

Analyzing the Cycle-to-Cycle Variations of Vapor and Liquid Phases of Evaporating SIDI Sprays via Proper Orthogonal Decomposition Technique

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ABSTRACT

In this study, the spray characteristics of three multi-hole injectors, namely a 2-hole injector, a 4-hole injector, and a 6-hole injector were investigated under various superheated conditions. Fuel pressure was kept constant at 10MPa. Fuel temperature varied from 20°C to 85°C, and back pressure ranged from 20kPa to 100kPa. Both liquid phase and vapor phase of the spray were investigated via laser induced exciplex fluorescence technique. Proper orthogonal decomposition technique was applied to analyze the cycle-to-cycle variations of the liquid phase and vapor phase of the fuel spray separately. Effects of fuel temperature, back pressure, superheated degree and nozzle number on spray variation were revealed. It shows that higher fuel temperature led to a more stable spray due to enhanced evaporation which eliminated the fluctuating structures along the spray periphery. Higher back pressure led to higher spray variation due to increased interaction between spray and ambient air. In addition, flash boiling sprays were more stable than non-flash boiling sprays. The spray variation of the 6-hole injector was the smallest under all test conditions. It was because a symmetrical hole distribution contributed to a more stable spray structure. Asymmetrically distributed holes would lead to larger spray variation under transition conditions due to more pronounced ambient air effects.

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INTRODUCTION

Fuel spray plays vital role in influencing fuel economy and emission quality in gasoline engines, particularly for the widely adopted spark-ignition direction-injection (SIDI) gasoline engines in modern vehicles [1]. In SIDI gasoline engines, liquid fuel is directly injected into the combustion chamber. The limited time for fuel evaporation and mixing in the combustion chamber has increased the requirements of atomizing and evaporating the liquid fuel. Flash boiling spray has been proven to be of great potential to achieve high fuel economy and emission reduction due to improved fuel atomization and evaporation within an extremely short atomization period [2, 3, 4, 5]. However, enhanced fuel evaporation and air entrainment would lead to strong cycle-to-cycle variation of fuel spray [6]. Strong cycle-to-cycle variations of air-fuel mixing process would result in large coefficient of variation (COV) of indicated mean effective pressure, particularly for stratified-charge lean-burn combustion system. As a result, large variation in mixture formation and combustion would then result in high fuel consumption and poor emission [7]. Therefore, high stability of spray and evaporation process are essential to maintain a stable and efficient combustion.

However, it has been proven that higher fuel pressure and temperature lead to increased spray variation due to stronger fuel evaporation [6]. High back pressure has positive effect on spray variation induced by enhanced air entrainment. In addition, the nozzle configuration also governs the spray stability. According to Marchi [8], the positive-step outward-opening injector produced the most robust spray structure. On the other hand, Chen et al. [9] also illustrated that cycle-to-cycle variations of flow fields and the equivalence ratio distribution at spark timing may lead to misfire of SIDI engines. With the purpose of solving the issues caused by spray variation and obtaining an optimized stable spray, it is of great importance to identify influencing factors that affect the spray structure and evaporation process. Although an extensive amount of work has been done to characterize the flash boiling sprays, very limited work focusing on the cycle-to-cycle variation has been carried out [4-5, 10, 11, 12, 13, 14, 15].

Various methods have been developed to study the spray cycle-to-cycle variations, including presence probability image (PPI) technique [16], constructing mean and root mean square (RMS) image [8], and proper orthogonal decomposition (POD) technique

[17]. All these methods are useful to analyze the cycle-to-cycle variation of pulsing sprays to a certain extent. However, PPI method can only provide a fuel presence probability without spatial resolution of a certain location. Constructing mean and root mean square (RMS) image also provided very limited information about the fuel distribution within different cycles. Recently, Chen [17] proposed a novel method, namely POD, to quantitatively analyze cycle-to-cycle variation of pulsing sprays. The POD was not only useful to assess the spray variation among a large set of cycles, but also could provide detail information about the fuel distribution of each specific cycle. Different modes obtained via POD method also possessed physical meanings. For example, mode 1 captured the ensemble-averaged spray structure, and its coefficients could be used to identify the variation of the intensity. Mode 2 and its coefficients characterized the spatial variation of the fuel plume distribution. Mode 3 and higher modes identified the cycle-to-cycle variations of some small spray structures. It showed that POD was powerful to quantitatively analyze cycle-to-cycle variations of pulsing sprays within a large data set, which would be applied in this research.

In this study, both vapor phase and liquid phase of the spray were captured via laser induced exciplex fluorescence (LIEF) respectively under non-flash boiling and flash boiling conditions. Various injectors with different configurations were investigated. Fuel pressure was maintained constant at 10 MPa. Fuel temperature varied between 45 °C and 85 °C. Back pressure ranged from 20 kPa to 100 kPa. The POD method is applied to analyze the cycle-to-cycle variation of vapor phase and liquid phase separately. At last, the effects of fuel temperature, back pressure, superheated degree and injector configuration on cycle-to-cycle variations of vapor phase and liquid phase of flash boiling sprays are revealed.

EXPERIMENTAL APPARATUS

Figure 1 shows the experimental setup of the LIEF imaging system. It consisted of a constant volume chamber which could mimic engine-like ambient conditions at quiescent state, a back pressure controlling system, a fuel pressure and temperature controlling system, a LIEF optical system and an image acquisition system. The constant volume chamber could reach a wide pressure (absolute) range varied from 10kPa to 2MPa at atmosphere temperature. High pressure larger than 1bar was supplied via a high pressure nitrogen cylinder, and the vacuum was achieved by a vacuum pump. During each test, high purity flow of nitrogen continuously flushed the chamber to prevent the exciplex quenching by oxygen. The fuel pressure was achieved via a piston accumulator pressurized by high pressure nitrogen. Fuel temperature varied from 20°C and 95°C through a water jacket which was controlled by a heat exchanger.

The fourth harmonic of a Nd: YAG laser (Litron, Nano L PIV) with the wavelength of 266nm to illuminate the spray. A laser sheet with thickness of 1mm was generated via a laser arm connected to the output port of the laser. A CCD camera (LaVision Image Intense) equipped with a UV lens (Nikon Rayfact) was used to record the spray images. In addition, an image intensifier (LaVision IRO) was applied to enhance the acquisition of fluorescence intensity. Synchronization among the injection timing, laser and camera was achieved via the LaVision PTU9 programmable unit. Different

optical bandpass filters, namely 289nm/10nm and 365nm/25nm, were used to capture the vapor phase and liquid phase, respectively. More information about LIEF can be found according to the reference [12].

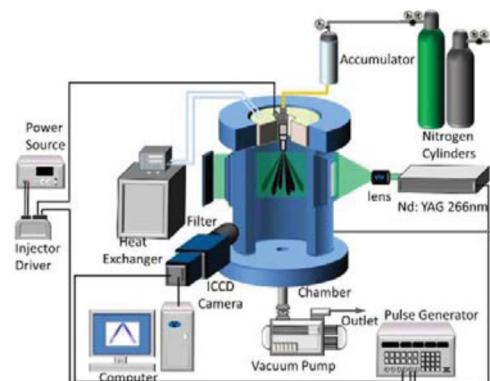


Figure 1. Experimental setup for LIEF imaging system

EXPERIMENTAL CONDITIONS

Table 1. Experimental parameters

Items	Specifications
Injector	2-hole, 4-hole, 6-hole
Injector type	sac injector
Hole diameter	0.2mm
Length-to-diameter ratio of hole	1.5
Injection duration	1.0ms
Injection pressure	10MPa
Injection mass	10.45mg (6-hole injector)
Fuel composition	n-hexane (89%) DEMA (9%) FB (2%)
Fuel temperature	20°C - 85°C
Back pressure	20 – 100kPa (abs.)
Back temperature	25°C +/- 1°C

Table 1 tabulates the experimental parameters. Three injectors with a 2-hole, 4-hole and 6-hole configurations were investigated. For all three injectors, the injection pressure was 10MPa and injection duration was 1.0ms. The injection mass of the 6-hole injector was 10.45mg at aforementioned injection pressure and injection duration. The 6-hole injector was the baseline. Mixture fuel of 89% n-hexane (spectroscopic grade), 9% diethyl-methyl-amine (DEMA) and 2% fluorobenzene (FB), was used as test fuel [12]. Fuel temperature varied between 25°C and 85°C. Back pressure ranged from 20kPa to 100kPa. This setting provided a wide range of superheated conditions as shown in Table 2. According to the research of Zeng et al. [10], this set of test conditions could be divided into three regions, namely non-flash boiling, transition, and flare flash boiling. The superheated degree was defined as the ratio of ambient pressure to vapor pressure

at current fuel temperature (P_a/P_s), which was the same with the difference between fuel temperature and boiling temperature at local ambient pressure [10].

Table 2. Superheated degrees of test conditions

$\frac{P_a}{P_s} \frac{T_{fuel}}{P_{amb}}$	20°C	45°C	65°C	85°C
20kPa	1.00	0.44	0.22	0.12
40kPa		0.89	0.44	0.24
80kPa		1.78	0.88	0.48
100kPa		2.22	1.11	0.61
Non-flash boiling		Transition		Flare flash boiling

INJECTOR NOZZLE CONFIGURATIONS

Nozzle distributions of the three injectors are shown in Figure 2. The cross point of two axis indicates the position of the injector tip. The nominal spray angle between the opposite nozzles was 60°. The length-to-diameter ratios of all injector holes were 1.5. The hole diameter was 0.2mm. Sprays from the nozzles filled with red color were illuminated by the laser and the corresponding plumes were analyzed.

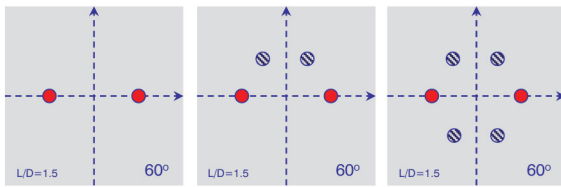


Figure 2. Nozzle distribution of three injectors

OVERVIEW OF POD METHOD

The objective of POD method was to find a sequence of basis functions φ_m to represent the dominant structures from a given scalar field set. It means that the input scalar field V_k can be characterized via the basis functions, shown in equation 1.

$$V^k = \sum_{m=1}^M c_m^k \varphi_m \quad (1)$$

where M is the quantity of the basis functions which always equals the number of input scalar fields, and it is the number of total images in one imaging loop here. φ_m is the m -th basis function, which is the m -th POD mode. c_m is the m -th coefficient of corresponding to m -th POD mode. k is the k -th input scalar field which means the k -th spray image.

All POD modes are orthogonal and normalized. The total image intensity of the k -th input image (E^k) could be calculated via equation (2). It is because the coefficients of POD modes are computed by projecting the input spray images onto basis functions.

$$E^k = \sum_{m=1}^M (c_m^k)^2 \quad (2)$$

Thus the intensity percentage (R_m) of m -th mode can be calculated using equation (3).

$$R_m = \frac{\sum_{k=1}^M (c_m^k)^2}{\sum_{k=1}^M \sum_{j=1}^M (c_j^k)^2} \quad (3)$$

Figure 3 shows a spray image decomposed into 20 POD modes and corresponding coefficients. The spray image and POD modes are scaled differently as shown in the color bar. Positive values of image intensity shown with red color indicated that fuel was present at that corresponding positions. Negative values of image intensity shown with blue color exhibited that no fuel distributed at that position if the coefficient was positive. Blue color and red color alternated in higher modes, which exhibited the smaller fluctuating spray structures. Mode 1 had the largest coefficient compared to that of the higher modes. Figure 4 depicts the intensity percentage of each mode. Modes higher than 2 possessed extremely small intensity of the spray structure. Thus, the analysis of energy intensity of mode 1 could reveal the characteristics of the spray structure. According to the research of Chen et al [17], larger intensity percentage of mode 1 means more stable spray structure, since the ensemble-averaged spray pattern of all input images are fully captured by the mode 1 and its coefficient. Therefore, POD is more insightful if the intensity percentage of mode 1 is used to characterize the spray variation.

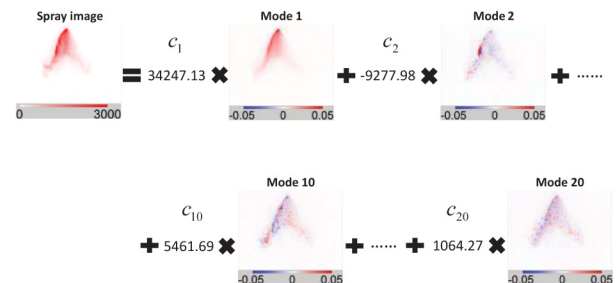


Figure 3. Spray image decomposed into 20 POD modes and corresponding coefficients

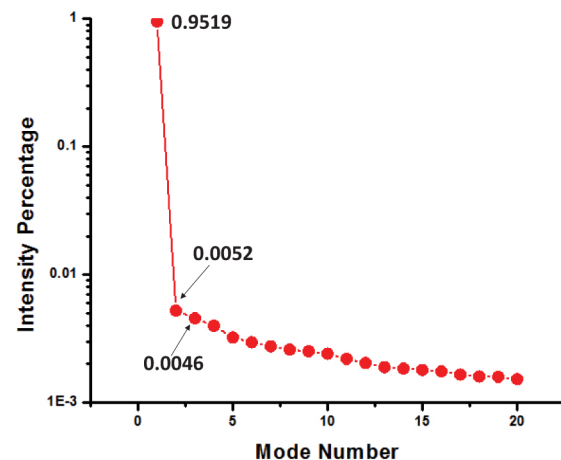


Figure 4. Intensity percentage of each POD mode