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Investigation of the temporal evolution and spatial variation of in-cylinder engine fuel spray characteristics

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ABSTRACT

The proper orthogonal decomposition (POD) method is applied to analyze the pulsing spray characteristics of the fuel injection inside a four-valve optical spark-ignition direct-injection (SIDI) engine. The instantaneous spray structures are decomposed into four parts, namely the mean structure, large scale structure, transition structure and small scale structure, respectively, by using POD quadruple decomposition. The cycle-to-cycle variations (CCV) of the in-cylinder pulsing spray structure are examined separately based on the four parts. Analysis results indicate that the four parts have different characteristics, and each individual part represents a specific instantaneous spray structure. First, the mean part contains more than 90% of the total intensity of the spray field throughout the whole injection process. Moreover, the large scale structure part has the highest CCV level among all four parts, and it dominates the CCV of the entire spray field. The CCV of spray can be influenced by different engine operating conditions. In particular, the in-cylinder flow field has the strongest effect on the spray CCV. The varying motion of the in-cylinder flow field significantly influences the CCV of the large scale spray part, which in turn affects the CCV characteristics of the whole spray field.

1. Introduction

In contrast to the port fuel injection (PFI), the spark-ignition direct injection (SIDI) is designed to provide flexible injection strategy because it can precisely control the quantity and timing of the fuel injection process into the engine cylinder. In addition, the flexible switching between homogeneous and stratified combustion modes under different engine loads provides significant potentials for vehicles with the SIDI engine to increase fuel economy and reduce engine emissions. As a result, many automobile makers have already adopted this technology to develop and manufacture high efficient clean engine.

In SIDI engine, liquid fuel is injected directly into the cylinder. The physical processes of liquid breakup, evaporation, and fuel–air mixing all happen in a very short time duration, especially when the engine is operating at high speed and load conditions. Due to the highly transient manner of the IC-engine, there exists cycle-to-cycle variation (CCV) phenomena, which are reflected in various processes such as in-cylinder turbulent flow, fuel spray injection, fuel–air mixture formation, and combustion. All these CCVs are strongly coupled with each other during engine operation, which could lead to various levels of fluctuations of heat release, fuel consumption, and exhaust emissions. Consequently, high levels of CCV could make harmful impacts on engine performance. For example, in SIDI engine, high speed intake air and the transient movement of intake/exhaust valves and piston can make in-cylinder flow field highly cyclic. Under these transients, numerous local small scale vortexes are randomly distributed among the bulk flow, leading to the obvious flow field CCV. When fuel is injected into this transient environment, the moving air influences the liquid atomization significantly, and clear indication of spray CCV can be observed. The cyclic variations of spray structure pattern might deteriorate the fuel–air mixing CCV, which leads to the combustion instability. Previous engine testing showed that if CCV were to be minimized or largely eliminated, the power output of the engine could be increased up to 10% with the same fuel consumption [1]. Therefore, the research about flow field CCV and in-cylinder spray CCV is a critical step towards the understanding of special CCV phenomenon inside an engine cylinder.

The rapid development in the optical diagnostic techniques can provide powerful technical guidance for the research on engine performance [2–4]. In addition, the advanced numerical simulation tools can also help the researchers to understand the in-cylinder phenomena [5–11]. Extensive research studies have been

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Nomenclature

aSOI	after start of injection
BTDC	before top dead center
CCV	cycle-to-cycle variations
COV	coefficient of variance
PFI	port fuel injection
POD	proper orthogonal decomposition
RMS	root-mean-square
SIDI	spark-ignition direct-injection
$a(t)$	time-dependent coefficient
C_{ij}	correlation tensor
cycle_i	the *i*th cycle
D	space dimension
i, j	different time samplings
N_{mode}	time sampling point number
N_x	space sampling point number
$R_{1,2,3}$	correlated relationship coefficients
R_p	relevance index
S	spray field
s^{large}	large scale structure part
s^{mean}	mean structure part
s^{small}	small scale structure part
$s^{\text{transition}}$	transition structure part
$u^{(i)}$	velocity field
$\Psi(x)$	POD mode

performed to study in-cylinder turbulent flow field CCV [12–20]. In addition, the fuel spray CCV characteristics under realistic engine configurations have also been investigated [21–23]. In the traditional analysis, the phase average or ensemble average method is normally undertaken to study the CCV characteristics, and the original database is separated into a cycle mean part and a cycle fluctuation part. The cycle mean part is used to reflect an entire physical or chemical field characteristics, and the cycle fluctuation part can be used to quantify the CCV intensity. This method is efficient and effective in a stable working condition. However, it still has several limitations. For example, it only uses a root-mean-square (RMS) value to quantify the CCV intensity and ignores the difference among individual cycle detail, especially in an unstable working condition. To resolve this drawback, the proper orthogonal decomposition (POD) method has been deployed. This method can translate an infinite dimensional nonlinear system into a finite one by using a linear combination of a set of functions and their corresponding coefficients. The original field can be separated and reconstructed by using the functions. POD was firstly introduced to the turbulence research by Lumley [23]. Recently, the POD method has been adopted in the engine in-cylinder applications [24–29]. This method can provide a deeper insight into the in-cylinder physical and chemical phenomena including CCV. Extensive work has been performed to investigate the CCV characteristics using the POD method [30–36]. Recently, some researchers used the POD method to separate the in-cylinder flow into different field parts, and then studied the characteristics of each part separately. By doing so, they obtained more insightful details of the in-cylinder flow field [37–39].

A previous study by the author has introduced the POD quadruple decomposition method [5,6]. It has demonstrated that the in-cylinder flow field CCV by using the quadruple POD method can provide more insightful information about the in-cycle turbulent fluctuations and the inter-cycle (i.e. cycle-to-cycle) variations. As a result, the original flow field can be separated and reconstructed into four different parts, and each part has its own characteristics which can be fully connected with others. The CCV characteristics can be revealed through the analysis of each part separately.

In this paper, the CCV of fuel spray is studied using the POD quadruple decomposition method. The original instantaneous spray fields are separated into four parts, namely, (1) mean structure part, (2) large scale structure part, (3) transition structure part, and (4) small scale structure part. Each part represents different structure of the instantaneous spray field. Subsequently, the temporal and spatial evolutions of CCV characteristics of each part are examined separately.

2. Experimental setup and test procedure

The spray imaging experiments were conducted in a four-stroke four valve single-cylinder optical SIDI engine, shown in Fig. 1. The fuel injector had eight holes and delivered a symmetric spray pattern along the imaging plane. The spray angle was 60°. The optical engine had a full quartz glass liner, two pent-roof windows and a quartz-insert piston in order to realize a wide range measurement. The engine was motored at 800 r/min by an AVL AC dynamometer. The engine parameters and operating conditions are summarized in Table 1.

A Nd:YLF laser (527 nm wavelength, 24 mJ/pulse @ 1000 Hz, 100 ns pulse width) was used as the light source to illuminate the spray structure in the engine cylinder. High-speed camera (Vision Research Phantom V7.3) was used to capture the

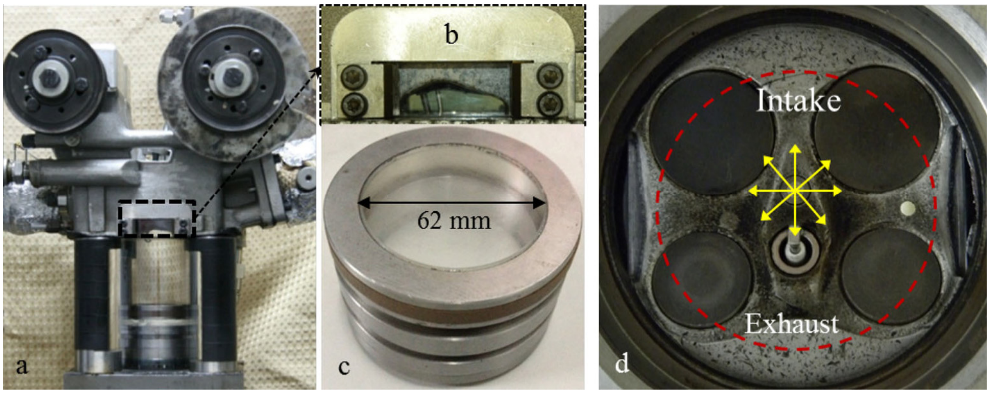

Fig. 1. (a) Optical engine. (b) Pent-roof window. (c) Quartz optical piston. (d) Cylinder head and valve arrangement.