Characterization of an evaporating direct-injected gasoline spray using laser-induced exciplex fluorescence and particle image velocimetry techniques

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Abstract: The purpose of this study is to characterize an evaporating direct-injected (DI) gasoline spray from a high-pressure swirl injector using the laser-induced exciplex fluorescence (LIEF) technique and particle image velocimetry (PIV). A fluorobenzene/diethylmethylamine (DEMA) system was used as the exciplex-forming dopants. The behaviour of the liquid and vapour phases was analysed by image processing. For the analysis of vorticity inside the spray, droplet velocity data obtained by PIV were used. The experiments were performed at two ambient temperatures (293 and 473 K) and three different ambient pressures (0.1, 0.5 and 1.0 MPa). It was found that ambient temperature had a significant effect on the axial and radial growth of the liquid phase of the evaporating spray at atmospheric pressure while it had little effect under elevated pressures. Radial growth of the vapour phase of the evaporating spray was more dominant than axial growth under high temperature and pressure conditions. As the ambient pressure was elevated, the liquid phase of the spray transformed from a hollow cone to a solid cone of bell shape, while the vapour phase varied from a widespread distribution to a compact shape with a locally richer mixture. The evaporating spray could be divided into two spray regions from the analysis of vorticity and the distributions of liquid and vapour phases. The cone region (penetrations of 0.3–0.5) was mainly liquid phase and disappeared rapidly at the end of injection. The mixing region contained the active interaction between entrained air and fuel vapour.

Keywords: direct-injected gasoline spray, laser-induced exciplex fluorescence, particle image velocimetry, cone region, mixing region

NOTATION

A	area	L_m	length of the mesh
A_o	optical constant	N, n	number of pixels
CCD	charge coupled device	PDA	phase Doppler anemometry
C	vapour concentration	PIV	particle image velocimetry
DEMA	diethylmethylamine	P_a	ambient pressure
DISI	direct injection spark ignition	S	spread
I	intensity	t	time after injection start
K	rate coefficient	T_a	ambient temperature
K_{eq}	quenching coefficient	u	radial velocity of the droplet
LIEF	laser-induced exciplex fluorescence	w	axial velocity of the droplet
L	spray penetration	x	radial direction
		z	axial direction
		Z	axial distance from the nozzle tip
		ϵ	molar absorption coefficient
		ρ	density of the fuel
		ω_y	vorticity

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Subscripts

a	ambient
ave	average
<i>i</i>	<i>i</i> th mesh
l	liquid phase
v	vapour phase
max	maximum value
min	minimum value

1 INTRODUCTION

Attention has been drawn to the direct injection spark ignition (DISI) engine owing to various potential advantages such as fuel economy and the reduction in pollutant emissions. The mixing of fuel and air inside the cylinder of DISI engines permits precise control of the amount of fuel burned and of the injection timing [1–3]. Fuel injection, therefore, is one of the major parameters realizing the advantages of DISI engines. The characteristics of evaporating direct-injected (DI) gasoline sprays need to be investigated since fuel injection for a stratified mixture under compression stroke can improve fuel economy [4, 5]. Furthermore, fuel injection for a stoichiometric mixture under intake stroke can also minimize emission problems by utilizing a catalytic converter [6, 7]. These concepts could be realized in two DISI systems: stratified charge and homogeneous charge systems. Accordingly, it is important to characterize the evaporating spray in terms of the behaviour of the liquid and vapour phases under elevated temperature and pressure conditions.

Previous work [8–10] on non-evaporating sprays has been performed to investigate spray patterns, droplet size and spray structures using the imaging technique, phase Doppler anemometry (PDA) and particle image velocimetry (PIV). Evers [8] reported that a transient swirl spray could be divided into four regions, namely the leading edge, the cone, the trailing edge and the vortex cloud. Preussner *et al.* [9] suggested the basic mechanisms of the interaction between droplets and air over a hollow cone swirl spray. Wicker *et al.* [10] provided a more complete understanding of the spray structures and the evolution of the instantaneous, transient direct-injected gasoline spray by digital PIV. Studies on evaporating sprays have been mostly concentrated on diesel sprays. However, the evaporation processes of DI gasoline sprays are quite different from those of diesel sprays because they have a different spray formation. Han and Reitz [11] computed the internal structure of the evaporating DI gasoline spray. The computed results indicate that the fuel vapour exhibits a solid cone distribution in the spray region while the liquid fuel keeps a hollow cone structure. Ipp *et al.* [12] experimentally investigated the spray formation and qualitatively provided the distribution of liquid and vapour phases using

the laser-induced exciplex fluorescence (LIEF) technique. Choi *et al.* [13] quantitatively investigated the structures and evaporating characteristics under elevated temperature and atmospheric pressure using the LIEF technique and PDA. There is, however, little quantitative information on the evaporating spray experimentally obtained at elevated pressures.

The main objective of this study is to characterize the evaporating spray with the quantitative behaviour of the liquid and vapour phases, which could provide validation data for computational studies. To separate the liquid and vapour phases in evaporating sprays, LIEF was employed as the main measurement technique. Particle image velocimetry was also used for the analysis of vortex flow and classification of the spray regions. The images of liquid and vapour sprays were analysed by an image processing method. The location and size of maximum vorticity was calculated from the velocity data. On the basis of these experimental results, the evaporating spray was divided into two spray regions: the cone and mixing regions. In addition, the vapour concentration in the mixing region was quantified through a calibration procedure.

2 EXPERIMENTAL SET-UP AND CONDITIONS

Figure 1 shows the experimental set-up used to investigate evaporating DI gasoline sprays using the LIEF and PIV techniques. A spray chamber was designed to analyse the behaviour and structure of the evaporating sprays under high pressure and temperature. The possible maximum ambient temperature and pressure were 600 K and 3 MPa respectively. Nitrogen was used as the ambient gas to prevent the quenching of liquid and vapour fluorescence by oxygen. To maintain the uniformity of temperature distribution within the test area of the spray, nitrogen flow passed through inside the spray chamber at a velocity of less than 0.1 m/s. The spray chamber was purged with nitrogen and then evacuated to remove exciplex-forming dopants from previous measurements completely. Different ambient temperatures (293 and 473 K) and pressures (0.1, 0.5 and 1.0 MPa) were set to study non-evaporating and evaporating sprays.

The high fuel pressures were generated using a compressed nitrogen supply and a hydraulic accumulator to avoid pressure fluctuations in the fuel rail. The injector was a high-pressure swirl injector with 70° cone angle. The injection pressure was 5.1 MPa as rail pressure. The injection duration and injection quantity were 2 ms and 15 mg respectively, which correspond to the fuel requirement at medium speed and load in typical DISI engines.

The spray images were digitally recorded with an intensified CCD camera providing 640 × 480 pixel images at a resolution of 8 bits. The imaging control system

Fig. 1 Experimental set-up for LIEF and PIV measurement

consists of a personal computer (PC) with an image grabber, a shutter controller and a pulse generator.

The exciplex-forming dopants fluorobenzene and DEMA in a non-fluorescing base fuel of hexane were employed. The boiling points of these components are 358, 338 and 342 K, and the solution composition was 2, 9 and 89 vol%. The fourth harmonic of the Nd:YAG laser at 266 nm with a duration of 7 ns and a laser power of 50 mJ/pulse was used to excite the dopants from the sprays. The laser beam was formed into a thin light sheet approximately 60 mm high and 400 μ m thick. The fluorescence was caught through filters of 300 ± 25 nm for vapour phase and 400 ± 25 nm for liquid phase. An additional sharp cut-off filter was used to eliminate the incident light at 266 nm.

The velocity measurement of the sprays was performed using a two-frame PIV system. The PIV system consists of a two-head Nd:YAG laser, a CCD camera with a resolution of 1024×1024 pixels, a synchronizer and a PC, as shown in Fig. 1. The PIV system was controlled by a synchronizer which was triggered by the digital pulse/delay generator. Atomized liquid droplets were employed as tracer particles. The interrogation window size was 32×32 pixels.

Figure 2 shows the injector tip and the spray pattern. A nozzle tip of the injector is shown on the left-hand side of Fig. 2. To make a stratified mixture, more fuel vapour needs to move towards a spark plug in DISI engines with a wall-guided configuration. Thus, an asymmetric spray pattern is more advantageous to form a richer mixture near the spark plug. The injector can make an asymmetric spray pattern by a taper cut of the nozzle tip without changing any other components [14]. The spray axis has a slope of 5° from the vertical axis in an anticlockwise direction owing to the geometry of the nozzle tip. A toroidal vortex appears at the outer skirt of the spray periphery, which is a typical characteristic of high-pressure swirl sprays [8]. The size of the field of view was 40×50 mm.

Fig. 2 Nozzle tip configuration and spray pattern

3 EXPERIMENTAL RESULTS

3.1 Spray development

Figure 3 shows the evolution of the evaporating DI gasoline spray at ambient pressures, P_a , of 0.1 and 1.0 MPa and an ambient temperature, T_a , of 473 K. To compare the liquid and vapour phases easily, the left- and the right-hand sides illustrate liquid and vapour phases respectively. Comparing Figs 3a with b, ambient pressure has a significant effect on the spray pattern. For lower ambient pressure, most of the liquid phase of the spray kept a hollow cone shape. However, the vapour phase was distributed in the whole spray region and had a solid cone structure. These distributions of both phases were also simulated by a computational approach [11]. A vortex generated by entrained air, which is also to be observed in PIV results, appeared in the outer edge of the liquid spray. In addition, the vapour phase followed this vortex flow. For higher ambient pressure, both phases were crushed by elevated ambient density. The front edge of the spray rolled up largely owing to the vortex flow and higher ambient density. Accordingly, vortex flow of large scale was formed. The vapour phase also followed this flow and resulted in higher fluorescence intensity.

Fig. 3 Evolution of the evaporating sprays at different ambient pressures

The temporal changes in penetrations of liquid and vapour sprays are shown in Fig. 4 at different ambient temperatures and pressures. The penetrations, L_l and L_v , were defined as the length from the nozzle tip to the front edge of the liquid and vapour sprays respectively. For an ambient pressure of 0.1 MPa, penetration data after 2.25 ms could not be acquired since the spray was out of the field of view. Ambient pressure had a significant effect on the spray penetration up to 0.5 MPa at room temperature. However, the effect was reduced owing to active vaporization at the elevated ambient temperature. This indicates that ambient temperature has a more dominant effect on the growth of liquid spray. At a higher temperature of 473 K under atmospheric pressure (0.1 MPa), the penetration decreased 1.75 ms after the start of injection owing to vaporization of atomized droplets. From this result and spray images, the time for the full development of the spray is around 1.75 ms. The other coordinate represents the penetration ratio of vapour spray to liquid, L_v/L_l . If this ratio is

Fig. 4 Spray penetration of the liquid phase and the penetration ratio of vapour phase to liquid

unity, the axial growth of the vapour and liquid sprays is equal. At the early stage of injection ($t \leq 0.5$ ms), the ratio was less than unity, which means that the growth of the liquid spray is dominant. The ratio became greater than unity with time. However, the ratio kept a value of about 1.2 after 2 ms at an ambient pressure above 0.5 MPa. This indicates that both liquid and vapour sprays developed axially at a constant rate after the full development time under higher ambient pressures.

Figure 5 shows the temporal change in widths for liquid and vapour sprays with different ambient temperatures and pressures. The growth tendency of width was similar to the case of penetration. In addition, the full development time of the liquid spray was also around 1.75 ms. The right-hand axis, as shown in Fig. 4, represents the width ratio of vapour spray to liquid, W_v/W_l . Regardless of the ambient density, the ratio kept increasing even after 1.75 ms. This indicates that the radial growth of vapour phase is much more dominant than that of liquid phase under higher ambient temperature and pressure.

Fig. 5 Spray width of the liquid phase and the width ratio of vapour phase to liquid

3.2 Distribution of the liquid and vapour phases

To compare the distribution of liquid and vapour sprays, the boundaries of the sprays were detected by image processing, as shown in Fig. 6. In addition, the area of each spray region was calculated and normalized by the maximum area for both sprays. The distributions were quite different with respect to ambient pressure, as shown in Fig. 6a. The sprays in the liquid phase maintained their momentum and went through downwards within their spray angle at an ambient pressure of 0.1 MPa. At 1.0 MPa, the liquid sprays showed a bell shape and the front edge of the sprays rolled up owing to the higher ambient density. Vapour sprays at 0.1 MPa diffused towards the radial direction owing to vaporization of atomized droplets under lower ambient density. At higher ambient pressure (1.0 MPa), fuel vapour was compressed and distributed in a narrow spray region. Figure 6b shows the relative area, $A/A_{\max}$, for liquid and vapour sprays with time after the start of injection. The spray area, A , was calculated by image processing at each injection moment, which was then normalized by the maximum spray area, $A_{\max}$, for both phases throughout the injection. This parameter represents the change in spatial distribution of liquid and vapour sprays. For an ambient pressure of 0.1 MPa, the relative area for liquid spray increased after the start of injection and remained constant from 1.0 to 2.0 ms. This indicates that the development of liquid spray during this period becomes slow owing to the vaporization of atomized droplets. No value was defined at 3.0 ms since liquid phase disappeared after 2.5 ms. On the other hand, the relative area for the vapour spray continued to increase. For an ambient pressure of 1.0 MPa, the spray development in each phase was observed to be different from the case of 0.1 MPa. The relative area of liquid spray increased slowly throughout the injection. This implies that the

stronger drag force due to higher ambient density prevents liquid spray from growing and confines it to a narrow spray region. Accordingly, this effect results in a slow increase in the relative area of liquid spray even after the end of injection. The relative area of vapour spray was, however, increased inspite of the increase in the relative area of liquid spray compared with that for the case of 0.1 MPa. At 2 ms, which is just after the time for full development of the spray, the differences between the liquid and vapour spray areas were 48.5 per cent for 0.1 MPa and 22.7 per cent for 1.0 MPa. This indicates that the vapour phase only occupies about 50 per cent of the overall spray region for 0.1 MPa and about 20 per cent for 1.0 MPa.

To investigate the distribution of liquid and vapour sprays along the spray axis and predict the change in relative fuel concentration, a spread, S , and a radial intensity, I , were newly defined. The spread is the sum of radial pixels, N , occupying the spray at each axial position. The radial intensity represents averaged fluorescence intensity with respect to the radial width at each axial position. The two parameters S and I are given by the following expressions and represent the spray distribution and fuel concentration respectively

$$S = \sum_{i=1}^n N_i \quad (1)$$

$$I = \frac{\sum_{i=1}^n I_i}{S} \quad (2)$$

The relative spread along the spray axis is shown in Fig. 7. The spread was normalized by the maximum value, $S_{\max}$, for both phases, defined as the relative spread, $S/S_{\max}$. The spray penetrations in the liquid and vapour phases were also normalized by their maximum values, defined as the relative penetrations, which are used as the vertical axis. For an ambient pressure of

Fig. 6 Traces and distribution area of the liquid and vapour phases at 473 K: (a) overlapped traces of liquid and vapour phases; (b) relative area of liquid and vapour region

Fig. 7 Temporal change in the spread ratio for the liquid and vapour phases

0.1 MPa, the relative spread of the liquid and vapour phases had a triangular shape and a nearly constant slope from the nozzle tip to a relative penetration of 0.2. Its shape for both phases was maintained with time, and the relative spread of the liquid phase disappeared after 2.25 ms. However, the relative spread of each phase was obviously distinguished in the rest of the relative penetration. In other words, the liquid phase became narrower and disappeared along the axis, while the vapour phase had a triangular shape and expanded rapidly. This indicates that the development region of the vapour phase was formed by the atomization and vaporization of fuel droplets. For an ambient pressure of 1.0 MPa, as shown in Fig. 7b, the liquid phase had a triangular shape and was distributed in the upper spray region compared with the case of lower ambient density, while the vapour phase had a bell shape and moved downwards. In addition, protrusion at the outer edge of the liquid phase on account of the vortex flow was observed.

Figure 8 shows the relative radial intensities with respect to the relative penetrations for the liquid and vapour phases. The radial intensity was normalized by the maximum value, $I_{\max}$, for both phases, defined as the

relative intensity. The vertical axis is the same as in Fig. 7. For an ambient pressure of 0.1 MPa, the liquid phase had very high relative radial intensity in the region ranging from the nozzle tip to a relative penetration of 0.15. This means that most liquid fuel is concentrated near the nozzle tip. In contrast to the liquid phase, the relative radial intensity of the vapour phase had a nearly uniform value of 0.2. Compared with Fig. 7, the vapour phase at lower ambient density showed a lean and wide distribution. For an ambient pressure of 1.0 MPa, the liquid phase had a similar tendency to that at lower ambient pressure, while the vapour phase had very high intensity downstream of the spray. This indicates that the vapour phase diffuses widely and is distributed uniformly under lower ambient density, while the vapour phase forms a narrow, high-concentration layer under higher ambient density.

3.3 Spray structures

The distribution and intensity of the liquid and vapour phases made it possible to divide the spray region into two regions, namely the cone and mixing regions. To set the boundary of the two spray regions, the vortex

Fig. 8 Temporal change in the intensity ratio for the liquid and vapour phases

flow of a non-evaporating spray was characterized. Vorticity, ω_y , was calculated from velocity data obtained by PIV

$$\omega_y = \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x} \quad (3)$$

where

- u = radial velocity of the droplet (m/s)
- w = axial velocity of the droplet (m/s)
- x = radial direction
- z = axial direction

Figure 9 shows the location and size of maximum vorticity inside the spray. Spray penetration and width were normalized by their maximum values at each ambient condition, defined as the relative penetration and width respectively. The vorticity became greater with time. For a lower ambient pressure, the vorticity was relatively small and widely distributed. For a higher ambient pressure, it was greater and located in a narrow spray region. The location of the vorticity could provide the transition point to the mixing region, where entrained air and atomized droplets interacted and

Fig. 9 Location and size of maximum vorticity

actively formed a mixture. Its axial locations ranged from relative penetrations of 0.3–0.5 at both pressures. Radial locations ranged from relative widths of 0.2–0.5 for an ambient pressure of 0.1 MPa and were fixed at around 0.21 for 1.0 MPa.

From the distributions and intensity of the liquid and vapour phases and the characterization of vortex flow, the evaporating gasoline DI spray could be divided into two spray regions: cone and mixing regions, as shown in Fig. 10. The flow characteristics of the evaporating spray were greatly changed with relative penetrations of 0.3–0.5, as shown in Fig. 9. In the cone region, the spray mainly consists of liquid phase, where liquid and vapour phases nearly keep a conical shape regardless of ambient density throughout the injection. In the mixing region, the distribution characteristics of the liquid and vapour phases are determined by the vortex flow and the effect of ambient density becomes significant.

3.4 Quantification of fuel vapour

When the sectional area of the spray is divided into a mesh of n pixels with the same length L along the incident laser light sheet direction, the intensity of the laser light sheet, I_i , at the i th mesh is given by the equation

$$I_i = I_0 \exp\left(-\varepsilon L_m \sum_{i=1}^n C_i\right) \quad (4)$$

where

- I_0 = intensity of the incident laser light sheet ($\text{J}/\text{m}^2 \text{ s}$)
- ε = molar absorption coefficient for the wavelength of the incident laser light sheet ($\text{m}^3/\text{mol m}$)
- L_m = length of the mesh (m)
- n = number of pixels
- C_i = molar concentration of fluorescence material at the i th mesh (mol/m^3)

The fluorescence intensity at the i th mesh, I_{vi} is given by the following equation, from which the concentration of fluorescence material at the i th mesh can be obtained

$$I_{vi} = A_o K I_0 \exp\left(-\varepsilon L \sum_{i=1}^n C_{i-1}\right) \{1 - \exp(-\varepsilon C_i L_m)\} \quad (5)$$

where

A_o = proportional constant associated with the optical systems

K = rate coefficient for the excited transition

Figure 11 shows the change in the fluorescence intensity ratio with different vapour concentration ratios at ambient pressures of 0.1 and 1.0 MPa and an ambient temperature of 473 K, where both quantities are normalized with the minimum intensity, $I_{v,\min}$, and minimum concentration, $C_{v,\min}$. In this figure, the solid line is the theoretical value from equation (5), and the dotted lines represent the experimental data obtained from the calibration test. The length of the mesh is $1.4 \times 10^{-4} \text{ m}$ and $\varepsilon = 73.56 \text{ m}^3/(\text{mol m})$ for an incident laser light sheet of 266 nm. The difference between the experimental and theoretical results in this figure seems to be due to the quenching effect of the vapour concentration. To correct this difference, the experimental value in Fig. 11 was subtracted from the theoretical value at each concentration ratio. Each subtracted value was normalized by its maximum value within the experimental range. These normalized values were defined as the quenching coefficient, K_{cq} , shown in Fig. 12. Thus, equation (5) should be transformed into

$$I_{vi} = A_o K K_{cq} I_0 \exp\left(-\varepsilon L \sum_{i=1}^n C_{i-1}\right) \times \{1 - \exp(-\varepsilon C_i L_m)\} \quad (6)$$

Temperature is also one of the quenching factors. To correct the quenching effects of temperature, the relation between the relative fluorescence intensity ratio and temperature was investigated. The result is shown in Fig. 13. The quantitative analysis scheme for vapour concentration provided by Senda *et al.* [15] was used. The spray images were then converted into concentration values (mol/m^3).

To quantify the concentration of vapour phase exactly, the mixing region, where there is little absorption and

Fig. 10 Classification of the cone and mixing regions for evaporating DI gasoline sprays

Fig. 11 Calibration curves for the vapour phase ($T_a = 473 \text{ K}$)

Fig. 12 Concentration quenching coefficient ($T_a = 473$ K)

Fig. 13 Relative fluorescence intensity of the vapour phase with different ambient pressures

scattering of laser light by liquid droplets, was selected as the quantification region. Figures 14a and b show two-dimensional distributions of vapour concentration at 473 K under 0.1 and 1.0 MPa respectively. Quantified

images were presented for 1.5–3 ms after the start of injection. For a lower ambient pressure, a vortex structure was developed by momentum exchange between the swirl momentum of the spray and the air entrainment, as explained in Fig. 9. Fine droplets of less than $5 \mu\text{m}$ diameter [13] lose their momentum and follow the reverse ambient gas flow. Vapour phase also follows this gas flow, and consequently a vortex structure develops. From the concentration distribution, a higher concentration due to vaporization of many fine droplets appears 2 ms after the start of injection. In addition, the concentration fields continue to become uniform owing to mixing of droplets and ambient gas. For a higher ambient pressure, the vapour region was compressed and rolled up owing to the higher ambient density. A high vapour concentration ($\geq 12 \text{ mol/m}^3$) was formed inside the spray. This indicates that the vortex flow by entrained air and higher ambient density results in a higher vapour concentration within the spray.

4 CONCLUSIONS

Evaporating direct-injected gasoline sprays from a swirl injector have been characterized as a function of ambient temperature and pressure using the laser-induced exciplex fluorescence technique and particle image velocimetry. The main findings can be summarized as follows:

1. Ambient temperature had a significant effect on the axial and radial growth of the liquid phase of the evaporating spray at atmospheric pressure, while it had little effect under elevated pressures.
2. Radial growth of the vapour phase of the evaporating spray was more dominant than axial growth under elevated pressure conditions.
3. As the ambient pressure was elevated, the liquid phase of the spray transformed from a hollow cone to a

Fig. 14 Quantified vapour concentration fields with different ambient pressures

- solid cone of bell shape, while the vapour phase varied from a widespread distribution to a compact shape with a locally richer mixture.
4. The evaporating spray could be divided into two spray regions from the analysis of vorticity and the distributions of the liquid and vapour phases. The cone region (penetrations of 0.3–0.5) had mainly liquid phase and disappeared rapidly at the end of injection. The mixing region included active interaction between entrained air and fuel vapour.
 5. As the ambient pressure was varied from 0.1 to 1.0 MPa, the vapour concentration at the maximum vorticity location became about 2 times richer.

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