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Research on Performance and Temperature Control of Glow Plugs for PPCI Low Load Assist

Tianyuan. Zhou*. Changsheng. Yao*. Yaodong. Hu*. Fuyuan. Yang*. Jinli. Wang*. Minggao. Ouyang*.

** Department of Automotive Engineering, State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing 100084, PR China*

Abstract: Partial premixed compression ignition (PPCI) combustion is one of the most promising concepts to achieve combustion with high efficiency and low engine emissions. Glow plugs can be utilized to increase the combustion stability of PPCI combustion at idle or low loads, assisting the auto-ignition of gasoline or fuel with high octane number, which are major challenges remaining in PPCI combustion. The low load ignition assist application of glow plug is quite different from the traditional cold start assist. Other than simply heating the air in the cylinder, in the PPCI application the glow plug needs to heat the charge to specific temperatures at specific time, because the heating is vital to the ignition timing control in PPCI combustion. As a preliminary work of PPCI combustion low load assist application, in this paper infrared thermometer and some other devices were utilized to study the performance of representative glow plugs in open air. Based on the experiments, GPCU (glow plug control unit) was designed, open-loop and closed-loop temperature control algorithms were proposed. Further a lumped heat capacitance model of the glow plug was built based on system identification to study glow plug surface temperature behavior. It was found that PSG glow plug has excellent performance, maximum temperature of more than 1200°C was observed, 600 °C surface temperature was achieved in around 3 seconds. Open-loop temperature control was verified on GPCU; two glow plug temperature models were proposed, which can estimate the glow plug temperature for feedback control.

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Keywords: PPCI, glow plug, pressure sensor glow plug, preheating control, low load control, cold start.

1. INTRODUCTION

1.1 PPCI combustion overview

HCCI (Homogenous Charge Compression Ignition) is considered as a hybrid concept between gasoline spark ignition engines and diesel compression ignition engines, it has the potential of reducing the engine NO_x and soot emissions to meet the requirements of the stringent emission regulations in combination with high thermal efficiency. Many researches have indicated that despite the low emission and high efficiency characteristics, there are limitations with HCCI in terms of combustion control, power density and maximum pressure rise rate. As a result, HCCI was extended to two branches, SACI (spark assisted compression ignition) and diesel PPCI (partial premixed compression ignition).

SACI can be regarded as an intermediate process between flame propagation in SI (spark ignition) engines and HCCI auto ignition. NVO (negative value overlap) is usually utilized to trap hot residual gases in order to achieve HCCI combustion. However, it was found that the applicability of SACI was limited because it is difficult to master and the cycle to cycle variation is very high, (Manente et al., 2012).

Diesel PPCI is a combination of CI (compression ignition) on diesel engines and HCCI combustion. The fuel is injected during the compression stoke and completed before start of combustion. The charge is typically partially homogenous, which reduces the engine emissions. And as a result of large amount of pre-mixed charge, the combustion speed is high, making the combustion relatively efficient. In PPCI it's desirable to separate the end of injection from the start of combustion, (Suzuki, Koike and Odaka, 1998). The separation can be achieved using a large amount of EGR, low compression ratio etc. Large EGR ratio and low compression ratio contribute to low efficiency and worsened CO (carbon monoxide) and UHC (unburned hydrocarbon) emissions.

Gasoline partial premixed combustion concept was introduced by Kalghatgi in 2006, (Kalghatgi, Risberg and Ångström, 2006; Kalghatgi, Risberg and Angstrom, 2007). In this concept, a fuel which has lower ignitibility is injected in a compression ignition engine. This kind of fuel, e.g. gasoline, which has higher resistance to auto-ignition, enables a longer premixing time from the end of injection to the start of combustion without excessive usage of EGR or low compression ratio.

However, challenges remain in low load control of gasoline partial premixed combustion, in particular for engines running with high octane number fuels. At idle or low loads, it is difficult to reach the conditions, which are necessary for fuel to auto ignite. Borgqvist et al (Borgqvist et al., 2013) used NVO (negative valve overlap) to improve the

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combustion stability at low load and low engine speed operating conditions. The fuel used was 87 RON (research octane number) gasoline. The effect of glow plug was also investigated, but glow plug was not the focus and there was not detailed analysis on the glow plug control. Rebreathing of hot exhaust gases was utilized by Delphi to provide stable compression ignition in a 1.8L gasoline injection compression ignition (GDCI) engine, fuel used was 91 RON gasoline. Ultra-low pressure injection was utilized by Wang (Wang, Yang and Ouyang, 2015) at small load range to improve combustion stability, the fuel used was dieseline of different blend ratios, e.g. G80D20 (volume: 80% gasoline, 20% diesel).

1.2 Combustion assists using glow plugs in internal combustion engines

A typical glow plug is shown in Figure 1. The external cover is usually made of steel, e.g. Inconel, and is usually connected to GND (ground). Inside the cover are the heating resistance R_h (on the right in Fig.1) and controlling resistance R_c (on the left in Fig.1), which are connected in series. The gap between the cover and the resistance is filled with insulation powder. Upon power-on, an electric voltage is built between one end of the controlling resistance and the cover, so that an electric current starts flowing through the coil. At ambient temperature the heating resistance is much larger that the controlling resistance, namely $R_h >> R_c$. This makes sure that R_h generates more heat than R_c, enabling the fast temperature rise at the tip. The controlling resistance R_c is temperature dependent and increases with temperature rise, thus producing more heat at higher temperature. This ensures a more evenly distributed temperature along the glow plug.

Traditionally glow plugs are designed for cold start assist in diesel engines. Numerous research work on glow plug has been done to assist cold start, e.g. glow plug simulation models, (Formaggia et al., 2007); glow plug surface temperature control, (Suteekarn, Sackmann and Guhmann, 2012); influence of glow plug temperature, (McGhee et al., 2012) etc.

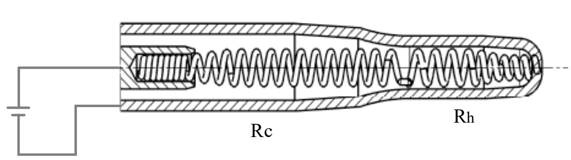

Fig. 1. Typical glow plug geometry (Houben et al., 2007)

Other than the cold start assistance, the usage of glow plugs has been extended to some other applications. Cheng et al (Xu Cheng and Wallace, 2012) studied the transient behaviour of glow plugs in direct injection natural gas engines, the glow plugs were used to assist the ignition of natural gas. Mueller et al (Mueller and Musculus, 2001) investigated the use of glow plug for methanol ignition. A number of research have been done in this field.

However, according to the author's knowledge, the use of glow plug for PPCI low load assist is a relatively new research direction. Borgqvist et al (Borgqvist et al., 2013) investigated the effect of glow plug on gasoline PPCI combustion, only combustion stability and efficiency were compared with glow plug turned on or turned off. Wang (Wang, Yang and Ouyang, 2015) pointed out that it is possible to extend the low load range of gasoline PPCI using glow plug, but there was no result given or further research.

In summary, glow plug has long been studied, but mainly in cold start assistance or natural gas ignition assistance applications. Only few researchers have investigated the use of glow plug for PPCI low load assist. It seems to be a relative new and promising research direction.

1.3 Work carried out in this paper

Based on previous research of glow plug for other applications, the work in this paper is focused on glow plug for PPCI application, in particular at idle or low loads engine operating conditions. Firstly, the glow plug preheating properties e.g. electrical properties and temperature profile, were studied through transient response experiments in open air. Secondly a GPCU (glow plug control unit) was designed, open-loop temperature control algorithm and closed-loop temperature control algorithm were proposed. The open-loop algorithm was verified experimentally based on GPCU; A lumped capacitance model based on system identification was built to study the glow plug surface temperature variation. The work in this paper is the preliminary part of the PPCI combustion low load assist research. As a next step, the in-cylinder preheating test and engine CFD modelling will be done based on the work in this paper.

2. TESTED GLOW PLUGS

2.1 PSG glow plug

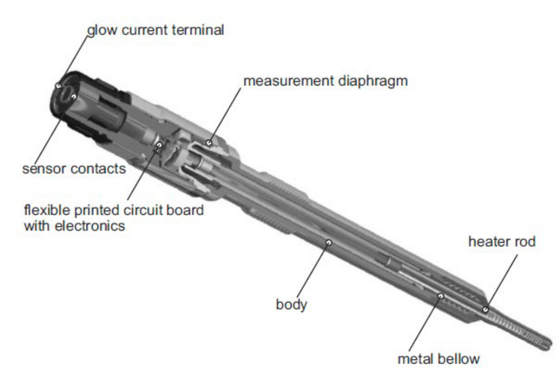

Fig. 2. Components of PSG (Houben et al., 2007)

The glow plug of interest in this research is a mass-produced Pressure Sensor Glow Plug (PSG). The PSG is a fast response glow plug that is capable of cylinder pressure measurement. In-cylinder pressure contains rich combustion information and will be utilized to achieve closed-loop combustion control and to analyse the effect of glow plug on PPCI combustion. However, the focus of this paper is on the glowing function of PSG. Its structure is shown in Figure 2,

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