed when the light is passing through three sets of cylindrical lenses made of quartz. The width and the thickness of the light

**Table 1** Experimental conditions

| | | |
|---|---|---|
| Injection nozzle | Type : Hole nozzle DLL-p | |
| | Diameter of hole $d_n$ [mm] | 0.2 |
| | Length of hole $L_m$ [mm] | 1.0 |
| Ambient gas | | $N_2$ gas |
| Ambient temperature $T_a$ [K] | | 700 |
| Ambient pressure $p_a$ [MPa] | | 2.55 |
| Ambient density $\rho_a$ [kg/m$^3$] | | 12.3 |
| Injection pressure $p_{inj}$ [MPa] | | 22, 42, 72, 112 |
| Injection quantity $Q_{inj}$ [mg] | | 12.0 |
| Injection duration $t_{inj}$ [ms] | | 2.82, 1.98, 1.54, 1.24 |
| Impngement distance $Z_w$ [mm] | | 40 (Impinging spray) |

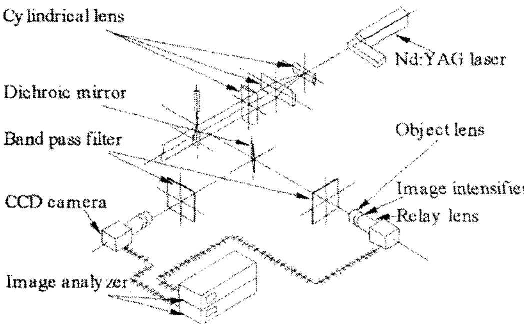



**Fig. 1** Schematic diagram of laser sheet optical system and photography system

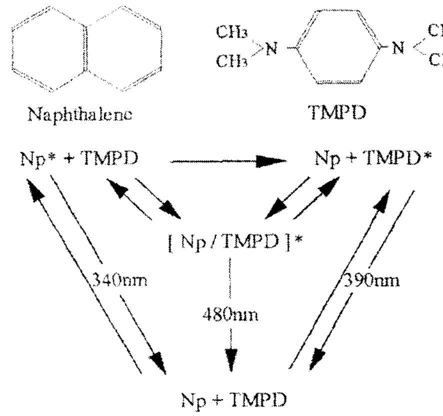



**Fig. 2** Schematic summary of naphthalene and TMPD exciplex system

were 50 mm and 0.2 mm, respectively. The uniformity of the intensity of laser light was confirmed by calculation experiments. The lenses have high transmissivity in the ultraviolet region by their material and they were given the coating of non-reflection, as a consequence, the energy of laser light hardly damped. Then a thin sheet of laser light was coming to the section of an impinging and free diesel spray and the fluorescence emissions from both vapor and liquid phases were generated. The spectra separation of fluorescence emissions from both phases was made by the system of a dichroic mirror and two sets of band pass filters. The dichroic mirror was a type of the blue reflection and its wavelength of 50% refection was 470 nm. The center wavelength of the band pass filter for liquid and vapor phases widths were 390 nm and 532 nm and their half widths were 19 nm and 2 nm, respectively. In the exciplex fluorescent system of naphthalene and TMPD, the exciplex corresponding to the information of the liquid phase generates its fluorescence at 480 nm. However, the selected wavelength of the liquid phase was different from this wavelength. This is the reason why the fluorescent intensity from this phase is very stronger than that from the vapor phase (Senda et al., 1996). The emissions from both phases are increased in their luminosity by the image intensifiers after they are coming through the objective lenses. Thereafter, they are going to the relay lenses and are taken by the CCD cameras (number of pixels : 540×480, S/N : 50 dB). The photographing speed of CCD camera is 1/30 $\mu$sec. and the life-time of fluorescent emissions of TMPD and exciplex are ranged from 1 nsec. to $10^3$ nsec.. This experiment was carried out in a perfect photo darkroom. Consequently, the frozen image at the incidence of the laser light could be caught by this CCD camera. The spatial resolution is about 0.1 mm/pixel. The signals from images of both phases were transferred into the image analyzers and were processed by the A/D conversion (resolution : 8 bits) to obtain the image of 256 gradation.

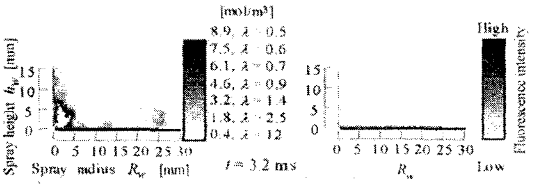
In Fig.2, a schematic summary of the photophysics of the naphthalene/TMPD exciplex fluorescence system is shown (Melton et al., 1983).

## 3. Results and Discussion

### 3.1 Impinging spray

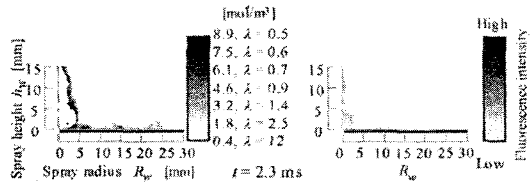
Figure 3 shows the history of distributions of the vapor concentration $\lambda$ mol/m$^3$ and liquid fluorescence intensity. The Figs. 3(a) $p_{inj}=22$ MPa, 3(b) $p_{inj}=42$ MPa are the cases of the low injection pressure and 3(c) $p_{inj}=72$ MPa, 3(d) $p_{inj}=112$ MPa are those of the high injection pressure. Each image was measured in the range from wall surface to 15 mm. The impingement distance $Z_w$ is 40 mm in the all cases. Provided that, in the vicinity of the spray center, the fluorescence intensity exceeds sensitivity of CCD camera, because there is in liquid phase. The vapor concentration of mixture was increased in accordance with increasing injection pressure on the wall. The vapor concentration on the wall in the high pressure injection case is much leaner and its distribution is more uniform than that in the low injection pressure. The other distinguished fact is the liquid phase that dose not shows the rebounding development in the case of the high injection pressure at the wall. The width of liquid phase is much thinner than that in the low injection pressure. The reason for these tendencies are because the momentum at the nozzle exit is larger, the atomization process is more vigorous before impingement and the momentum at the impingement point is larger in the case of the high injection pressure than those in that of the low injection pressure. After impinging on wall surface, the vapor phase grown up to the radial direction on wall surface, besides that grown up to the upper direction of the wall surface in the spray tip region. The reason for such shown tendency is stagnation of spray tip by drag force of ambient gas at the wall region. Spray tip region was pushed and revolved to upper direction by the continued vapor group with momentum. Also such tendency can obtain from other reaction and non-reaction impinging diesel spray.

Figures 4 and 5 show the temporal changes in



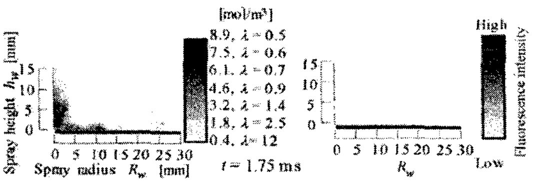

(a) Vapor concentration (b) Liquid fluorescence intensity

(a) $p_{inj}$=22 [MPa]



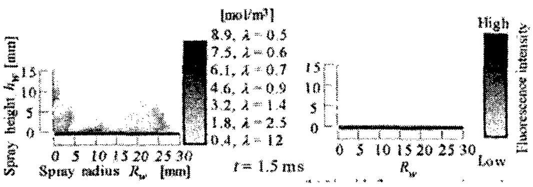

(a) Vapor concentration (b) Liquid fluorescence intensity

(b) $p_{inj}$=42 [MPa]




(a) Vapor concentration (b) Liquid fluorescence intensity

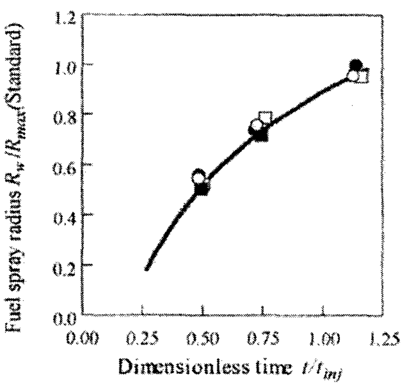
(c) $p_{inj}$=72 [MPa]



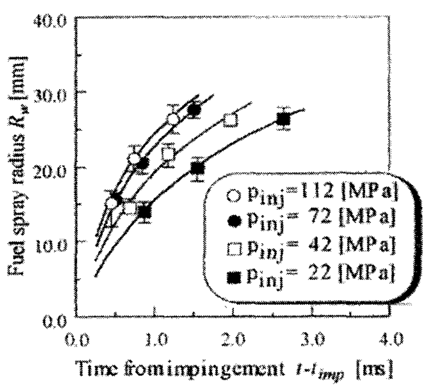

(a) Vapor concentration (b) Liquid fluorescence intensity

(d) $p_{inj}$=112 [MPa]

**Fig. 3** Temporal change in distributions of the vapor concentration and liquid fluorescence intensity with exciplex fluorescence method ($Q_{inj}$=12.0 [mg], $\rho_a$=12.3 [kg/m³], $T_w$=55 [K], $Z_w$=40 [mm])




(a)




(b)

**Fig. 4** Temporal change in spray radius $R_w$, Parameter : Injection pressure $p_{inj}$ ($Q_{inj}$=12.0 [mg], $T_w$=550 [K], $\rho_a$=12.3 [kg/m³], $Z_w$=40 [mm])

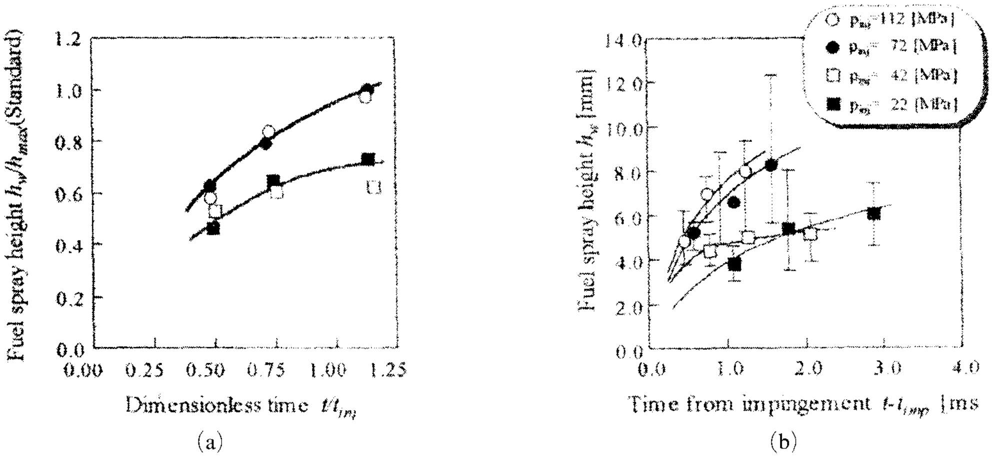



**Fig. 5** Temporal change in spray height $h_w$, Parameter : Injection pressure $p_{inj}$ ($Q_{inj}$=12.0 [mg], $T_w$=550 [K], $\rho_a$=12.3 [kg/m$^3$], $Z_w$=40 [mm])

the spray radius ($R_w$) and the spray height ($h_w$) taken by visualized images of the fuel vapor phase after impinging on the wall. The y-axis of Figs. 4(a) and 5(a) show dimensionless spray radius and height by maximum value of spray radius and height in each experiment condition, and x-axes of the Figs. express dimensionless time from injection start by injection duration in each injection pressure, respectively. Figs. 4(b) and 5(b) show spray radius and height in y-axis, also x-axis is time after spray impinging on wall surface. From the results of Figs. 4(b) and 5(b) it could be speculated that the development of spray tip and the upper direction at the wall surface is much rapider according to increase of injection pressure. The spray radius can express a curved line when those results were arranged by dimensionless time. As a consequence, it was found that the spray development at the radial direction depended on the injection pressure $p_{inj}$ as well as the injected fuel mass in the spray.

### 3.2 Free spray

Figure 6 shows the two-dimensional fluorescence intensity images of the free spray with injection pressure change obtained by exciplex fluorescence method. In the figures, the (i), (ii) are the vapor and liquid phase of the injected fuel, respectively. The photographing timing was set when the injected fuel mass was almost the same in the each injection pressure, that is, when $t/t_{inj}$ was almost equal at each injection pressure. In the each figure, the liquid phase width is wider than the vapor phase one in the upper region of the spray, because photographing the vapor phase, a large aperture was selected in order to reduce the halation region due to the TMPD monomer fluorescence of liquid phase. On the other hand, when photographing the liquid phase, the small aperture was selected in the optical system to capture the liquid phase region of low concentration. Consequently, the liquid phase image is larger than the vapor phase image. In the Fig. 6, the low vapor luminance of the upstream spray spreads in the radial direction. With increasing injection pressure, the atomization and evaporation of the diesel spray were promoted by the increase of shear force caused by the interaction between the injected fuel and ambient gas. The fluorescence intensity of the liquid phase rapidly decreases in the vicinity of $Z$=40 mm from the nozzle tip. Also, in each condition of injection pressure, the meandering flow of the mainstream region starts on the spray radial direction at the distance of $Z$=40 mm. As a result, it could be speculated that the transition point at which the momentum of the spray interchanges with the ambient gas is, approximately, in the vicinity of $Z$=40 mm. Consequently, the vortex flow of the ambient gas dominates spray development in the

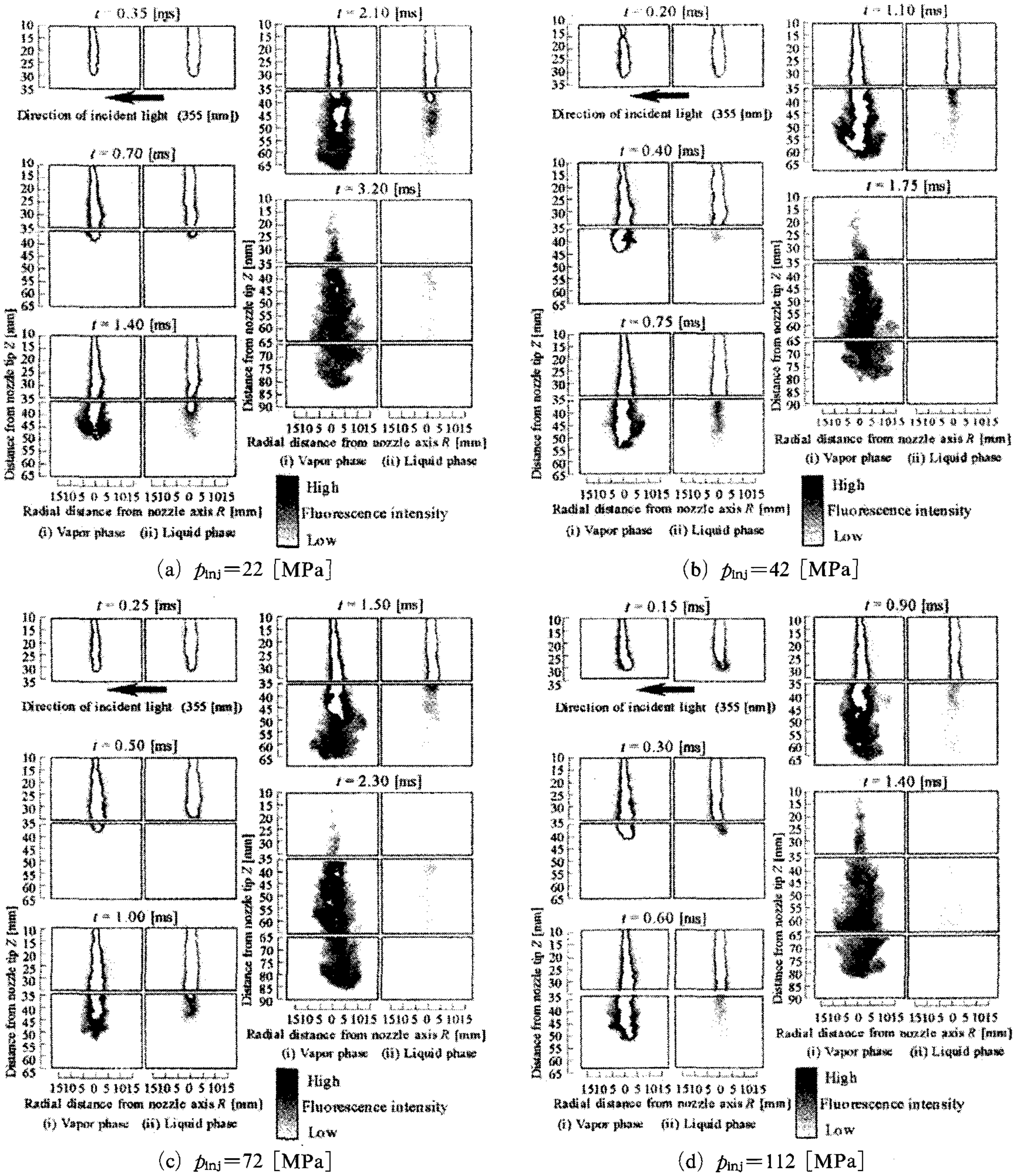
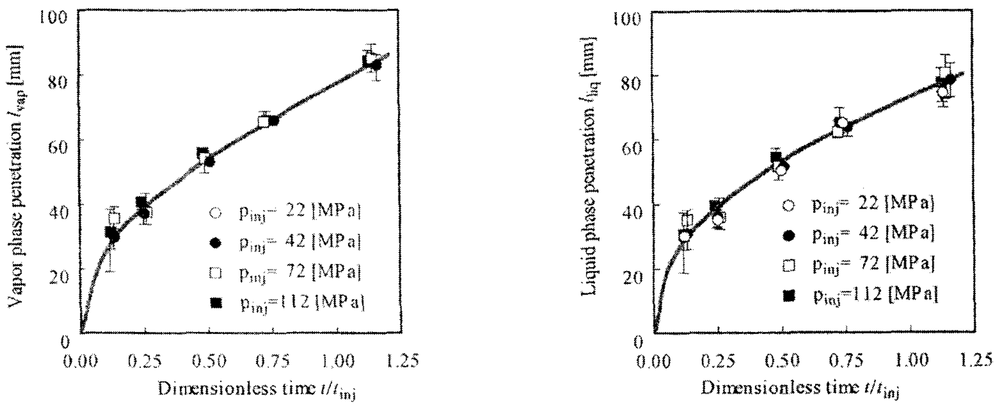



**Fig. 6** Temporal change in free spray image with exciplex fluorescence method ($Q_{inj}$=12.0 [mg], $\rho_a$=12.3 [kg/m$^3$], $T_w$=700 [K])

latter part of the injection.

Figure 7 shows the temporal change in spray tip penetration of the vapor and liquid phase. In the figure, the horizontal axis is the non-dimensional time from the start of injection with each injection duration. The spray tip penetration of liquid phase $l_{liq}$ is determined by the overall fluorescence intensity region in the images. Then, the penetrations at each injection pressure is compared with the same mass of injected fuel, because the profile of the injection rate with time is almost rectangular in this study. The spray tip




(a) Vapor phase penetration $l_{vap}$ (b) Liquid phase penetratin $l_{liq}$

**Fig. 7** Temporal change in penetration of vapor and liquid phase (parameter : injection pressure)

penetrations of the vapor and the liquid phase were plotted in the same curve as shown in Fig. 7. Consequently, they are independent of injection pressure in non-dimensional time. As a result, with the same mass of fuel in the injected spray, the spray tip penetration does not depend on injection pressure, the same as a non-reaction diesel spray (Dan et al., 1996). As shown in Fig. 7, the penetration of liquid and vapor phase increase with elapsing time. However, a convergence tendency of the liquid phase length value, as shown in the other experiments using evaporative spray (Espey et al., 1994, 1995, 1997 ; Hodges et al., 1991 ; Baritaud et al., 1994), could not be observed. Hence, we conducted tuning for images of liquid phase.

Figure 8 shows the liquid phase length $l_{lc}$ versus the elapsing dimensionless time. In this study, the liquid phase length $l_{lc}$ is defined by the spatial region where fluorescence intensity marked by 255 gradation of the spray's center decreases to 10% (230~255) of it value in each image. As shown in Fig. 8, the value of the liquid phase length is almost 38 mm in the curve. As a result, the liquid phase length as measured in Fig. 8 is equal to the liquid phase lengths of experiments (Espey et al., 1994, 1995, 1997 ; Hodges et al., 1991 ; Baritaud et al., 1994). Moreover, the behavior tendency of liquid phase was found to change at the start point of spray development in the radial direction as shown in Fig. 6. This means that the distance of 38 mm from nozzle exit

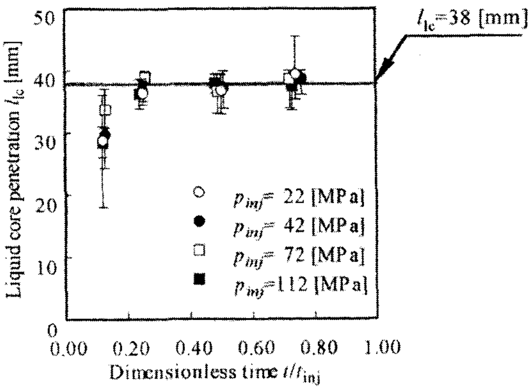



**Fig. 8** Temporal change in liquid core penetration (parameter : injection pressure)

corresponds to the end of momentum exchange from the liquid jet to the ambient gas in non-evaporating spray (Dan et al., 1997).

## 4. Conclusions

An experiment was performed for the evaporating diesel impinging and free spray in this study. Exciplex fluorescence method was used, which can simultaneously measure the vapor and liquid phase of evaporative diesel spray.

The following conclusions are drawn from this study.

(1) The degree of vapor distribution is more uniform in the case of the high injection pressure than in that of the low injection pressure in diesel impinging and free spray.

(2) In the case of the high injection pressure, the spray radius and the spray height of the vapor phase are larger than those in the case of low injection pressure at the wall of the impinging spray.

(3) With entraining ambient gas, the injected fuel is atomized with tearing of spray periphery by shearing action between injected fuel and ambient gas at vicinity of the nozzle hole of the free spray.

(4) In the case of the same mass of the injected fuel in the inner spray, the spray tip penetration of the free spray does not depend on the change of injection pressure.

(5) The liquid length of free diesel spray converges on a value regardless of the change of injection pressure. In this study, the value is close to 38 mm.

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