

Effect of Ethanol Ratio on Ignition and Combustion of Ethanol-Gasoline Blend Spray in DISI Engine-Like Condition

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ABSTRACT

To reduce carbon dioxide emission and to relieve the demand of fossil fuels, ethanol is regarded as one of the most promising alternative fuels for gasoline. Recently, using ethanol in the state-of-the-art gasoline engine, direct-injection spark-ignition (DISI) engine, has become more attention by researchers due to less knowledge of the ignition and combustion processes in that engine.

In this study, different ethanol-gasoline blended fuels, E0 (100% gasoline), E85 (85% ethanol and 15% gasoline mixed in volume basis) and E100 (100% ethanol) were injected by a valve-covered-orifice (VCO) hole-type nozzle. The experimental environment was set to the condition similar with the near top dead center (TDC) in DISI engine. The high-speed imaging of shadowgraph, OH* chemiluminescence and flame natural luminosity were used to clarify the characteristics of the ignition process, flame development and propagation. Results revealed that the flame propagation was directed towards the downstream of spray but not the upstream where the local mixture became diluted. In comparison to the pure gasoline, adding ethanol increased sensitivity to the spark energy. The good burn showed a fast flame growth and larger flame radius. While the poor combustion revealed a long-narrow flame shape and inferior development of the flame radius. Also, the E85 and E100 demonstrated a moderate natural luminosity or nearly transparent-like appearance. Different ignition position and timing were investigated in this study. The ethanol-gasoline blend showed a potential favorable combustion when the fuel was ignited at advanced timing and the middle to downstream of spray.

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INTRODUCTION

The most significant engineering achievement of the 20th century recognized by society is the automobiles. In every year, about 60 million new personal automobiles and light trucks are built and sold. Nearly all of those are powered by reciprocating-piston internal combustion (IC) engines, which mainly burn petroleum-derived hydrocarbon fuels: gasoline and diesel.

The multi-port fuel injection (PFI) system has been introduced into gasoline engines for many years ago in order to improve the in-cylinder combustion and emission. Although the PFI engines are able to ensure the equivalence ratio $\Phi=1.0$ in chamber which is required for the work of three-way oxidation/reduction catalysts [1,2,3], they still have several disadvantages. The relative low-pressure fuel injector installed in the intake port can cause fuel film on the wall, even on the intake valves leading the unsatisfactory emission during the cold start. Also, the large-scale swirl and tumble flow induced by the intake movement can produce an intense in-cylinder turbulent flows, and hence decrease the cycle-to-cycle variability [4]. In order to prevent the knocking, the compression ratio is limited to $\sim 10:1$ which also restricts the enhancement of thermal efficiency. Moreover, a decrease of fuel economy at part load occurs as a result of the pumping (throttling) losses [5,6,7].

Therefore, the direct-injection spark-ignition (DISI) concept was proposed, and greatly developed in the recent decade. The significant advantages of this system can be summarized as:

- improve volumetric efficiency by the direct fuel injection;
- enhance thermal efficiency by less pumping losses;
- increase specific output at part load by stratified mixture combustion;
- improve fuel economy by precisely transient response of fuel injection;

All these factors are considered as the main reasons to ensure the high efficiency in DISI gasoline engine. On the other hand, because of the energy crisis and more strict emission regulation, the alternative fuels introduced into the gasoline engine is now considerably receiving more attention. Ethanol is regarded as one of the most excellent alternatives for conventional fuels (in particular for the gasoline), since it can be used as a fuel extender for petroleum-derived fuels, oxygenate, an octane enhancer, and a pure fuel [8,9,10]. Thanks to the advantages of higher vaporization heat and increasing octane rating compared with gasoline, adding ethanol allows the DISI engine to achieve, first, the increased thermal efficiency by the deeper cooling charge at the suction stroke [11,12,13], and, second, excellent knock resistant in the high-

compression ratio combustion [14,15]. However, because of the lower heating value ($\sim 66\%$ to gasoline in volume basis) and stoichiometric ratio, more injection mass of ethanol is required to maintain the same air/fuel ratio in combustion. Therefore, if using the ethanol-gasoline blended fuel in DISI engine, some issues should be carefully examined and resolved, such as:

- how the DISI engines fed by ethanol-gasoline perfectly works;
- the mechanism of spray/combustion characteristics of the ethanol-gasoline blend used in DISI system.

Many previous studies have focused on the usage of ethanol-gasoline blend in DISI engine. Chen et al. [16,17] used a multi-hole injector in a DISI engine to study the correlation of particle matter (PM) emissions and the ethanol blending ratio. They reported that the PM emissions could be decreased with the increase of ethanol addition under the rich mixture ($\lambda=0.9$), due to the presence of oxygen in fuel molecule. While in the stoichiometric condition, ethanol addition led to an increase of PM emissions as a result of its higher latent heat at the early injection during the suction stroke. The combustion stability and efficiency of ethanol-gasoline blend in DISI engine were examined by Turner et al. [18], in which showed the result of more stable combustion and higher efficiency for ethanol-gasoline blend. Moreover, NO_x emissions were reduced because of the lower combustion temperature resulted from the higher latent heat of ethanol. This result also was verified by Wallner and Miers [19]. Most of researchers focused on the macroscopic characteristics of engine combustion and emission. However, less reports paid attention to the microscopic characteristics of ethanol-gasoline blend under the DISI-like condition during the combustion, such as the ignition, flame development and propagation.

Therefore, this work was concentrated on the characteristics of ignition and combustion of ethanol-gasoline blend in a high-pressure and high-temperature constant volume vessel. The combustion behaviors of the fuels with different ethanol blending ratio, E0 (100% gasoline), E85 (85% ethanol and 15% gasoline mixed in volume basis) and E100 (100% ethanol), were characterized by several optical observation methods. Typically, the high-speed imaging of shadowgraph was used to clarify the overall process of spray and combustion. While the flame characteristics and appearance were estimated by the OH^* chemiluminescence and flame natural luminosity. Furthermore, the effects of ignition energy, ignition location and timing on the flame development/propagation of different blended fuels were clarified and discussed.

EXPERIMENTAL APPARATUS

Firstly, in order to qualitatively clarify the overview process of spray and combustion (include the spray, ignition and combustion), the Z-type shadowgraph was employed in this study as shown in Fig.1. The xenon flash lamp (Mizojini Optical Co., 1kW) was used as a continuous light source. A white light source is convenient, and in fact, preferred in shadowgraph/schlieren imaging over a laser since it avoids diffraction (or speckle) effects that occur with coherent light source. The point-like light from the xenon lamp was collimated by the first concave mirror, then passed through the

vessel and illuminated the spray. After the light attenuation, the parallel light was re-focused by the second concave mirror and finally captured by a black-white high-speed camera (FASTCAM-APX RS, Photron Co.) which coupled with a Nikon lens ($F=105\text{mm}$, $f/4.0$). In addition, this camera was operated at the 1/10000 frame rate and 512×512 pixels resolution.

Many previous reports have used the shadowgraph/schlieren in premixed mixture to study the laminar or turbulent combustion, since the edges of thin/thick flame can be quantitatively identified based on the schlieren theory [20,21]. In this study, the observation of the flame front in the shadowgraph image may be disturbed by the sooting flames which are resulted by the premixed-diffusion combustion. Therefore, the intermediate specie in the chemical reaction, OH radical, which is regarded as an effective way to clarify the combustion behavior was used in this work. The signal of OH^* chemiluminescence is well employed to characterize the flame front and heat release rate due to its primary production at the near stoichiometric and high-temperature region [22,23]. Although this light-of-sight technique prevents a straightforward interpretation on the local flame compared with the spatial resolved imaging using sheet-like laser beam, the distribution of OH^* intensity can provide an useful information on the global flame development.

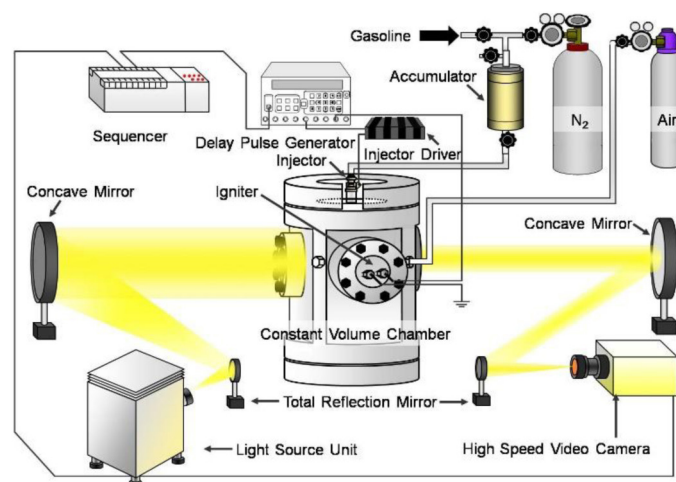


Figure 1. Schematic setup of shadowgraph

On the other hand, compared with the gasoline, the visual characteristics of ethanol-gasoline would be altered due to the ethanol content. The flame natural luminosity (NL) by the direct imaging was employed to clarify the flame appearance of the ethanol-gasoline blends. The simultaneous imaging of the OH^* chemiluminescence and flame natural luminosity are shown in Fig.2.

In the measurement of OH^* emission, since the signal of OH^* was weak, the capturing necessitated the image intensifier (HS-IRO, LaVision Inc) with a carefully chosen gain value of $85\mu\text{s}$ for the reliable image acquisition without saturation. The black-white camera (FASTCAM-APX RS, Photron Co.) was again used to record the OH^* chemiluminescence with a resolution of 512×512 pixels. To avoid the interference from the soot incandescence, a narrow-band filter for the OH^* signal detection is needed. One of the strongest bands of OH^* emission occurs near 310nm . Furthermore, Dec. et al.

[24] reported that the light at near 310nm was dominated by OH* chemiluminescence rather than soot emission. While the soot incandescence became the primary emission at over the wavelength of 340nm. Therefore, a bandpass filter of 313nm (10nm full width at half-maximum (FWHM)) coupled with a UV lens (Nikon, F=105mm, f/5.6), was used to detect the electronically excited A²Σ wavelength from the OH* emission. The frame rate was set to 1/10000. For the direct imaging, a high-sensitive color video camera (MEMRECAM, GX-1, Nac Co.) was employed to capture the flame NL images by a high resolution of 468×468 pixels. A short focus lens (Nikon, F=50mm) was used, the same frame rate (1/10000) was set to the color camera.

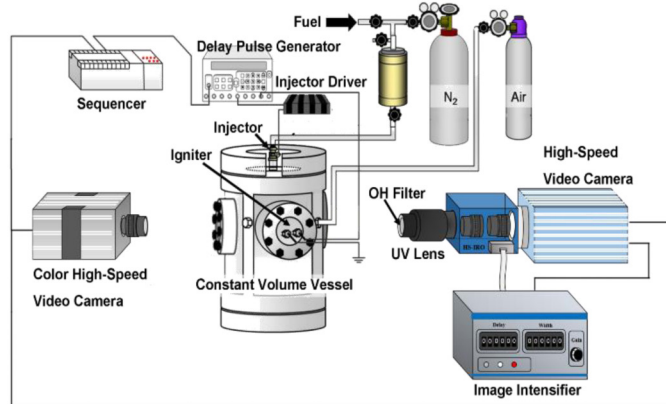


Figure 2. Simultaneous imaging of OH* chemiluminescence and flame natural luminosity

EXPERIMENTAL CONDITIONS

For all of the experiments, the experimental conditions were focused on the condition of that the high pressurized fuel was injected into the chamber at the near top dead center (TDC). Therefore, the ambient pressure of 1.0MPa and ambient temperature of 500K were set in this study respectively. Table 1 shows the list of the experimental conditions and nozzle specifications.

Table 1. Experimental conditions

Ambient Condition			
Ambient Gas	Air		
Ambient Temperature, T_a (K)	500		
Ambient Pressure, P_a (MPa)	1.0		
Injection Condition			
Injector	VCO Single Hole		
Hole Diameter, D (mm)	0.15		
Injection Pressure, P_{inj} (MPa)	20		
Injection Duration (ms)	E0	E85	E100
	1.1	1.42	1.43
Test Fuel			
E0	Gasoline 100%		
E85	Ethanol 85% + Gasoline 15%		
E100	Ethanol 100%		
Ignition Condition			
Ignition Position, $[Z,r]$	[25,3], [35,3], [45,3]		
Ignition Timing, t_{ign} (AEOL, ms)	-0.5, -0.25, 0, 0.25, 0.5		
Ignition Dwell Time, t_d (ms)	2, 3, 4, 5, 6		

AEOI: time after end of injection, ms

The valve-covered-orifice (VCO) injector with a nozzle hole of 0.15mm, was centrally mounted in the top of the vessel cover and pressured to 20MPa. A special igniter with two independent stainless steel electrodes was installed perpendicularly to the spray axis.

Due to the lower air/fuel ratio (AFR) in stoichiometry and the less lower heating value (LHV) of ethanol compared with the gasoline (typical AFR of 9.0 and LHV of 26.99MJ/kg for ethanol, 14.7 and 44.4 MJ/kg for gasoline), more injection mass of ethanol is needed to maintain the same calorific value with the gasoline in the engine chamber. Therefore, the longer injection durations of 1.42 and 1.43ms were set for the E85 and E100 respectively.

The effect of different ethanol blending ratio on the ignition and combustion was investigated under different ignition strategies in this study. The ignition positions were carefully chosen in order to obtain the effective spark and combustion for the comparison and analysis. Previous work demonstrated that the ignition probability would greatly decrease when the fuel was ignited either at the spray axis (affected by dense liquid droplets) or closed to the spray periphery (affected by over-lean mixture) [25]. To prevent these impacts, the appropriate ignition locations, namely [Z,r]=[25,3], [35,3] and [45,3] (which represented upstream, middle and downstream of the spray), were selected. The definition of the ignition position is shown in Fig.3. The capital Z represented the spray axis distance from the nozzle tip. While the radial distance away from the spray axis was denoted by the lower-case r. Also, the ignition timings were set to -0.5, -0.25, 0, 0.25 and 0.5ms time after end of injection (AEOI). Furthermore, different ethanol-gasoline blends were ignited under several spark energies, which were controlled by the ignition dwell time. For example, the ignition dwell time of 2 and 6ms would approximately produce the spark energy of 25.42 and 35.96mJ respectively.

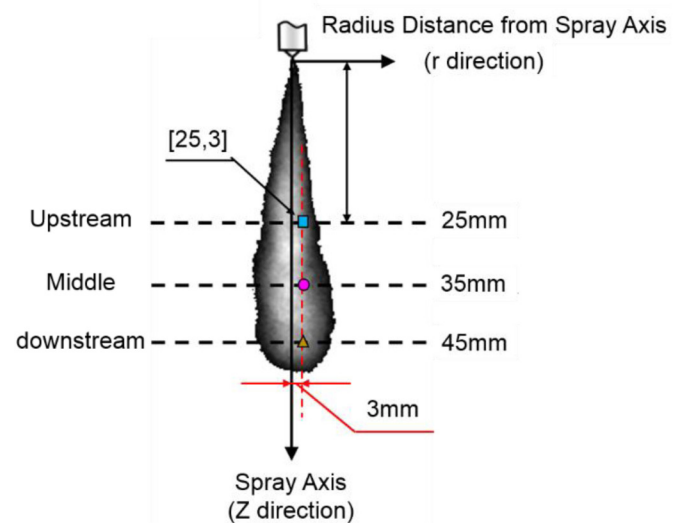


Figure 3. Schematic of ignition location

RESULTS AND DISCUSSION

In this section, the characteristics of ignition, flame development and propagation will be discussed. First of all, the overview of flame propagation was proposed. The four different blended fuels, the

effects of several ignition strategies, such as spark energy, ignition location and timing, on the flame growth and propagation were clarified. Finally, the ignition delay and combustion stability were analyzed and discussed.

Overview of Flame Propagation

Image Results of Shadowgraph

The vapor and liquid phases of fuel spray can be detected simultaneously by the shadowgraph. Even if the separation of those in the liquid-vapor interface is difficult, this method is able to provide an overview image of spray, ignition and combustion. Because the refractive index gradient which was induced by the temperature in the vessel, presented in the ambient gases and along the boundary layer of the observation quartz window. It was hard to clearly clarify the unburnt fuel vapor in the raw shadowgraph images (I_n) as shown in Fig.4 (a) in which presented a typical combustion case of E85 to interpret the flame propagation by shadowgraph.

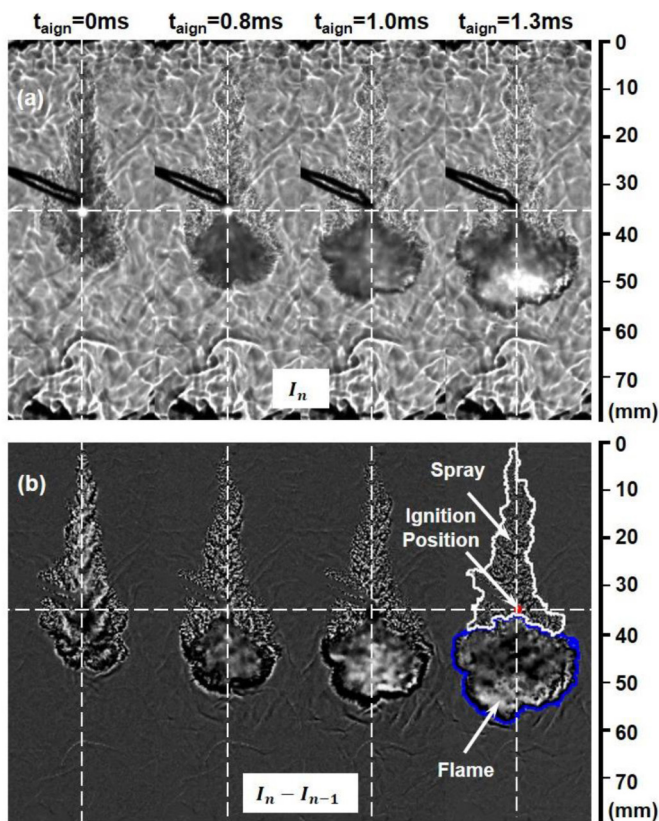


Figure 4. Schematic of flame development by shadowgraph, (a) the original images, (b) the post-processed images, (Fuel: E85, $P_a = 1.0\text{MPa}$, $T_a = 500\text{K}$, $P_{\text{inj}} = 20\text{MPa}$, $[Z, r] = [35, 3]$, $t_{\text{ign}} = 0\text{ms}$ AEOL, $t_d = 6\text{ms}$)

An effective way to resolve the above issue is using the intensity of background in the preceding image to moderate the ambient noise [26]. Figure 4 (b) shows the corrected results processed by the intensity of the current image (I_n) subtracting that of the preceding image (I_{n-1}). The appropriate brightness and contrast are necessary to

highlight the spray and combustion features. Thereafter, less background noise at the successive images can be obtained in the corrected results.

After the ignition and initial development of flame kernel, the flame propagates towards the downstream of spray rather than the upstream. An explanation for this is that the upstream mixture (above ignition position) becomes diluted during the flame fast propagation, because of the bulk air entrained into that region after the end of injection (EOI) [27, 28]. Over lean air-fuel mixture would block the flame propagation. Another possible reason is attributed to the high velocity of the spray. The high spray velocity at the ignition position predicted as 20 to 30m/s at the start of ignition (SOI_g) by the numerical simulation [29], is faster than the maximum flame growth speed (about 14m/s) in this study. Locally speedy spray tends to increase the heat dissipation, then results in the flame front quenching at the interface between the burned and unburned gas. Both the reasons discussed above may contribute to the result of that the flame is impeded to propagate towards upstream of the spray.

One should be mentioned that none luminous flame can be found at the early state of combustion for E85, i.e., before t_{align} (time after start of ignition) = 1.0ms. This flames also are corresponded to the gray-black region in Fig.4 (a) or a smooth gray texture in Fig.4 (b), especially at $t_{\text{align}} = 0.8\text{ms}$. Thereafter, somewhat high luminosity in flame occurs at the flame fully developing ($t_{\text{align}} = 1.3\text{ms}$), which indicates a large amount of soot production.

Flame Visualization by Direct Imaging

Since the ethanol mixing with gasoline would alter the physical and chemical characteristics, one of the noticeable differences in the blended fuel versus gasoline is the visual characteristics of flame. Fig.5 shows the flame natural luminosity and the corresponded profiles of RGB (red, green and blue channels) in a typical case.

For the E0, the profiles of R, G and B are similar to each other due to the pronounced luminous flame. Also this flame is recognized by a large number of pixel near the maximum intensity (255) in R channel. While E85 presents a distinct difference in color channel at the early stage of combustion (see $t_{\text{align}} = 1.0\text{ms}$ in Fig.5 (b)), where the blue channel becomes dominant instead of the red one. However, this feature tends to weak, and becomes similar to E0 since the soot incandescence primarily occurs at the fully developing stage of flame (see from $t_{\text{align}} = 1.6$ to 2.2ms in Fig.5 (b)). On the other hand, the flame of pure ethanol (E100) shows a typical 'transparent' like appearance. Also, the blue color channel becomes dominant in the RGB profile. The E100 shows a less luminosity flame during its whole burning process, which implies that E100 is able to achieve the extremely lower soot emission. Furthermore, it is worth noticing that some bright 'spots' exist in the E100 flame, which highlights the droplet burning.

The result of flame visualization reveals the fact that the ethanol addition is able to delay the early soot production during the combustion and reduce the total soot emission, probably as a result of the oxygen content in ethanol.