Applied Energy 221 (2018) 55–66

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Additional injection timing effects on first cycle during gasoline engine cold start based on ion current detection system

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HIGHLIGHTS

- Diagnosis of misfire are compared for two kinds of ion current detection systems.
- Substantial influential factor is explained for a side-mounted injector engine.
- Mechanism of how the factor works are detailed interpreted by numerical simulation.

ARTICLE INFO

Keywords:
Ion current
Misfiring diagnosis
Additional injection
Additional spark ignition
Emissions
Mixture formation

ABSTRACT

This paper focuses on the first firing cycle of a cold start process as a means to improve combustion performance and reduce emissions during the cold start of a combined injection strategy engine. A novel additional firing strategy, based on a modified form tandem ion current (IC) signal detection system, was applied to avoid an in-cycle misfire condition. Specifically, by detecting the misfire with the IC signal and then using an additional injection and spark ignition strategy, misfire can be avoided in the current cycle by successful survival combustion. However, if the quantity of additional injection fuel is improper, a misfire may still happen even if this strategy is applied. Furthermore, the requirement for additional fuel was found to be sensitive to the primary ignition timing. Thus, the effects of different ignition timings on the combustion and emissions of the first cycle were also studied. If the additional injection occurs near top dead centre, less fuel needs to be injected to avoid misfire. Having the additional injection timing occur too early or too late were both disadvantageous for additional spark ignition. This is determined by spray condition and piston movement in the cylinder, which is explained in detail by numerical simulation in this paper. Increasing the amount of additional injection fuel can stabilise combustion, but this also increases the hydrocarbon (HC), particulate number (PN), and particulate mass (PM) emissions. If the additional spark ignition fails to cause the combustion after additional injection and ignition, the HC emissions will not dramatically increase compared with basic misfire operation, but the PM will. However, the PM emissions are still at the same level as in normal combustion because the basic misfire condition causes ultra-low PM emissions.

1. Introduction

With increasingly stringent emissions regulations proposed for the automobile industry [1], more efforts should be made to reduce hydrocarbon (HC), particulate number (PN), and particulate mass (PM) emissions during cold start. Because of the ineffectiveness of catalysts [2], HC emissions during a cold start are severe and may account for most of the total HC emissions under test procedures such as the Federal Test Procedure (FTP) [3]. Furthermore, misfire can happen during cold start, especially during the first firing cycle, owing to an improper mixture concentration near the spark plug and the low temperatures of the mixture, cylinder wall, and piston [4], resulting in HC emissions many times that of the fired condition. Additionally, during a typical crank-start process, the emitted PN is nearly half of the quantity specified by the Euro 6 limit [5]. Therefore, the application of new strategies to solve these current problems are worth exploring, especially from the perspective of comparisons and trade-offs that can be made.

In-cycle closed loop control is one of the most potential strategies for solving this problem, which involves avoiding misfire when it is detected in the current cycle. It is apparent that this strategy strongly depends on fast response and accurate detection of the in-cylinder condition. The detection of combustion in engines is usually based on

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https://doi.org/10.1016/j.apenergy.2018.03.056
Received 26 November 2017; Received in revised form 19 March 2018; Accepted 22 March 2018

cylinder pressure in the laboratory. However, this is not suitable for utilisation in passenger cars because of excessive cost and durability. Revolution can also reflect some combustion information, for example, misfire. However, it is too late to control or avoid the occurrence of misfire in the current cycle. By contrast, the spark plug ion current (IC) detection method used the spark plug of an engine as a sensor for real-time online detection, which was a simple measurement method.

Previously, many studies have been done on IC detection. Large numbers of experiments have been done on combustors and engines to study the relationship between IC signals and combustion. IC was first used for fundamental research in the field of combustion. For example, it is proved to be able to detect lean blowout in a pulse combustor [6] and is quite useful in an industrial furnace for high-temperature air conditions [7]. More experiments on engines show that the air-fuel ratio can be estimated by the IC current signal under different conditions [8–15]. The IC signal can also be utilised to detect abnormal combustion such as knock in a spark ignition (SI) engine [12,16–18] and misfire [19]. Other engine operating parameters such as start of combustion in the diesel engine [20,21] and homogenous charge compression ignition (HCCI) [22] engine, combustion phase [23,24], and engine-out torque [25] also show good correspondence with the IC signal and can be well predicted. Some research studies also exist on the relationship between emissions and IC. Nitrogen oxide (NOx) emissions in the HCCI engine [26], diesel engine [27], and HCCI engine [28] are studied, and they show good correspondence with IC mainly because of the common influence of temperature on both IC and NOx formation based on chemical kinetics. Soot formation can also be estimated based on IC in [29].

In particular, for misfire detection with an IC signal, it is quite essential that misfire can be efficiently and timely detected, and thus, a control strategy is possible. Accordingly, two forms of IC detection systems are compared for detecting misfire of combustion, and one of them is employed for detailed research in this paper.

Therefore, misfire detection at cold start and in-cycle control are possible, and some work has been done in this regard [4], but there are still issues and uncertainties. For example, the requirements for additional injection fuel have not been thoroughly studied, and the emission effects of additional firing strategies, under conditions of both successful and failed additional firing, are not clear. Considering that the condition of the first combustion cycle at cold start is usually the harshest, the first firing cycle is focused upon in this paper, and efforts are taken to study the requirement for additional injection fuel and its specific effects under different conditions. These issues will be compared and discussed in this paper.

2. Experimental setup

The experiments were performed using a gasoline direct injection (GDI) engine, with a modified port fuel injection (PFI) system added to the intake manifold of the test engine. The specifications of the engine are presented in Table 1, and an overview of the experimental set-up is shown in Fig. 1. A side-mounted engine is employed because fuel spray can be optimised by injection timing and piston movement, which is also shown by numerical simulation. However, an engine with a central-mounted injector is more suitable for the strategy developed in this study and will be compared in later experiments. The engine was tested using a KAMA AC electric dynamometer. The signals for the engine cylinder pressure, crank angle, IC, and HC emissions were simultaneously collected by the NIPCI-6250 high-speed data acquisition card. More importantly, the fuel, intake air, and coolant temperature were kept at 20 °C.

Table 1
Engine specifications.

Parameters/unit	Value
Diameter/mm	82.5
Stroke/mm	92.8
Displacement/L	1.984
Compression ratio	11.5
Fuel injection type	GDI & PFI
Injector position	Side-mounted

A fast-response HC analyser, a Cambustion HFR FID 500 gas analyser, was employed to measure the HC emissions transiently. Its accuracy class is 5×10^{-6} with a response time less than approximately 0.9 ms.

A DMS 500 device, produced by the Cambustion Corporation, was employed to measure particulate numbers ranging from 5 nm to 1000 nm. In this paper, Dp represents the particle diameter, and the size distribution is expressed as dN/dlogDp with the unit of $1/cm^3$.

Based on the field-programmable gate array (FPGA) system, a self-coded control unit was developed to coordinate the engine actuators. Details of the IC detection system and control strategy are explained as follows.

3. IC detection system and IC signal characteristics

In this study, a self-designed IC signal detection system (hereafter called capacity charged system) was established and compared with the most commonly used IC signal detection system (hereafter called bias voltage system). The schematic diagrams of the detection circuits are shown in Fig. 2. For the capacity charged system, the engine spark plug was used as a sensor to detect the IC signal, and this detection circuit mainly consisted of a capacitor, diode, and sliding rheostat element. By making full use of the capacitance characteristics during the data acquisition process, the discharge current charges the capacitor during the period of spark plug ignition discharge, and the capacitor acts as a power source after the end of the ignition discharge. Therefore, the directional movement of charged ions and electrons in the mixed gas forms an IC. The calculated results indicate that the capacitor circuit charging energy is only 0.5 mJ, which will not affect normal ignition when compared with the ignition energy. In addition, the capacitor only releases approximately 10% of its stored energy during the discharge process of each cycle, which means that the actual energy consumption of this IC detection circuit was only 0.05 mJ per cycle, or approximately 1.5% of the original engine ignition energy.

Owing to the inability to isolate the signal interference caused by ignition, the IC signal generally appeared in three parts: the interference of the ignition energy charge, interference of the spark plug ignition energy release, and combustion-related IC. Therefore, this characteristic of the detection circuit can be used for on-board diagnostic (OBD) detection of the engine ignition system and real-time monitoring of the engine ignition timing. However, sometimes a third peak appears, as seen in Fig. 3. This is also caused by spark plug ignition energy release and is revealed by the nonideality of components in the circuit. Furthermore, this third peak interference can be optimised by changing more ideal components. In this study, the effective IC signal is from the combustion-related part to avoid interference from the circuit. In Fig. 3, the IC signal for the misfire and normal conditions are compared, focusing on the part related to combustion. It is obvious that the IC signal voltage was quite small when misfire occurred, and, in comparison, was much larger during the normal combustion condition. Therefore, with careful calibration and validation, this can be utilised to determine the combustion state in the cylinder.

As for the bias voltage system shown in Fig. 2(b), it needs an additional direct current power supply to generate IC. Another obvious difference between a capacity charged system and bias voltage system is the relationship of IC and interference current directions caused by ignition through sample resistance. In the bias voltage system, the currents are in different directions, but in the capacity charged system, they are in the same direction. Signal characteristics of the two systems are compared in Fig. 4, both for misfire operation and normal