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Experimental study of glow plug assisted compression ignition

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ABSTRACT

The purpose of this study is to investigate the effects of glow plug assist on a four-cylinder compression ignition (CI) engine fueled with dieseline. Pressure sensor glow plugs (PSG) are utilized to assist low temperature combustion (LTC) at low to medium load range, and the glow plugs are required for fast response and accurate output control. Therefore, a glow plug control unit (GPCU) is developed, and a closed-loop power feedback control algorithm is used. Equipped with PSGs and GPCU, the engine is tested at three speeds under varying loads. As a part of multi-mode combustion for CI engines, glow plug assisted combustion (GA-CI) appears earlier combustion phases and higher peak in-cylinder pressure. GA-CI can effectively reduce cycle-to-cycle variations and misfire is avoided, especially at low load conditions. The nature of the glow plug assisting process is to enhance the in-cylinder temperature and fuel reactivity. Plus, glow plugs also play a role in triggering the auto-ignition of the pre-mixture. With glow plug assist, NOx emissions rise slightly but are still below 0.2 g/kW h, whereas particulate matter (PM) emissions drop sharply and decrease to under 0.02 g/kW h. Since CO emissions and HC emissions decrease as well, the combustion efficiency is significantly enhanced, with the maximum being over 98%.

1. Introduction

As a combination of gasoline spark ignition and diesel compression ignition, Homogeneous Charge Compression Ignition (HCCI) was proposed and widely investigated due to its high thermal efficiency and low particulate matter (PM) and NOx emissions. However, difficulties in controlling combustion phases and chemical reaction processes drove engine researchers to shift their focus to other low temperature combustion (LTC) modes in order to extend the load limit and improve the combustion performance [1]. In such studies, many assisting methods have been utilized to help the process of compression ignition be more stable and efficient. Spark Assisted Compression Ignition (SACI) and Partially Premixed Compression Ignition (PPCI) were developed as two of the most promising alternative combustion modes for HCCI [2–5]. SACI is described as a bridge across the gap between HCCI and spark ignition (SI) [5]. In the SACI concept a spark plug is used as an additional means of combustion control. It starts propagating a flame and then the rising temperature triggers auto-ignition of the rest of the fuel-air mixture. A negative valve opening (NVO) is usually utilized to trap hot residuals that form at higher pre-combustion temperature and induce the mixture to tend toward auto-ignition [6–8]. However, SACI is still limited in medium to high load conditions due to high cycle to cycle variation [9].

PPCI combines conventional diesel combustion (CDC) and HCCI. In the PPCI concept, gasoline-like fuels are directly injected into the cylinder during the compression stroke, and the end of injection (EOI) is ahead of the start of combustion (SOC) [10,11]. Precise injection control is needed for the formation of the partial pre-mixture. A large amount of exhaust gas recirculation (EGR) is used to prolong the ignition delay in order to form the pre-mixture of fuel and air. Researchers have found that fuels with a low octane number and a high volatility are ideal for PPCI, and studies have been carried out to find the proper fuels compression ignition [12–23]. For instance, Wang et al. [17,18] and Yao et al. [19] tested naphtha under different loads. Wang et al. [20] studied the emission characteristics of biodiesel. Manente et al. [20,21] and Splitter [23] conducted research on a blend of ethanol and gasoline. Liu [24,25] and Tong [26] investigated using a blend of gasoline and polyoxymethylene dimethyl ethers (PODE). Among the above test fuels, the blend of gasoline and diesel, which is also called 'dieseline' [27,28], could be the most feasible solution because it is the easiest to obtain in most commercial markets. Therefore, dieseline seems to have the highest potential to be popularized. According to the research of Xu et al. [27,28], Weall and Collings [29] and Han et al. [30,31], dieseline can maintain the thermal efficiency of diesel while reducing the total concentration and mean diameter of PM emissions significantly.

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Nomenclature

CA10	crank angle when 10% heat is released	LTC	low temperature combustion
CA50	crank angle when 50% heat is released	MPRR	maximum pressure rise rate
CDC	conventional diesel combustion	NVO	negative valve opening
CI	compression ignition	PM	particulate matter
COV	coefficient of variation	PPCI	partially premixed compression ignition
ECU	engine control unit	PSG	pressure sensor glow-plug
EGR	exhaust gas recirculation	PWM	pulse-width modulation
EOI	end of injection	SACI	spark assisted compression ignition
GA-CI	glow plug assist compression ignition	SI	spark ignition
GPCU	glow plug control unit	SOC	start of combustion
HCCI	homogenous charge compression ignition	TDC	top dead center
$IMEP_m$	measured indicated mean effective pressure		

Based on LTC research with dieseline, Yang et al. [32] proposed a multi-mode combustion concept for compression ignition engines. In this study, low temperature combustion (LTC) modes with direct injection were divided into two detailed branches [1,32]. One is early direct-injection LTC, known as PPCI, and it is used for the medium load range due to its higher thermal efficiency and low emission levels. Near-top dead center (TDC) direct-injection LTC is used for medium to high load range because emissions of PPCI deteriorate at such load conditions. However, challenges remain in low load combustion control. Due to differences in fuel reactivity, stable combustion is more difficult to achieve for gasoline-type fuel and in particular for high octane fuels. Some previous studies used spark plug assist [2–5], NVO [33,34], rebreathing [14], and intake heating [35], requiring the diesel engine to have special modifications. In the multi-mode combustion concept, Yang proposed Glow Plug Assisted Compression Ignition (GA-CI) for low load range, which utilized a glow plug as an additional means for increasing the fuel reactivity and helping trigger the pre-mixture to auto-ignite. Of note, glow plugs are commonly equipped on diesel engines and the glow plug used in this study is also a mass-produced product so extra modifications are not necessary.

Generally, glow plugs are designed for cold start assist in diesel engines, and their use for cold start has been widely investigated [36]. Other than cold start assistance, Cheng et al. studied the performance of natural gas ignition assisted with glow plugs. Mueller et al. applied glow plugs for methanol ignition [37]. Ambekar et al. investigated glow plug assist for spray combustion of liquid nitromethane [38]. At the same time, using glow plugs for a gasoline premixed combustion is a relatively new area. Manente et al. applied glow plugs on a model engine [39]. Borgqvist et al. studied the effect of glow plugs on gasoline PPCI combustion, and combustion stability and efficiency were compared with glow plugs turned on or turned off [34]. However, further research on glow plug assist is missing.

In this paper, as a part of the multi-mode combustion concept, GA-CI is proposed and studied via engine experiments. First, the characteristics of the glow plugs are presented and a self-developed control unit is introduced. Second, engine experiments are undertaken at different loads and speeds, and a comparable study of engine performance with or without glow plug assist is presented in this paper.

2. Glow plugs and the glow plug control unit for GA-CI

2.1. Pressure sensor glow plugs (PSG)

The Pressure Sensor Glow Plug (PSG) is a mass-produced resistance-type pressure sensor integrated with a fast response glow plug, which means PSG is a sensor as well as an actuator. In previous studies, the pressure sensor function of PSG played an important role in developing a closed-loop combustion control system based on in-cylinder pressure [40–42]. In this paper, we focus on the glowing function of PSG and using it as one of the actuators of the control system to assist PPCI at low loads.

Zhou et al. undertook experiments to study the glowing performance of three different glow plugs [43]. Their results showed that PSG could achieve much higher temperatures than another two glow plugs at both high and low voltages. At the same time, PSG had the widest high temperature region and the fastest temperature response among the test glow plugs. The excellent performance makes PSG suitable for GA-CI.

The structure of PSG is shown in Fig. 1 [44] consisting of such elements as a glow plug heating rod, a glow plug body, the glow current terminal, a pressure measurement diaphragm, a printed circuit board, and sensor contacts. The dimensions and electric characteristics of PSG are listed in Table 1.

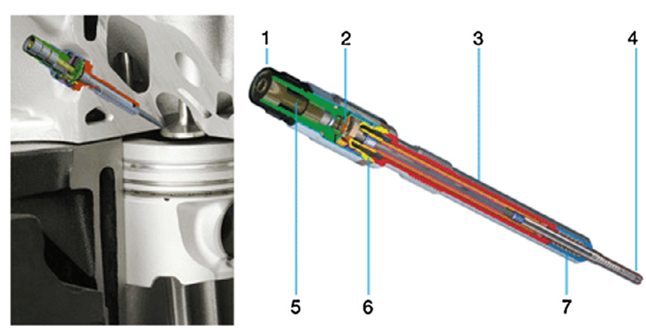

Fig. 1. Components of PSG: 1 – Plug, 2 – Circuit board with electronics, 3 – Glow plug body, 4 – Glow plug heating rod, 5 – High voltage connection, 6 – Measuring diaphragm, 7 – Gasket [44].

Table 1
PSG specifications.

Dimensions	
Rod diameter (mm)	3.3 (front), 4 (rest)
Rod length (mm)	24
Rod thickness (mm)	0.75
Thread	M10
Total length (mm)	148.5
Electrical characteristics	
Maximum voltage (V)	11
Time to reach 1000 °C (s)	<2