

Quantitative Study of Concentration and Temperature of a Diesel Spray by Using Planar Laser Induced Exciplex Fluorescence Technique

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ABSTRACT

The Lambert -Beer's coefficient K_{vapor} was measured in a wide range of temperature (400-1200K) and pressure (2-8.2MPa) in this paper. Based on the measured MAP of K_{vapor} and principle of energy conservation in the sprays mass and transfer, a quantitative presentation of equivalence ratio and temperature in vapor phase sprays at diesel engine like conditions was put forward. The experimental range of temperature was 800-1100K and 20-100 kg/m³ for density. It was found that the maximum equivalence ratio of vapor phase spray remained fairly constant at about 3.0 and the maximum equivalence ratio appearance earlier as the ambient density increased, while the ambient temperature in the constant volume vessel was set at 800K. The maximum equivalence ratio of vapor phase spray increased from about 3.0 to about 3.7 as ambient temperature increased from 800 to 1100K. The spray structure (including distribution of equivalence ratio of vapor phase spray, spray penetrations of liquid and vapor phase et al) of diesel spray was studied near ignition timing at full load diesel engine like conditions in this paper.

INTRODUCTION

The spray geometry including penetration, cone angle and so on was measured by early researchers [1-2]. Epsey and John E. Dec used Mie scattering for liquid-phase fuel distributions[3], Rayleigh scattering for quantitative vapor-phase spray concentration and temperature[4], laser induced incandescence (LII) for relative soot concentrations[5] and so on in a single-cylinder optical engine. They proposed a conceptual model of DI diesel combustion including liquid and vapor fuel zones, quantitatively vapor-fuel/air mixing, soot distributions, particle-size distributions and the diffusion

flame structure[5]. The ambient density and temperature ranged in 11.1-33.2kg/m³ and 800-1100K respectively in their experiment. It was found that just prior to the first indicated heat release (4.5 ° after start of injection (ASOI)), the fuel and the air are quite uniformly mixed throughout the leading portion of the diesel jet, with the equivalence ratio ranging mostly from 2 to 4. The model showed the initial premixed burn in typical heavy duty diesel engine is fuel rich (equivalence ratio 2 to 4), and that it occurs almost simultaneously over the entire volume of the leading portion of the fuel jet. But the model is currently at one typical operating condition with idealized fuels. And Rayleigh scattering only was applied in the environment virtually free of particles.

Melton [6] first developed laser-induced fluorescence exciplex techniques, and applied to study diesel spray. Felton et al [7] study spray characteristics in a two-stroke engine by this technique. They found that when the temperature exceeds 500K, the fluorescence intensity of vapor spray declined rapidly. Senda et al [8] quantitatively measured the vapor concentration of the hit wall spray by laser-induced fluorescence techniques. Senda found the fluorescence intensity increases with the temperature down under the ambient temperatures from 600K to 740K. Yeh et al [9] established a quantitative calibration experimental system in a rapid compression machine, and found that the ambient temperature has no effect on the fluorescence intensity.

Afterward, the 4-methyl-p-phenylene diamine (TMPD) fluorescence and concentration was calibrated to quantitatively investigate the effects of ambient gas temperature (800-1200K) and injection pressure (60-150MPa) and nozzle hole size (0.14-0.2mm) under ambient density of 15 kg/m³ on evaporating diesel sprays by

Tongwoo Kim [10,11,12] by using Planar Laser Induced Exiplex Fluorescence (PLIEF) technique in a combustion-type constant volume bomb. It was found that the effects of pressure and collision partner on TMPD fluorescence can be negligible. The effect of temperature was found to increase the fluorescent yield up to 600K, and then decrease it for further increases in temperature. The liquid length reaches a terminal value and the vapor phase continues to penetrate. Lower ambient density was shown to have faster vapor penetration and longer liquid lengths. Higher ambient temperature was shown to produce a wider radial vapor extent with higher equivalence ratios and higher gradients at the edge of jet. But the laser energy was only 13.5mJ/pulse, and the image need to be modified for laser energy attenuates obviously when penetrates through the spray.

Later, it was found that the effect of laser energy attenuation on measurement accuracy could be negligible when passes through the spray if laser energy was over 100 mJ/pulse by Jong-uk Kim and Byungyou Hong [11] in a heated constant volume vessel by using PLIEF technique. Subsequently, the effects of ambient density (10-25 kg/m³) and temperature (874-1295K) on the vapor phase fuel distribution was studied by M. S. Beckman [12] in a single-cylinder optical engine by using PLIEF technique. Notice that the experiment was carried out under conditions with oxygen. In this experiment, the TMPD fluorescence and concentration was calibrated in the way like that used by Tongwoo Kim. It was found that increase in Top Dead Center (TDC) temperature has a stronger effect on the amount of vapor mass than increases in ignition delay.

However, modern diesel engine is often highly turbocharged, and the ambient density reaches 60kg/m³ and even higher (which is far beyond the ambient density in the concentration study mentioned above) at full load operating conditions when it's near the top dead center. To understand the spray structure and vapor phase fuel distribution under the engine full load conditions, the air/fuel mixing process and vapor phase fuel distribution were quantitatively studied at the full load diesel engine like conditions by using PLIEF technique in a constant volume bomb with ambient density of 20-100 kg/m³ and ambient temperature of 800-1200K in this paper. Then spray structure model at near ignition time was proposed according the research.

EXPERIMENTAL APPARATUS

The planar laser induced exciplex fluorescence (PLIEF) technology was employed in this study to visualize the behavior of both vapor and liquid phase sprays simultaneously. Figure 1 shows the experimental layout, which consists of a high pressure single injection fuel system, a constant-volume bomb, a laser source, a laser path, a spectroscope for separating vapor and liquid phases fluorescence, two ICCD cameras for collection of the two

phases images separately, a gas intake system and a PC based control system. The specifications of the optical apparatus are listed in Table 1. The laser energy was set to 150±5 mJ/pulse. The gate width of the two ICCDs was set to at 10ns.

Figure 2 is the schematic of the constant volume bomb system, including quartz windows, pressure sensor, thermocouple, spark plug, gas inlet system. To avoid the danger appearance if ambient pressure is too high after ignition, an insurance valve was fixed in the bomb with opening pressure of 16MPa. In order to prevent the hot gas flow backwards into inlet pipe, a check valve was fixed into the pipe. An inducted barrier and two spark plugs were set in the bomb so as to form local dense mixture to be ignited easily. CO₂ (or SF₆), H₂, O₂ were charged into the bomb in turn, and then ignited by spark plug, so the high temperature and high pressure environment came into being. In order to minimize the extinguishment of fluorescence signal caused by oxygen, H₂ and O₂ were charged into the bomb by mole ratio of 2.1:1. Injection starts as the ambient temperature drops to the set value, when the ambient gas mainly consists of CO₂ (or SF₆), H₂ and H₂O. The ambient pressure was measured by Kistler 6125B type pressure sensor during the experiment.

The fuel used in the experiment was a mixture of n-decane (C₁₀H₂₂), naphthalene (Np), and 4-methyl-p-phenylene diamine (TMPD) by mass proportion of 90:9:1. Their physical properties were given in literature 9 detailedly. A FIRCRI electronically controlled injector developed by our research group with single hole of 0.10mm diameter (D_n) along its axis was used in this paper. The experimental conditions were set as Table 2 showed.

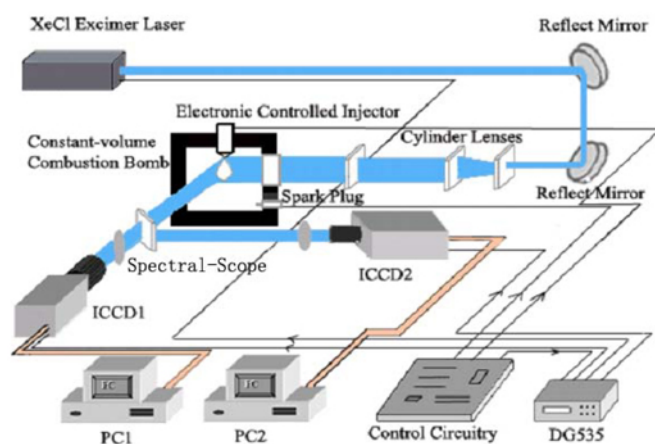


Figure 1. Experimental layout for PLIEF system

Table 1. Specifications of the optical apparatus

Apparatus	Model	Resolution/ Wavelength	Remark
ICCD1	Andor DH712-1F	512x512 pixel ²	0.31 mm/pixel
ICCD2	Princeton PI-MAX	512x512 pixel ²	0.31 mm/pixel
Laser Source	COMPex 102	308nm	20ns-150mj /pulse

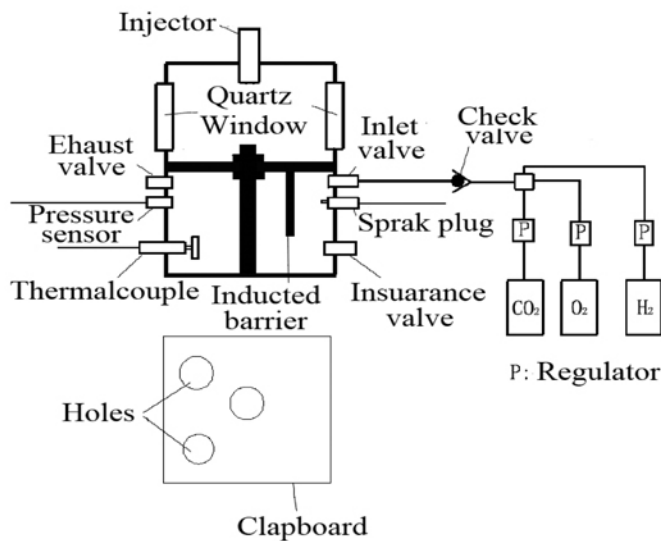


Figure 2. Constant volume bomb system

Table 2. Experimental conditions

Case	Injection pressure P_{inj} [MPa]	Injection duration $\Delta\tau$ [ms]	Ambient temperature T_a [K]	Ambient density ρ_a [kg/m ³]	Laser timing [ms ASOI]
1	180	1.0	800	20	0.1-0.8
2			800	40	0.1-0.8
3			800	60	0.1-2.4
4			800	80	0.1-0.8
5			800	100	
6			950	20	
7			950	60	
8			1100	20	
9			1100	60	

According to Einstein's photoelectric equation and Lambert-Beer's law, the relationship between fluorescence intensity and the concentration of fluorescent substance can be expressed by the equation below in the case of non-fluorescent saturation [14,15,16]:

$$I = K \cdot I_0 \cdot (1 - e^{-\alpha \rho L}) \quad \text{Eq.1}$$

Where I is fluorescence intensity [photon], ρ is the concentration of fluorescent substance [mol/m³], α is molar absorption coefficient [m²/mol], L is the distance laser passed through [m], K is the formula coefficient [photon·L/mol], I_0 is the incident laser intensity [photon].

In the saturation of the excitation laser energy, fluorescence is saturated, the effects of α and L on the I_0 can be ignored [13] the Eq.1 can be rewritten as following for 2-D vapor phase cone:

$$I_v(i, j) = K_v(i, j) \cdot \rho_v(i, j) \quad \text{Eq.2}$$

where v represents vapor phase, i and j are natural number.

The K_v can be determined by quantitative calibration experiments: the calibration experiment was carried out in homogeneous mixture generator with 128mL volume. Firstly, the fuel mass injected was measured by fuel consumption meter, and the TMPD concentration, ρ_v , can be deduced in the calibration volume; Secondly, the fluorescence intensity, I_v , was detected by ICCD corresponding to ρ_v at the calibration conditions; Finally, the K_v can be determined basing on the Eq.2 at the calibration conditions. Details are given in literature 5.

The effects of fuel, water vapor, ambient gas, ambient temperature (400~1100K) and ambient pressure (0.1~8.2MPa) on the K_v were studied in the calibration process. To decrease the deviation of the results, quartz windows and spectroscope and so on were carefully cleaned after each test in the calibration experiment. Moreover, the calibration was made until the fuel injected was thought to be completely evaporated homogeneously distributed, reflected by no liquid phase fluorescence signal with its mean square error was lower than 5%, so as to eliminate the cross talk effects. To simulate the high density environment, SF₆ was used as charger for its big molecular. SF₆ has been used as ambient gas to quantitatively study the fuel concentration by Jose V. Pastor et al [15] at room temperature using PLIF technique so far. H₂O and CO₂ and SF₆ have little impact on the fluorescence characteristics of TMPD. The dependence of the K_v on the ambient temperature and pressure was shown in Figure 3. The K_v decreases as ambient pressure increases. This is because the laser-induced fluorescence is in an unstable state and higher pressure would lead to more molecule annihilation resulted from more dramatic collision between molecules. Ambient temperature has great impact on the K_v . As the temperature rising, K_v firstly rises before 600K

with the increase of ambient temperature, but decreases as temperature increases further. At relatively low temperature, the activity of fluorescence molecules was intensified as the temperature increases so that the molecules become easier to be excited. But as the temperature rises to be over 600K, molecular activity is too high, and collision between fluorescent molecules were intensified resulting in reduction of fluorescence intensity and K_v . Moreover, thermal decomposition of fluorescent substances should also be one of the reasons which cannot be ignored at high temperature.

Table 3. Experimental conditions of K_v calibration

Ambient temperature [K]	Ambient pressure [MPa]	Compositions of ambient gas	Laser energy [mJ/pulse]	Gate of ICCD [ns]
400-1100	2.3-8.2	SF ₆ , H ₂ , N ₂ , CO ₂ , H ₂ O ₂	150±5	10

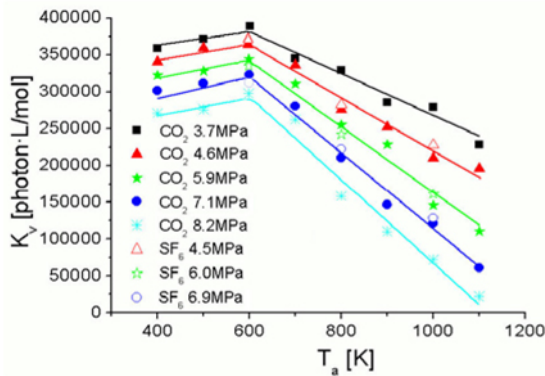


Figure 3. Dependence of the K_v on the ambient temperature and pressure

As can be seen from Figure 3, the K_v was dependent on the ambient temperature. Thus the concentration of vapor phase cone cannot be accurately calibrated before local temperature is determined. The local temperature of vapor phase cone was estimated in the same way as used by John E. Dec [3] and Tongwoo Kim [10] based on adiabatic mixing assumption and energy conservation law. Then, vapor phase cone concentration can be quantitatively calibrated based on the local temperature and K_v .

On the assumption that both liquid and vapor phase cones are axisymmetric and laser sheet passes through the spray axis, the liquid droplets cone concentration can be expressed by Eq.3 and Eq.4:

$$\rho_l(i, j) = I_l(i, j) \cdot \frac{F_{inj} - F_v}{V_l} \cdot \frac{\iint_{l-pl} I_l(i, j) dx dy \cdot \text{pixel}^2 L_L}{\iint_{l-pl} \text{pixel}^2 L_L dx dy} \quad \text{Eq.3}$$

$$F_v = \frac{V_v}{\iint_{v-pl} \text{pixel}^2 \cdot L_L dx dy} \cdot \iint_{v-pl} \frac{I_v(i, j)}{K_v(i, j)} \text{pixel}^2 \cdot L_L dx dy \quad \text{Eq.4}$$

Where l represents liquid droplets cone; F is the mole quantity of fuel in a pixel [mol]; inj represents injected fuel at a moment; V is spray volume [L]; $l-pl$ and $v-pl$ represent the liquid and vapor phase cone planes laser passed through respectively. The I_l can be determined by liquid phase fluorescence image, F_{inj} can be determined by fuel mass injected and fuel molecular weight. $Pixel$ is the real size of a pixel [mm], which is about 0.31mm in this paper, L_L is the thickness of laser sheet [mm], which is around 1mm in this paper. The vapor phase concentration was expressed by fuel/air equivalence ratio (Φ) in this paper, which is defined as following:

$$\phi(i, j) = \frac{\frac{I_v(i, j)}{K_v(i, j)} \cdot 10^{-4}}{\frac{1}{1 + \frac{1}{C_{O_2}} \left(c + \frac{h}{4} - \frac{o}{2} \right)} \cdot \frac{p \cdot M_{amb}}{8.314 T(i, j) \cdot M_{air}}} \quad \text{Eq.5}$$

where c, h, o are the atom numbers of C, H, O in the fuel molecular, M is molecular weight, amb represents ambient gas, C_{O_2} is oxygen volume concentration.

Figure 4 shows the calibrated results of temperature and concentration both of liquid and vapor phase diesel sprays, in which black solid lines are marked for liquid fuel contours, and oxygen volume concentration (C_{O_2}) is 21%. It can be seen that the local temperature has great effect on the local equivalence ratio of the vapor phase cone. The equivalence ratio calibrated using mean temperature is obviously bigger than that using local temperature where equivalence ratio is big. The maximum equivalence ratio, Φ_{max} , calibrated using mean temperature is 4.3, which is much bigger than 3.4 using local temperature as shown in Figure 4. Moreover, the liquid droplets cone concentration has important influence on that of vapor phase. Vapor spray with high equivalence ratio mainly locates in the liquid phase area with relatively lower temperature.

<figure 4 here>

RESULTS AND DISCUSSIONS

IMAGE PROCESS

In order to obtain the accurate results, the original fluorescence images were processed as following: average result of 3 pieces fluorescence images was used to minimize

the effect for random variety, and a threshold tripling to the background noise was used to define the spray boundary; To weaken cross talk effect from liquid phase fluorescence, the mean vapor phase fluorescence intensity just leave the nozzle where was thought to be only liquid phase signal was subtracted from the vapor phase fluorescence intensity; Since the cross talk effect to liquid phase fluorescence from vapor phase fluorescence is very weak, there is no need to consider the effect for liquid phase fluorescence.

SPRAY STRUCTURE AND PARAMETER DEFINITION

Figure 5 shows the typical free diesel spray structure or characteristics including the spray cone angles (θ_v , θ_l) and penetrations (S_v , S_l) of vapor and liquid phases, fuel-lean region ($\Phi \leq 2$) and fuel-rich region ($\Phi > 2$) of vapor phase spray, the concentration in the head of vapor phase spray and the axial distance (L_n) from the maximum equivalence ratio (Φ_{max}) location to the injector nozzle which were analyzed in this paper.

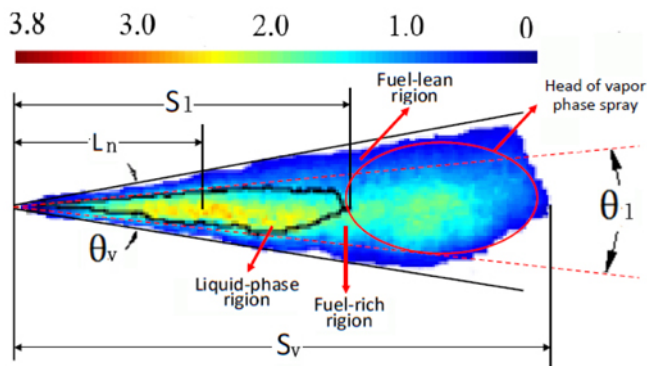


Figure 5. Spray structure

Figure 6 and Figure 7 give the effects of ambient density on diesel spray structure and concentration under the same conditions of $T_a = 800K$ and $C_{O_2} = 21\%$ at two different ambient density of $\rho_a = 20kg/m^3$ and $\rho_a = 60 kg/m^3$. The liquid cone contour was marked by black solid lines, and F_ϕ is mass fraction to total vapor fuel mass at ϕ . Under the HD engine like full load conditions (as Figure 6-(2) and Figure 7-(2) show), at the injector there was only liquid fuel, but downstream air is entrained and fuel vaporizes so these gases are present along with the liquid fuel droplets, and the contours both of vapor phase and liquid phase were almost the same at the initial spray development as shown in the 0.1ms ASOI schematic, the maximum volume concentration of liquid phase spray is about 110mg/mL and keeps as a constant by 0.8ms ASOI. Then Φ_{max} rises, and the fuel rich region begins to appear and expand rapidly, a vapor phase region begins to develop along the sides of the jet beyond the extent of liquid vapor spray (0.2-0.3ms ASOI schematics).

This vapor region grows thicker with low equivalence ratio as the jet continues to penetrate. And the vapor phase cone angle begins to be over that of liquid phase. Then at the 0.4 ms ASOI the liquid phase spray reaches its maximum penetration of about 18 mm, the entrainment of hot air into the jet has been sufficient to vaporize all the fuel by this point. Following, the Φ_{max} increases to its maximum value of around 3.0 at about 0.5ms ASOI, almost at the same timing, the fuel rich-region reaches its maximum level, the vapor phase spray continues to penetrate and exceeds the liquid region along its axis, a head vortex eventually develops as is typical of penetrating gas-phase jets. By 0.8ms ASOI the vapor spray has penetrates to about 26 mm, and its head contains a “relatively uniform” air/fuel mixture with equivalence ratios mainly ranging from about 0.5 to 2.5. In general, the vapor spray with high equivalence ratio mainly locates in the range of liquid phase area.

Comparing to the lower ambient density conditions (Figure 6-(1) and Figure 7-(1)), the penetrations both of vapor and liquid phases at the diesel engine like full load conditions are obviously smaller at the same timing (ms ASOI), the corresponding spray angles increase. The sheath of vapor phase with $\Phi \leq 2$ becomes wider, and the head of vapor phase spray are more homogeneous with more smooth and regular edge. But the maximum vapor equivalence ratio keeps almost no change; the fuel-rich regions appear earlier, and fuel-lean regions relatively become more in the mid-late spray development. The maximum volume concentration of liquid phase spray decreases by a little, and the sheath of liquid phase spray with low concentration become wider. Moreover, the homogeneity is improved with higher ambient density.

<figure 6 here>

<figure 7 here>

Figure 8 and Figure 9 show the effects of ambient density (20-100kg/m³) on spray penetrations and cone angles at ambient temperature of 800K. It can be seen from them hat both of vapor phase and liquid phase spray penetrations decrease remarkably as ambient density increases from 20 kg/m³ to 100 kg/m³, and the corresponding spray cone angles increase. But the effects caused by ambient density increase become weaker as ambient density increases.