

Characteristics of Evaporating Diesel Spray: A Comparison of Laser Measurements and Empirical/Theoretical Predictions

Jian Gao

University of Wisconsin-Madison

Keiya Nishida, Seoksu Moon and Yuhei Matsumoto

University of Hiroshima

Copyright © 2009 SAE International

ABSTRACT

The objective of the paper is to characterize the diesel spray under the ambient conditions relevant for direct injection (D.I.) diesel engines. The particular emphasis is on the comparisons between laser measurements and predictions by empirical correlations and theoretical analyses. The ultraviolet-visible laser absorption-scattering (LAS) imaging technique is employed to quantitatively determine the spray/mixture properties of the diesel spray injected by a hole-type injector, in terms of spray tip penetration and spatial concentration distributions of liquid and vapor phase. The structure of evaporating spray is obtained and analyzed. Based on the penetration correlations in the literature, a non-dimensional analysis of the spray tip penetration data is carried out. The results indicate that a self-similar state of the evaporating fuel spray is achieved. The measured mean fuel concentration distribution along the spray axis is in good agreement with the predicted one by the quasi-steady momentum theory for the spray with constant mass flow rate.

INTRODUCTION

Fuel injection plays a vital role in the combustion performance of diesel engines. A better understanding of the fuel injection process is necessary to improve the engine performance, efficiency and emissions in direct injection (D.I.) diesel engines. Experimentally and

theoretically, detailed studies of diesel spray [1, 2] and gas jet [3, 4] have enabled to understand various aspects of mixture formation and air entrainment. However, most of them are limited to non-evaporative situations. Since the spray is injected into the high-density high temperature in-cylinder environment, apparently, evaporating diesel sprays have to be explored.

As vapor and liquid droplets exist concurrently in evaporating diesel spray, the quantitative measurement becomes rather complicated. Over the past several decades, many diagnostic methods have been developed in attempts to make such measurements. Shadowgraph and Schlieren photography are two of the earliest available optical diagnostics; these were originally applied to observe the structure of the evaporating diesel spray qualitatively [5-7]. Holography is considered the unique way to gather three-dimensional information on a fuel spray by utilizing the interference of laser light to record spray information. It has shown the potentials for providing the droplet sizing, velocity, concentration and temperature distributions inside a fuel spray [8, 9], but it is constrained to measurements at moderate ambient temperature/density and relatively low vapor concentration conditions due to the noise interference. Raman spectroscopy was proposed for a single-point or line-imaging measurement of local fuel/air ratio in a diesel combustion chamber [10-12]. However, Raman scattering is a very weak process and requires careful signal-to-noise consideration. And it

is a quite time-consuming work when Raman spectroscopy is applied to the whole spray region. Planar laser Rayleigh scattering (PLRS) is often employed for quantitative vapor phase equivalence ratio measurements at low gas density [13-15]. Especially, PLRS vapor-fuel measurements in an evaporating liquid-fuel spray require that strong elastic scattering from liquid droplets be suppressed. In other words, PLRS is inherently not suitable to measure fuel vapor concentration in the presence of liquid droplets. The laser induced EXCIPLEX fluorescence (LIEF) technique should be particularly mentioned, because it is widely used to determine both vapor and liquid phase concentrations simultaneously in this field [16-20]. Nevertheless, difficulties are usually encountered in this measurement such as fluorescence quenching by oxygen and cross-talk between monomer (vapor) fluorescence and exciplex (liquid) fluorescence due to an overlap in the emission spectra. In addition, the quantitative application of LIEF to the evaporating sprays in a high-temperature environment is difficult, because the fluorescence depends greatly on the temperature when temperature exceeds 500K [18].

The dual-wavelength laser absorption-scattering (LAS) technique is based on the principle of the fuel vapor absorption at one wavelength and the droplets scattering at another wavelength. Based on Lambert-Beer's law and light scattering theory, the vapor and liquid phase concentrations can be simultaneously quantified through transmission measurements at the two wavelengths. LAS technique was initially proposed by Chraplyvy [21], and later the infrared LAS technique was applied to measure the vapor mole fraction, vapor flux and droplet density in a steady iso-octane spray by some researchers [22, 23]. However, the infrared extinction is usually strongly temperature-dependent, which incurs errors when the local temperature distribution is unknown. It is also easily influenced by water vapor in the ambient gas and the heat-radiation from the heating system in the case of high-temperature experiments. Differing from the infrared LAS technique, the ultraviolet-visible (UV-Vis) LAS technique, adopting the ultraviolet and visible wavelengths as the absorbing and transparent wavelength respectively, was developed by Suzuki and Nishida [24], and subsequently improved by Zhang and Nishida [25, 26]. The UV-Vis LAS technique has advantages of high signal-to-noise ratio and exemption from the interference of water in the ambient gas and the radiation from heating system. In addition, UV and Vis laser beams can be emitted by the same laser simultaneously, which facilitates the implement of the measurements. Thus, the UV-Vis LAS technique is regarded as a promising approach for quantitative and simultaneous measurements on the concentration distributions of vapor/liquid phases in evaporating fuel sprays.

In this paper, in order to characterize the evaporating diesel spray, imaging was carried out in a high-pressure and high-temperature constant volume vessel providing the thermodynamic conditions similar to those of a diesel engine. By means of the UV-Vis LAS technique, the spray and mixture properties of the evaporating diesel spray were obtained in terms of spray tip penetration, liquid phase penetration and concentration distributions of vapor and liquid phase. The results obtained have been compared with those achieved following a theoretical analysis or an empirical prediction.

The paper is structured in four main sections. First, an introduction to the principle of UV-Vis LAS technique is presented. The experimental facilities and conditions are described in the second section. Next, LAS results on spray tip penetration and liquid phase penetration are presented and analyzed. Finally, in section four an analysis of fuel concentration distribution is carried out.

PRINCIPLE-OF UV-VIS-LAS TECHNIQUE

The UV-Vis LAS technique consists of two measurements: a transmission measurement of visible light to detect the droplets optical thickness at the transparent wavelength (532nm) and a transmission measurement of ultraviolet light to determine the joint optical thickness of vapor and droplets at the absorbing wavelength (266nm). The total line-of-sight extinction of the absorbing wavelength light passing through the spray is a result of droplets scattering, droplets absorption, and vapor absorption. The extinction of the transparent wavelength is only contributed by the droplets scattering. Especially, it has been experimentally testified that the extinction efficiency by the droplets tends to be identical at the two wavelengths previously [26]. Therefore, the line-of-sight optical thickness of vapor can be obtained by removing the optical thickness at 532nm from the optical thickness at 266nm. In order to get spatial distributions of the liquid and vapor phase concentrations from the line-of-sight optical thickness, an onion-peeling model is applied for the case of axisymmetric spray [27]. The vapor concentration can be then yielded according to the Lambert-Beer's law. Assuming a uniform Sauter mean diameter (SMD) in the spray and based on the light scattering theory, the liquid phase concentration is able to be attained from the droplets optical thickness with knowledge of total liquid mass. SMD in the entire fuel spray can be determined with either the Fraunhofer diffraction method or the light extinction measurement. In this work, measurement of SMD was measured by using the summation of the optical thickness due to the fuel droplets scattering in the entire extinction image of the spray [28]. The following equations are therefore obtained, which are treated as the fundamentals of the UV-Vis LAS technique



$$\bar{C}_v = \frac{1}{\varepsilon(\lambda_A)L} \left[\log\left(\frac{I_0}{I_t}\right)_{\lambda_A} - R \cdot \log\left(\frac{I_0}{I_t}\right)_{\lambda_T} \right] \quad (1)$$

$$\bar{C}_L = 2.303 \cdot \frac{2}{3L} \cdot \rho_f \cdot \frac{D_{32}}{R_k Q_{ext}} \cdot \log\left(\frac{I_0}{I_t}\right)_{\lambda_T} \quad (2)$$

$$D_{32} = \frac{0.63 R_k Q_{ext} M_{fl}}{\rho_f \sum_S \log\left(\frac{I_0}{I_t}\right)_{\lambda_T} \Delta S} \quad (3)$$

where $\bar{C}_v$ and $\bar{C}_L$ is the line-of-sight averaged vapor and liquid concentration in kg/m³ respectively; I_0 and I_t is the intensity of the incident laser light and laser light transmitted by the spray; D_{32} is Sauter mean diameter (SMD) in m; L is the optical path length in m; M_{fl} is the total mass of liquid fuel within the spray in kg; Q_{ext} is the mean extinction efficiency for a ploy-dispersed particle cloud; R is the ratio of the optical thickness of droplets at the two wavelengths, and $R \cdot 1$ in this study [26]; R_k is the correction factor of the extinction efficiency; λ_A and λ_T is the absorbing wavelength (266nm) and transparent wavelength (532nm) respectively; ρ_f is the liquid fuel density in kg/m³; ε_A is the molar absorption coefficient of fuel vapor at the absorbing wavelength in liter/(mol-cm); $\bullet S$ is the unit projection area in m².

In the UV-Vis LAS technique, the extinction efficiency (Q_{ext}), which is a function of the size parameter (D/λ), approaches a constant 2 when the diameter of the droplet is sufficiently large compared to the wavelength of the laser light (λ) [25, 29]. R_k is a function of the size parameter and the detection half-angle of a lens-pinhole detecting system and is less than one because the detection half-angle is not zero. R_k is set to be 0.6 in this work according to previous studies [25, 29]. The local mixture temperature is estimated by use of a temperature model based on thermal energy balancing [24, 30]. Then, utilizing the onion-peeling model again, the local mass concentration of ambient gas entrained is calculated by using the ideal gas equation under the assumption that total gas pressure in each calculation cell is composed of the partial pressures of fuel vapor and ambient gas entrained. The detailed description of the gas entrainment calculation is referred to in the previous publications [29, 31]. Therefore, the line-of-sight averaged equivalence ratios of vapor and liquid phases fuel ($\bar{\varphi}_v, \bar{\varphi}_L$) can be expressed as

$$\bar{\varphi}_v = \frac{AF_{stoich}}{AF_v} = \frac{AF_{stoich}}{(\bar{C}_a/\bar{C}_v)} \quad (4)$$

$$\bar{\varphi}_L = \frac{AF_{stoich}}{AF_L} = \frac{AF_{stoich}}{(1 - \bar{C}_L/\rho_f) \cdot (\bar{C}_a/\bar{C}_L)} \quad (5)$$

where AF_{stoich} is the stoichiometric air/fuel ratio; AF_v and AF_L is the actual air/fuel ratio of vapor and liquid phase fuel respectively, and $\bar{C}_a$ is mass concentration of ambient gas entrained in kg/m³.

Attention should be paid to the important assumption of the spray axisymmetry. In precise terms, the instantaneous spray is not one of strict axisymmetry. However, considering the complexity of the measurement system and the time cost for data processing, the deconvolution method called onion-peeling model which is only applicable for the axisymmetric spray was employed in the UV-Vis LAS technique. It has an equivalent precision compared with the computed tomographic transformation but the algorithm is much concise [26, 27]. In order to reduce the error caused by non-axisymmetry of the spray, the LAS images were determined by averaging four images which were taken at four times under the same experimental conditions. Averaging the optical thickness of the right half with that of the left half of the spray was also carried out before the deconvolution. In addition, the deconvolution method used in this study (onion-peeling model) has the problem that the error is cumulated near the spray axis, because the concentration is deduced from the envelope to the spray axis. Besides the above, other error factors in the LAS measurement include: 1) difference between light extinction by droplets irradiated by two wavelength laser lights due to the droplets absorption, especially in the liquid-dense region; 2) Besides droplets absorption, another major uncertainty for the LAS technique is that of beam-steering, which is inevitable at high-temperature, high-pressure conditions. Beam-steering can cause photons passing through high- (or low-) vapor regions of the spray to be mixed with photons passing through entirely different regions of the fuel spray and be recorded in the same pixel of the CCD. Multiple scattering from liquid can also have similar effects; 3) fluctuation and non-uniformity in the laser light intensity and 4) dark current and shot noise in the CCD pixels. The measurement accuracy of the LAS technique was verified through a series of experiments on the completely vaporized fuel spray. An in-depth discussion can be found in the previous publications [25, 26, 29, 31]. The results show that, in a region where the fuel vapor dominates, an error of approximately 5% in vapor measurement is incurred. However, the error can rise up to about 20% in the region where the droplets dominate.

EXPERIMENTAL FACILITIES AND CONDITIONS

The LAS measurements were implemented in a high temperature and high pressure constant volume vessel. A schematic diagram of the optical arrangement of the LAS imaging system, the fuel injection system and the constant volume vessel is shown in Fig. 1. A pulsed Nd:YAG laser (NY61-10, Continuum) was employed to provide the two wavelength beams, one at UV 266nm (absorbing wavelength, pulse energy: 50mJ) and the other at visible 532nm (transparent wavelength, pulse energy: 300mJ). The two beams were separated by a dichroic mirror, and were magnified into a diameter of 100mm by the beam expanders. And then they were combined again, transmitted the spray and separated again on the other side. In order to adjust the laser intensity and minimize the schlieren-like effect on the LAS image, a diffuser (Mitsubishi Rayon Corp., thickness of the film: 18μm) was set between the first dichroic mirror and the window of the vessel. Finally, the two beams were focused and captured by two CCD cameras (C4880, Hamamatsu Photonics). Spectral filters and apertures before the CCD cameras cut off the optical noises beyond the incident wavelength and scattered light beyond the optical half angle respectively. The sizes of the apertures for UV and visible beams were selected as 10mm and 20mm respectively to ensure the same correction factor of the extinction efficiency by droplets at the two wavelengths. The image acquisition and arithmetic processing were carried out by an IPLab (Spectrum Signal Analytics) image analysis system.

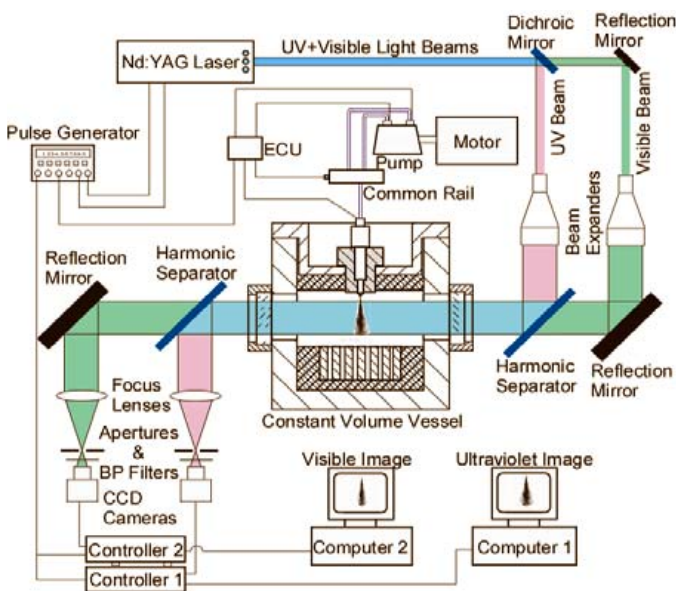


Fig.1 Schematic of LAS imaging system, fuel injection system and constant volume vessel

A common rail injection system (ECD U2-P, Denso Co.) was employed to inject the intermittent fuel spray into the high-pressure and high-temperature environment. The common rail pressure was set via an Engine Control Unit (ECU), and the maximum pressure could be up to 170MPa. A pulse generator (DG 535, Stanford Inc.) was used to synchronize the Nd:YAG laser, the CCD cameras and the injection system.

1,3-dimethylnaphthalene [$C_{10}H_6(CH_3)_2$] (abbreviated as 1,3-DMN) was selected to simulate the diesel fuel, as it has physical properties including boiling point, viscosity, and evaporating rate similar to those of the diesel fuel. Especially, 1,3-DMN strongly absorbs UV light near 266nm and almost does not absorb visible light near 532nm. It has been proved that the 1,3-DMN is the most suitable test fuel for the LAS diesel spray measurement, and details of the measurements of vapor absorption spectra at elevated temperatures and pressures can be found in Ref. [25].

An experimental matrix of five test cases has been performed. The experimental conditions are listed in **Table 1**. In order to study the characteristics of evaporating spray, the case 1-3 focused on the evaporating conditions, and the ambient temperature and pressure were set at 760K and 4.0MPa respectively, corresponding to the actual state in a diesel engine combustion chamber at the start of injection. The injection pressure was varied from 90MPa to 150MPa. For the case 4, the fuel spray was injected into the non-evaporating environment. The ambient conditions were kept at room temperature and an ambient pressure of 1.6MPa, while keeping the constant ambient density as the evaporating spray experiments. The case 5 investigated the evaporating spray for a short injection duration ($t_{inj}=0.75ms$). For all test cases, a hole-type single-hole injector which was especially manufactured for this research was used. The diameter and length of the orifice kept the same as those used in the production diesel engine, only the number of orifices was changed from originally 6 to 1. The timing of start of injection was carefully checked by spray imaging before the experiment. Then the imaging timings were decided and selected between 0.29-2.09 ms after the start of injection (ASOI).

RESULTS AND DISCUSSION

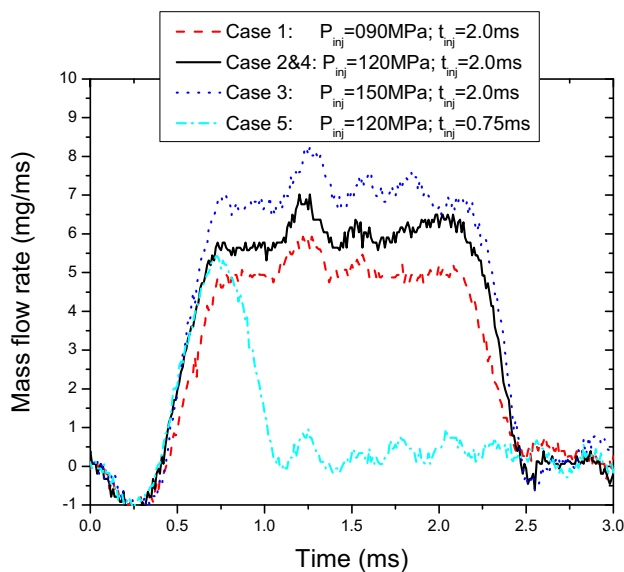
MASS FLOW RATE – Mass flow rate measurement based on Zeuch method [32, 33] was performed to confirm the fuel delivery and injection rate shape. The results for all test cases are shown in **Fig.2**. Except the short duration injection case 5, it shows that the mass flow rate reaches a stable and quasi constant value at around 0.3ms ASOI. The LAS imaging is therefore carried out during the injection event with the quasi

Table 1 Experimental conditions

	Ambient pressure, p_a , MPa	Ambient temperature, T_a , K	Ambient density, ρ_a , Kg/m ³	Nozzle hole diameter, d_0 , mm	Injection pressure, p_{inj} , MPa	Injection duration, t_{inj} , ms	Laser shot timing, t_s , ms
1	4.0	760	20.0	0.135	90	2.0	0.29,0.59,0.89,1.09,1.29,1.59,1.89,2.09
2	4.0	760	20.0	0.135	120	2.0	
3	4.0	760	20.0	0.135	150	2.0	
4	1.6	300	20.0	0.135	120	2.0	
5	4.0	760	20.0	0.135	120	0.75	

constant mass flow rate. The variations in the constant value of mass flow rate are due to pressure fluctuations in the nozzle because of the injection process [34].

It is also observed that the injection rate shape changes for different injection conditions. To put it more precisely, the higher injection pressure results in a faster needle rising and as a consequence, a higher slope of mass flow rate curve before reaching the plateau.

**Fig. 2** Mass flow rate for all test cases

STRUCTURE OF EVAPORATING SPRAY – Figure 3 shows the spray images photographed simultaneously at visible (left column) and UV (right column) wavelengths for the case 2 condition. In the figure, the brightness in the spray area of each image represents the line-of-sight optical thickness at the two wavelengths, and the surrounding gas area is colored in black. As stated in previous sections, the visible image is only attributed to the droplets scattering and therefore refers to the liquid phase distribution, while the UV image contains the information of both liquid and vapor phases. At 0.29ms ASOI, the visible (liquid phase) and UV (vapor phase) images present a similar shape of the spray, except that the vapor phase width is a little

bigger. After this time position, it is easy to find that the liquid phase evolution remains almost constant, whereas the vapor phase obviously grows as time progresses and distributes more extensively.

Figure 4 presents the corresponding result of equivalence ratio distributions of liquid and vapor deconvoluted by the onion-peeling model from the optical thickness images, after averaging the line-of-sight optical thickness of the right half with that of the left half of the spray. For every contour plot, the left-hand half shows the liquid phase whereas right-hand half refers to vapor phase. The results indicate that the liquid-containing core is observed in the region near the spray axis close to the nozzle tip, where the peak equivalence ratio exceeds 2.0. This region corresponds to the so-called “potential core region” in the conceptual model of free transient gas jet [3]. Again, the contours show the quite similar equivalence ratio distribution of liquid phase for all imaging timings. The fact that the liquid phase evolution remains almost constant implies that fuel evaporation takes place at the same rate as fuel is injected.

On the other hand, the appearance of vapor phase stabilizes at about 15mm downstream for all imaging timings. In other words, rare vapor is generated in the region near the nozzle tip within the axial distance of 15mm ($Z < 15\text{mm}$) where the liquid core exists. This distance coincides with the liquid length reported by Siebers [35]. More detailed analysis will be provided latter. For the fuel spray injected during the stable injection period ($t_s > 0.59\text{ms ASOI}$), it is found that vapor equivalence ratio is relatively low at the axial location between about 40mm and 60mm, indicating more ambient gas entrained and better mixing, while two peaks exist on the two sides of the location: $Z = 20 \sim 40\text{mm}$ region and spray tip region. These results are therefore similar to those obtained in a gas jet [3, 4], that is, $Z = 40 \sim 60\text{mm}$ region is the main mixing flow region where ambient gas entrainment due to shear turbulence dominates the jet dynamic; spray tip region is the stagnant region where the tip vortex is formed and is characterized by a lower mixing rate.