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Cycle-to-cycle variation analysis of early flame propagation in engine cylinder using proper orthogonal decomposition

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ABSTRACT

Experimental investigations on the cycle-to-cycle variations of early flame propagation were conducted at two intake air swirl ratio of 0.55 and 5.68 in a single-cylinder spark-ignition direct-injection (SIDI) optical engine. Both the crank-angle resolved flame images through the quartz insert in the piston and the in-cylinder pressure were simultaneously recorded for 250 consecutive cycles. An algorithm based on the cross-correlation of flame pattern was implemented to compute the two-dimensional velocity fields representing an early flame propagation. Afterwards, the proper orthogonal decomposition (POD) was performed to access the cycle-to-cycle variations of flame propagation. During early flame formation, the uncertainty of velocity was evaluated to be less than 5%. The velocity fields of early flame propagation were significantly affected by in-cylinder air flow. Increasing the swirl ratio from 0.55 to 5.68 augmented the average early flame propagation speed from 2.1 m/s to 3.2 m/s, and the COV of flame speed was reduced from 49.7% to 25.1%. Good correlations were identified between early flame speed and the pressure-derived results. Similar magnitude of reduction in COV (coefficient of variation) of IMEP (indicated mean efficient pressure) & PP was also found. The coefficients of POD mode 1 were found to represent the flame speed, and the remaining higher POD modes were related to the fluctuation in kinetic energy. The POD coefficients showed good correlations with the pressure-derived results such as CA05 (5% of total heat release) & PP (peak pressure). The weak spiral flow pattern, observed within the flame, was only found in higher POD modes. In summary, using the coefficients and modes of POD, the average and fluctuating parts of early flame propagation can be resolved, thereby providing more quantitative information of the cycle-to-cycle variation during the early combustion process in an engine cylinder.

1. Introduction

Strong cycle-to-cycle variations of engine flows often prohibit SIDI engines from reaching their full potential of efficient and clean combustion. It is because the variations of air flow, fuel and temperature distributions in the vicinity of spark plug prior to ignition all affect the early flame formation, propagation and the subsequent combustion processes [1–4]. Therefore, it is essential to investigate the flame propagation at early stage under realistic engine operating conditions. While in-cylinder pressure sensor is widely adopted to collect combustion data, pressure-based data can only provide very limited information when the flame begins at early stage. With the rapid development of high speed imaging hardware [5,6], taking combustion images inside an engine has evolved as a powerful technique to visualize the early flame formation.

The flame propagation speed, which is defined as the propagation rate of the flame through the air–fuel mixture, is a key combustion characteristic of early flame behavior. Previous studies [7,8] quantify the flame growth speed by taking the temporal derivative of flame radius. However, in their studies, only a single speed value was extracted from two sequential flame images, and no information about the velocity field within the flame structure was obtained. In addition, strong cycle-to-cycle variations must also be quantified to provide a complete spatial and temporal description of flame propagation. Since the calculations of flame speed based on flame sizes are inadequate to reveal the spatial information, a novel technique capable of resolving the velocity fields of flame propagating and providing quantitative cycle-to-cycle information is needed.

The current objective is to investigate the cycle-to-cycle variations of velocity fields within the flame pattern propagation at early stage using the proper orthogonal decomposition (POD)

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technique. POD technique has been widely applied by researchers to study the variations in engine turbulent flows [9–11], quantitative comparisons between the velocity fields of simulations and experiments [12–14], misfire analysis [15] and more recently on the variations of scalar fields in engine research [16–18].

In this study, the simultaneous high speed combustion imaging and in-cylinder pressure recording under different intake air swirl conditions are performed in an optical SIDI engine. An algorithm based on the cross-correlation of flame patterns is implemented to compute the velocity fields of flame propagation. Then, POD is conducted on the velocity fields, and the coefficients and modes of POD are used to resolve the average and fluctuating parts of early flame velocity field. It is believed that more quantitative information of the cycle-to-cycle variation at early combustion process will be revealed by this approach. Other POD-based studies on fuel spray development [19] and in-cylinder air flow evolution and variations [20] have been carried out using the same engine. Furthermore, it has been concluded from a previous study [2] that the flame speed increased nearly twice for high swirl compared with that of low swirl, and the flame location was much more repeatable under high swirl condition.

2. Experimental setup and data processing method

2.1. Imaging setup and operating parameters

An optical SIDI engine was utilized in this investigation. Fig. 1 depicts the experimental apparatus. Optical access into combustion chamber was achieved through two pent-roof windows and a quartz-insert piston. A spark plug and eight-hole fuel injector were centrally installed in the cylinder head. A pressure transducer (Kistler 6125A) was mounted to acquire in-cylinder pressure measurements. Heat release analysis of in-cylinder pressure was processed to obtain the engine combustion metrics including CA05 and IMEP.

Other related engine parameters and the test conditions for this investigation are summarized in Table 1. A 14-bit high-speed CMOS camera aiming at a 45° mirror located inside the elongated piston was used to capture the luminosity of combustion. The high-speed imaging system was utilized to capture the flame pattern, which means the gradient of the combustion luminosity. After the engine was stabilized, ninety-one consecutive images (400 × 400 pixels) per engine cycle were recorded at 9600 Hz (two images per CAD). Meanwhile, the in-cylinder pressure was recorded with a 0.1 CAD resolution. Therefore, a total of 250 engine cycles of combustion images together with their in-cylinder pressure were obtained for each test condition.

Table 1
Engine parameters and operating conditions.

Parameter	Value
Bore	86 mm
Stroke	94.6 mm
Clearance volume	54.95 cm^3
Compression ratio	11.0:1
Engine speed	800 rpm
Fuel injection pressure	10 MPa
Fuel mass/cycle	10.7 mg
Manifold absolute pressure (MAP)	40 kPa
Air/fuel ratio	14.7
Start of injection (SOI)	300 °BTDC
Spark timing	15 °BTDC

The operating conditions were selected to mimic an engine idle condition. While keeping other engine parameters constant, the initial combustion process under two extreme intake swirl air conditions was studied. As depicted in Fig. 2, when the swirl control valve was closed, a high swirl condition with a swirl ratio of 5.68 was achieved. In contrast, when the swirl control was in fully open position, it produced a low swirl condition with a swirl ratio of 0.55. The swirl ratio was measured using a steady flow rig. The dash circle in Fig. 2 illustrates the field of view of the cylinder chamber through the quartz piston insert with a diameter of 26 mm.

2.2. Computation of velocity field based on flame pattern

The present study focuses on the early stage of flame formation at 5 °BTDC. As depicted in Fig. 3, two sequential flame images are cross-correlated [21] to compute the velocity field of early flame propagation. It is the gradient of the combustion luminosity from each of the image pair which enables the robust cross-correlation

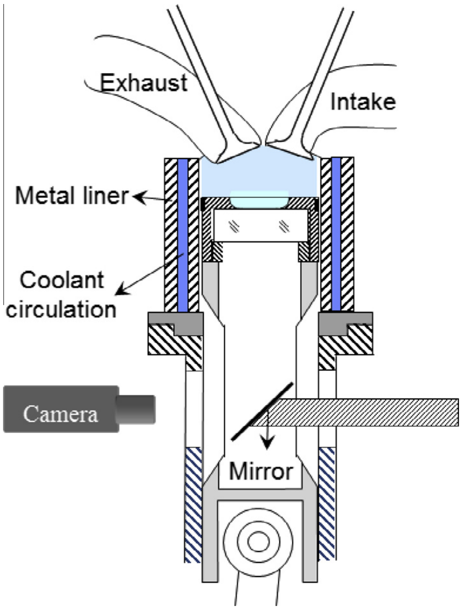

Fig. 1. Experimental setup.

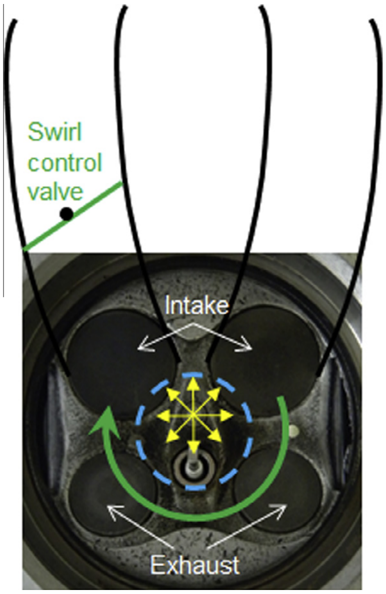

Fig. 2. Bottom view of cylinder head (dashed circle represents the field of view through quartz piston).