



Full Length Article

Characteristics of fuel evaporation, mixture formation and combustion of 2D cavity impinging spray under high-pressure split injection

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ARTICLE INFO

Keywords:

Split injection
2-D piston cavity
LAS
Spray mixture formation
Soot
OH^{*}

ABSTRACT

The objective of this study is to obtain an enhanced understanding of the effect of split injection on the mixture formation and combustion processes of diesel spray. The study focused on the evaporation, mixture, and combustion of diesel fuel under 2D piston cavity sprays with split injection strategies in a constant volume combustion chamber. Three injection strategies with injection pressures of 100 MPa and 160 MPa, respectively, and a single nozzle hole with a diameter of 0.111 mm were employed. The tracer Laser Absorption Scattering (LAS) technique was used to visualize the spray mixture formation process. High speed imaging of OH^{*} chemiluminescence and the two-color method were used to visualize the instantaneous spray combustion process. The experimental results reveal that the vapor distribution of the split main injection with a high injection pressure was more homogeneous than that of a single main injection with low injection pressure at the end of injection (EOI). The split injection can decrease the soot mass. Ignition is more easily during the main injection as a result of the pre-injection. High soot concentration appeared near the cavity wall region under the three injection strategies. The results also indicate that the split injection accelerates the soot oxidation process during the post combustion period.

1. Introduction

Spray-wall interaction is spotlighted by automobile engineers as fuel is injected into small-bore high-speed engines. Spray-wall impingement has a significant influence on mixture formation [1,2], combustion, and emissions in engines [3,4].

Bruneaux et al. [5] studied the air entrainment of an impinging spray and determined that spray-wall interaction also plays a role in air entrainment before impingement occurs. López and Pickett [6] investigated the effect of spray-wall interaction on soot formation processes and demonstrated that soot emissions of impingement flame were lower compared to that of free jet. However, a fuel film was formed after impingement, which caused inadequate combustion and undesirable emissions. Wang et al. [7] determined that flat wall impingement increases soot formation significantly. Dec and Tree [8] also concluded that that spray-wall interaction is likely to increase particulate matter and unburned hydrocarbon emissions and reduce thermal efficiency. Moreover, the structure of the impinging wall in a practical engine is complicated, wherein the impinging spray is formed on the piston crown. Therefore, it is worthwhile to investigate the spray mixture formation and combustion process by employing a 2D piston

cavity which was designed based on the Mazda Skyactiv-D engine.

Recently, multiple-injection has been widely employed [9] to reduce combustion noise and NO_x emissions and enhance soot oxidation rate. The term “split injection” is occasionally used to refer to multiple injection strategies wherein the main injection is split into two smaller injections of approximately equal size or into a smaller pre-injection followed by a main injection [10]. The pre-injection strategy is considered to be one of the most important methods to improve diesel engine performance, emission, and combustion [11]. Ricaud and Lavoisier [9] indicated that the effect of pre-injection depends on the pre-injected mass fraction, injection interval, and pre-injection frequency. With split injection, nitrogen oxide emissions and smoke emissions were reduced because of the moderated combustion speed and enhanced local homogeneity [12]. Skeen et al. [13] investigated the mixing, penetration, and ignition characteristics of high-pressure n-dodecane sprays with a split injection schedule. These studies significantly increased the amount of data available on split injections and improved understanding of split injections. Meanwhile, Nishida et al. [14] observed that the spray tip of the second injection pulse catches up and also passes the first one when the fuel quantity injected in the second pulse is significantly high and the dwell between the two

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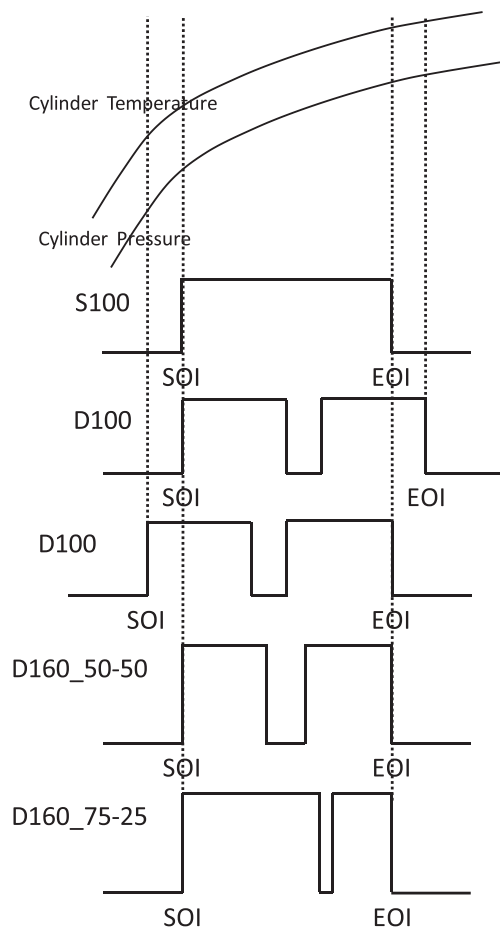


Fig. 1. The diagram of SOI and EOI under different injection strategies.

injection pulses is highly marginal. Nishioka et al. [15] compared the effect of single injection and split injection on a free spray and 2D impinging spray of diesel. It is determined that the soot emission with split injection is lower than that with single injection of free spray. However, soot emission with 2D impinging spray exhibits a trend opposite to that with free spray. Therefore, it is necessary to investigate the spray mixture formation and combustion process by adopting split injection in 2D impinging spray.

The aim of this study is to investigate the effect of split injection on the spray mixture formation and combustion characteristics in a 2D piston cavity with single hole nozzle (0.111 mm) and three injection strategies (Pre+S100, Pre+D160_50-50 and Pre+D160_75-25). Fig. 1 shows the diagram of SOI and EOI under different injection strategies. In order to maintain the same cylinder temperature and pressure at SOI and EOI, high-pressure split injection can be the possible way to achieve this. If just adopt the split injection but keep the same injection pressure, it will show different SOI or EOI. As for different SOI or EOI, the cylinder temperature and pressure are different. As for this, the three injection strategies, Pre+S100, Pre+D160_50-50 and Pre+D160_75-25 were adopted. Moreover, the OH* chemiluminescence and the soot mass which using the Kamimoto [16] method under Pre+S100, Pre+D160_50-50 and Pre+D160_75-25 conditions have been incorporated in this paper. In order to understand the spray mixture formation processes, the tracer LAS technique was employed. In addition, the combustion processes were observed by using a high-speed video camera and measured by using the two-color method and OH* chemiluminescence.

2. Methods

2.1. Tracer LAS technique

2.1.1. Principle and image processing of LAS technique

The details about the principle of the Laser Absorption Scattering (LAS) technique have been discussed in our previous papers [17,18]. In the LAS technique, laser beams comprising two wavelengths (ultra-violet light and visible light) are applied.

Vis light is attenuated only by droplet scattering; UV light is attenuated by droplet scattering as well as liquid and vapor phase absorption. The vapor absorbance can be calculated by subtracting the scattering light attenuation from the absorption light attenuation. The onion-peeling model is used to approximate T_{mix} in the spray.

The spray in a Diesel engine is non-axisymmetric. The onion-peeling model is unavailable to analyze the non-axisymmetric spray when LAS technique is applied. Therefore, Zhang and Nishida [19] modified the LAS technique, which rendered it capable of analyzing the concentrations of non-axisymmetric sprays (Fig. 2).

A blend fuel with 2.5 vol% of α -MN and 97.5 vol% of n-tridecane was adopted. As the blend fuel can satisfy the following requirements: (1) the applied fuels are to be intersoluble; (2) the selected fuels are to exhibit similar vaporizing velocity and other properties as diesel; and (3) the capability of UV beam absorbance to an appropriate level.

2.1.2. Experimental apparatus of LAS technique

The mixture formation process was investigated by tracer LAS technique, and the specific experimental apparatus is illustrated in Fig. 3.

In Fig. 3-(a), UV (ultraviolet, fourth harmonic, 266 nm) and Vis (visible, second harmonic, 512 nm) beams were generated using a pulsed YAG laser (Continuum NY 61-10). First, the two beams were separated by a dichroic mirror and expanded. Then, the two beams were combined and passed through the diffuser (Shinetsu film, polypropylene film) to homogenize the light intensity distribution prior to entering the chamber. Subsequently, the two beams pass through the spray. Then, the two beams were separated and recorded by two CCD cameras (C4880, Hamamatsu Photonics).

In the Mazda Skyactiv-D engine, the focus was on reduction of NO_x [20,21]; an “egg-shaped” engine was designed. Fig. 3-(b) shows the egg-shaped two-dimensional (2D) piston cavity, which was employed to form the impinging spray. The impinging distance between the nozzle tip and impinging point is 30 mm. Although the 2D cavity has the limitation of no air flow and no piston compression, the 2D cavity has the advantage to investigate the fixed compression ratio combustion phenomenon. Even though the 2D cavity has some limitation, we can also analyze the ignition and combustion process because the injection duration is very short.

2.2. Experimental apparatus for combustion observation

OH* chemiluminescence is widely considered as the indicator of high temperature reaction in a flame. The OH* chemiluminescence was evident in the spectral analysis of premixed diesel combustion when implementing the HCCI mode [22]. The energetic reactions and high temperatures in a diesel flame that occur during the stoichiometric combustion of typical hydrocarbon fuels form excited state species that include excited state OH (OH*) [23]. The primary kinetic path for forming OH* is the exothermic reaction $CH + O_2 \rightarrow CO + OH^*$ [23]. Once formed, OH* returns rapidly to its ground state, a portion through chemiluminescent emission and a portion through collisional quenching. For the typical mixing-controlled diesel flame, a distinct OH peak was observed at 310 nm, and a strong gray-body emission dominated the spectrum at wavelengths longer than 340 nm [24].

A high-speed camera (Photron Co., ultima FASTCAM-APX RS) with a Nikkor lens (Nikon, 105 mm, f/4.5) was used to capture the images. A

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