

Fuel Spray Evaporation and Mixture Formation Processes of Ethanol/Gasoline Blend Injected by Hole-Type Nozzle for DISI Engine

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ABSTRACT

Ethanol is regarded as the promising alternative fuel for gasoline to meet the strict low emission standard for spark ignition engines. In this study, the spray mixture formation process for different ethanol blended fuels, including E0 (gasoline), E85 (85% volume of ethanol and 15% volume of gasoline) and E100 (ethanol), has been evaluated using hole-type nozzle by the measurement of Laser Absorption Scattering (LAS) technique in a constant volume vessel. Based on the principle of LAS, the quantitative vapor and liquid phase distribution from different ethanol blended fuel can be obtained by the light extinction regime. Aiming to analyze the effect of mixture formation and evaporation for different components of blended fuel or pure gasoline and ethanol, the vapor distribution of gasoline was determined by using p-xylene, which had similar physical properties to gasoline, especially higher boiling temperature components, and higher absorption for ultraviolet. Likewise, the vapor behavior of ethanol was determined by using methylethylketone (MEK). The result shows that the evaporation of E100 is better than E85 and E0 corresponded to the order of fuel volatility, while the spray penetration reduces in the sequence of E0, E85 and E100 due to the higher volatility resulting in the increased spray volume and resistance of the ambient gas. The evaporation of E85 lies between E0 and E100 in terms of the saturated pressure curves, and the p-xylene in the blended fuel vaporizes faster than pure p-xylene.

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INTRODUCTION

Direct injection spark ignition (DISI) is well known as approaching to high fuel economy and low engine-out emission for gasoline engine aiming to moderate the energy crisis and get to environmental friendly, as a function of high fuel efficiency, low pump loss and reduction of charge temperature compared with port-fuel injection (PFI). One of the most important factors for the DISI engine is the spray mixture formation, since whether a proper mixture cloud

exists around the spark plug gap at the time of ignition and the injected liquid fuel can be vaporized in a short time have a great influence to improve combustion and emission properties. The DISI was classified in sequence of wall-guided, flow-guided and spray-guided, depending on the relative position of the injector to the spark plug and the piston crown shape. Due to the drawbacks of complicated piston shape, wall wetting, higher heat loss for wall-guided and flow-guided, the spray-guided concept, namely narrow spacing mounted between injector and spark plug, is referred

to the most potential method to solve the issues above for DISI [1,2,3,4]. In the case of the spray-guided direct ignition (SGDI), compared with an outwardly opening nozzle, a multi-hole nozzle shows its great advantages of the stable spray structure with increased backpressure, which is essential for realizing the SGDI engine, and lower fuel consumption as well as CO emission at almost all the operating conditions [5]. Consequently, many researchers show great actively to study the application of the multi-hole nozzle for SGDI in recent years.

Ethanol/gasoline blended fuel is widely applied in many countries as the alternative fuel for gasoline, such as Brazil, Europe and USA. Despite of lower energy density compared with gasoline, is still paid more attention to ethanol fuel in terms of cleaner engine-out and wider resource from plants, such as corn, sweet potatoes, and the like. In order to improve the combustion and emission of ethanol blended fuel, it is necessary to make acquaintance with its spray characteristics. Aleiferis, et al. utilized Phase Doppler Anemometry to investigate the spray behavior of E85 under various temperature and ambient pressure [6]. They reported that E85 was less sensitive to changes of temperature and pressure, and the droplet sizes were larger than gasoline. Su Han Park, et al. discussed the spray characteristics of bioethanol by means of the droplet analysis system, and presented that the spray droplet of E100 were larger than E0 and E85 due to higher kinematic viscosity and surface tension [8]. Matsumoto, et al. employed high-speed schlieren and Mie scattering images to study the mixture formation, and showed that occurrence of flash boiling of the ethanol spray is strong dependent on the fuel temperature and the earlier evaporation of gasoline and resultant spray collapse was observed [8]. Gao, et al. applied the high-speed schlieren photography to analyze the spray of the different blends of ethanol injected by swirl-type nozzle [9]. They argued that in the case of low ambient pressure, the spray penetration decreased and the spray angle increased with the blending ratio increasing. Zhang, et al. also analyzed the ethanol fuel in cold-start conditions by using Mie-scattering and Laser Induced Fluorescence (LIF) [10]. All of these literatures offer the constructive and valuable information to understand the spray mechanism for ethanol blended fuel. Nevertheless, up to now the studies of ethanol blended fuel have not been adequate due to the lack of knowledge about mixture formation process of gasoline and ethanol in blended fuel respectively, which has a great effect on the spray characteristics. Meanwhile, the quantitative analysis of vapor distribution, which indicates the detail mixture formation, has not been described yet.

The purpose of this work is to study the spray mixture formation process of E0, E85 and E100 injected by hole-type nozzle using dual wavelength laser absorption and scattering diagnose measurement. The quantitative of spatial concentration distribution of vapor and liquid phases were

obtained respectively to show the overall spray characteristics.

EXPERIMENT REGIME

LAS Methodology

According to the introduction from Fleton [11], et al. 1993; Pastor [12], et al. 2002; Zhang [13], et al. 2000, the commonly main variant applications of laser diagnose measurements in fuel spray atomization and vaporization involve Laser Induced Exciplex Fluorescence (LIEF), Planar Laser Induced Fluorescence (PLIF) and Laser Absorption Scattering (LAS) technique, as known as Laser Extinction Absorption (LEA). Although LIEF is widely used to measure both vapor and droplets of single component fuel, it also has difficulty to acquire a reliable quantitative analysis of vapor distribution in a spray, in terms of the collision quenching effect of the gas phase fluorescence by oxygen. Meanwhile, the absorption of fluorescence dopants is usually stronger temperature-dependent, which has a negative effect to make an implement. The other technique, the PLIF, can be used to measure fuel distribution. In this case, PLIF utilizes a ketonic or aromatic fluorescence as tracers mixed with other single component fuel, and the equivalence ratio distribution is derived from the measured tracer distribution. In addition, PLIF can be used to measure the fuel concentration in some commercial fuels by their natural fluorescence. But to a great extent, this implement is dependent on the fluorescence characteristics of test fuel as well as the isothermal condition due to the compact correlation between temperature and fluorescence [14]. Also this optical technique is poor in usage of measuring vapor distribution for multicomponent fuel, respect to the evaporation rates of the fuel and tracer are not match well due to the non-negligible molecular interaction of the components in solution [15].

Recently, the ultraviolet/visible dual-wavelength absorption and scattering technique was reported to be capable of measuring both vapor and droplet concentration distribution in quantify. Compared to the previous infrared extinction, the advantage of the new LAS optical technique, which employs ultraviolet as absorption wavelength, is less sensitive to the temperature of heating device, and no influence by the water vapor existing in the ambient gas and no oxygen quenching, which can be applied in more realistic conditions. As Fig. 1 shown the principle of LAS, the two wavelength (λ_A : absorption wavelength, λ_T : transparent wavelength), incident light of intensity I_0 traverses the spray mixture of liquid and vapor simultaneously, and then is attenuated into the transmitted light intensity of I_t . Based on the law of Bouguer-Lambert-Beer, the extinction of absorption wavelength $\ln(I_0/I_t)_{\lambda_A}$, as described in Eq.1, is attributed to the absorption of vapor $\ln(I_0/I_t)_{v_{abs}}$ and liquid droplet $\ln(I_0/I_t)_{L_{abs}}$ as well as the scattering of liquid droplet $\ln(I_0/I_t)_{L_{sca}}$. Likewise, the extinction of visible wavelength



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$\ln(I_0/I_t)_{\lambda_T}$ is only involves the scattering of liquid droplet $\ln(I_0/I_t)_{L_{sca}}$, as expressed in Eq.2. The extinction of liquid droplet for absorption wavelength can be neglected due to the amount of absorption is very small. In terms of the theory from Bohren, the limiting value of efficiency for extinction approaches to 2 if the droplet size parameter is sufficient large [16]. That is to say, the scattering extinction from liquid droplet in both absorption wavelength and visible wavelength are the same.

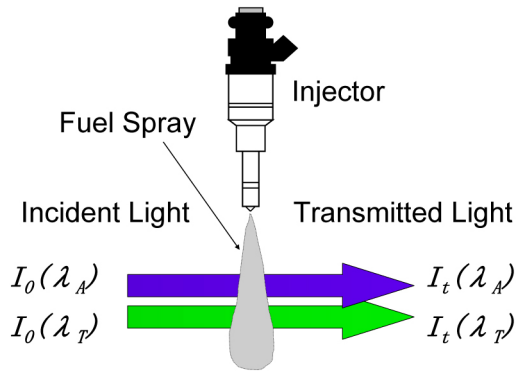


Figure 1. Principle of LAS Technique

$$\ln\left(\frac{I_0}{I_t}\right)_{\lambda_A} = \ln\left(\frac{I_0}{I_t}\right)_{L_{sca}+L_{abs}} + \ln\left(\frac{I_0}{I_t}\right)_{v_{abs}} \quad (1)$$

$$\ln\left(\frac{I_0}{I_t}\right)_{\lambda_T} = \ln\left(\frac{I_0}{I_t}\right)_{L_{sca}} \quad (2)$$

Then, by substituting Eq.2 into Eq.1, the equations expressed the extinction of vapor and the droplet can be shown as follow respectively:

$$\ln\left(\frac{I_0}{I_t}\right)_{v_{abs}} = \ln\left(\frac{I_0}{I_t}\right)_{\lambda_A} - \ln\left(\frac{I_0}{I_t}\right)_{\lambda_T} \quad (3)$$

$$\ln\left(\frac{I_0}{I_t}\right)_{L_{sca}} = \ln\left(\frac{I_0}{I_t}\right)_{\lambda_T} \quad (4)$$

With respect to introducing the optical thickness τ , according to the Bouguer-Lambert-Beer's law, the quantitative analysis of vapor distribution for symmetrical spray can be expressed:

$$\overline{Cv} = \frac{1}{\bar{\epsilon}(\lambda_A)L} \left[\ln\left(\frac{I_0}{I_t}\right)_{\lambda_A} - R \ln\left(\frac{I_0}{I_t}\right)_{\lambda_T} \right] \quad (5)$$

where

$$R = \frac{\tau(\lambda_A)_{drop}}{\tau(\lambda_T)_{drop}} \quad (6)$$

where $\overline{Cv}$ is the vapor concentration, $\bar{\epsilon}(\lambda_A)$ is the molar absorption coefficient at the wavelength of λ_A , L is the

optical path length. R is the ratio of the droplet optical thickness at the two wavelengths, which is approximately 1 when the droplet size is enough large. The equation (3) and (4) evidences the vapor distribution can be calculated after removing the optical thickness of liquid phase from the total extinction at absorption wavelength based on the onion peeling model. And the liquid phase distribution can be obtained from the non-absorption wavelength λ_T . Based on the assumption of spherical shape for drops in a spray, the line-of sight averaged droplets density $\overline{C_d}$ can be expressed as:

$$\overline{C_d} = \frac{2}{3} \rho_f D_{32} \overline{A_f} \quad (7)$$

where ρ_f is the density of liquid fuel, and the D_{32} is the Sauter mean diameter. $\overline{A_f}$ is the the surface area of droplets per unit volume. In order to show the vapor and liquid phase distribution clearly, the concentration of them can be expressed by the equivalence ratio ϕ_v and ϕ_d respectively due to the axisymmetric spray structure.

$$\phi_v = \frac{AF_{stoich}}{\bar{\epsilon}(\lambda_A)L\overline{C_d}} \left[\ln\left(\frac{I_0}{I_t}\right)_{\lambda_A} - \ln\left(\frac{I_0}{I_t}\right)_{\lambda_T} \right] \quad (8)$$

$$\phi_d = \frac{AF_{stoich}}{\frac{\overline{C_d}}{\overline{C_a}} \frac{\overline{C_a}}{\rho_f}} \quad (9)$$

Where AF_{stoich} is the stoichiometric air-fuel ratio, $\overline{C_a}$ is the ambient gas density. The more detail discussion of this theory was given in papers of Zhang, et al. [13, 17-18].

Experimental Setup

According to the theory above, the ultraviolet/visible dual wavelength imaging LAS system, including electrically controlled fuel injection system and constant volume vessel, shown schematically in Fig. 2, was established for the measurement of vapor and liquid phase distribution. A pulsed Nd: YAG laser (Continuum, NY 61-10) was responsible for a generated coaxial laser beam consisting ultraviolet band of 266nm (absorption wavelength) and the visible band of 532nm (transparent wavelength). This beam was separated into ultraviolet and visible light by a dichroic mirror and expanded to a 100mm diameter beam respectively. Then the two beams combined into a coaxial beam again by a harmonic separator and traversed through the constant volume vessel. After the light extinction of the liquid drop and vapor, the beam was transmitted and split into ultraviolet and visible light again by a dichroic mirror. Finally, these two beams were focused by a pair of CCD cameras (Hamamatsu Photonics, C4880). In order to eliminate the disturb of environment, such as ambient gas density and optical noises, the diffuser mirror and the special filters as well as apertures used in front of the CCD cameras were employed in this

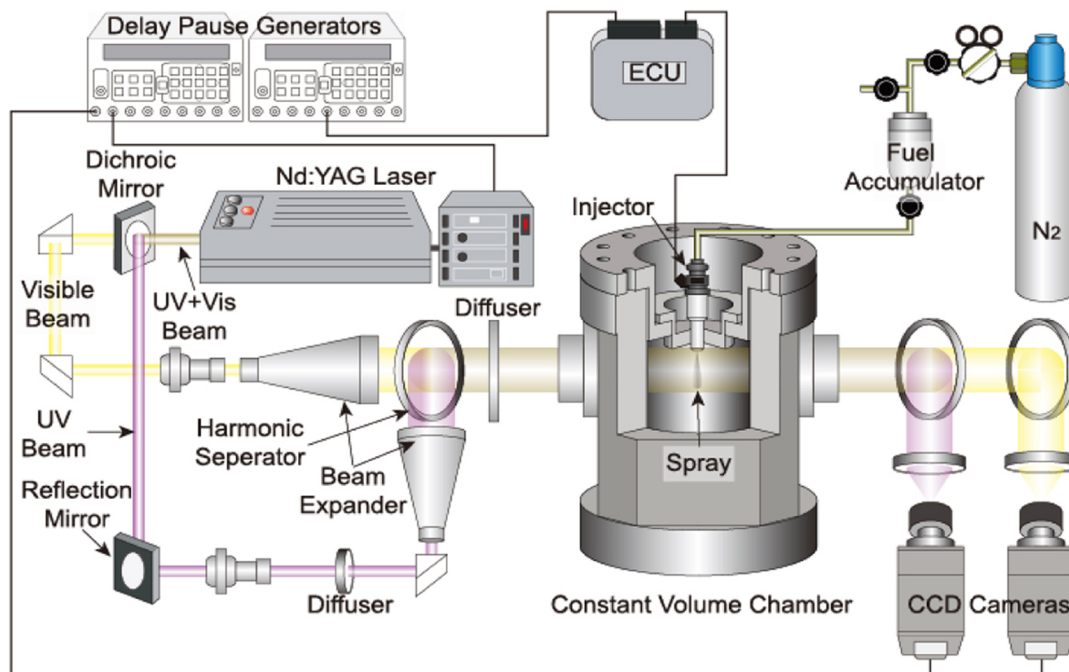


Figure 2. Schematic of laser absorption scattering (LAS)

system to cut off both schlieren-like and light noises. The final image analysis acquisition and arithmetic processing were implemented by IPLab imaging analysis system and each spray image was acquired from averaged per 4 laser shots consecutively. And the difference of the stoichiometric amount of air between the MEK and p-xylene were considered to calculate the equivalence ratio distribution of the vapor and liquid phase.

The injection system using a hole-type nozzle for DISI engine and an accumulator was applied to inject a single fuel spray into the constant volume vessel filled with nitrogen gas. And the electrical triggering signal from delay pulse generators (Stanford Inc., DG 535) was sent to govern the pulse of Nd:YAG laser generator and the shuttering timing of CCD cameras respectively.

As for the test fuel, based on the LAS theory, the different vapor phase of multi-component can be obtained as long as using one fuel of strong absorption for ultraviolet and the other fuel barely absorbs it. While if the two components have strong absorption for ultraviolet wavelength simultaneously, there is a problem to get the vapor phase distribution distinguished from the UV spray image. Nevertheless, the possibility of determining vapor behavior of any component in a multicomponent fuel spray by LAS has been proven in some reports of Zhang [13, 19-20]. With respect to use substitute fuel as the test fuel, it is necessary to meet the similar physical properties and evaporation characteristics of ethanol and gasoline. All the test fuel groups and the comparison of physical properties have been presented in Table 1 and Table 2.

Table 1. Experimental test fuel

	Original Fuel	LAS Test Fuel
E0	Gasoline	p-xylene100
E85	Ethanol85/Gasoline15	(i) MEK85/ p-xylene15
		(ii) Ethanol85/ p-xylene15
		(iii) MEK85/ iso-Octane15
E100	Ethanol	MEK100

Table 2. Fuel properties ($T=293.15K$, $P=1atm$)

	Fuel	Boiling Point [K]	Density [kg/m ³]	Kinetic Viscosity [mm ² /s]	Surface Tension [mN/m]
E0	Gasoline	T10<343 T90<453	<783	0.68	20.8
	iso-octane	372.45	688	0.689	20.8
	p-xylene	411.5	857	0.706	27.8
E85	Ethanol85/ p-xylene15	355.1	805.15	1.164	22.967
	MEK85/ iso-octane15	354.7	791.7	0.555	23.951
	MEK85/ p-xylene15	356.4	817.05	0.544	25.03
E100	Ethanol	351.6	796	1.373	22.27
	MEK	352.68	810	0.49	24.6

The substitute fuel, p-xylene, has similar value of boiling point, density, kinetic viscosity with the original fuel, gasoline. Meanwhile, the substitute fuel, methylethyketone (MEK), and its original fuel, ethanol, shares the similar