

A Study of Volumetric Ignition Using High-Speed Plasma for Improving Lean Combustion Performance in Internal Combustion Engines

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ABSTRACT

It is well known that ultra-lean combustion can result in higher thermal efficiency, better fuel economy, and greatly reduced NO_x emissions. Accomplishing ultra-lean combustion is very difficult with a conventional spark plug, and ignition instability can be cited as one of the factors. Therefore, it is thought that ignition system innovation is important for the achievement of ultra-lean combustion in gasoline engines. This study investigated high-speed plasma ignition as a new ignition system for internal combustion engines. High-speed plasma refers to the transient (non-equilibrated) phase of plasma before formation of an arc discharge; it is obtained by applying high voltage with an ultra-short pulse between coaxial cylindrical electrodes. High-speed plasma can inherently form a multi-channel discharge, with the electrical discharge spreading over a much larger volume than a spark discharge does. Accordingly, it is expected to achieve volumetric ignition different from the point ignition of a conventional spark plug. The results of verification experiments conducted with a single-cylinder engine showed that volumetric ignition was achieved with low energy consumption. It was also confirmed that ignitability was improved in comparison with a conventional spark plug. It was observed that the electric field strength in the air gap between the coaxial cylindrical electrodes during high-speed plasma formation was increased more by applying a shorter pulse. It was also clarified experimentally that the shorter pulse improved ignitability even further.

INTRODUCTION

There is a compelling need to curb atmospheric emissions of carbon dioxide (CO₂) that has been identified as a cause of the critical issue of global warming. According to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) [1] the concentration of CO₂ in the atmosphere needs to be stabilized at a level of 550 ppm or less in order to

keep the global mean temperature increase within 2°C. To achieve that target in the short to medium term, further improvements must be made to internal combustion (IC) engines. It is necessary to achieve lean combustion systems that attain the highest thermal efficiency in terms of combustion cycle theory.

In a conventional spark ignition (SI) engine, the spark plug forms a single flame kernel from which the flame propagates and grows in the surrounding area to complete combustion of the air-fuel mixture. In the vicinity of a stoichiometric mixture, stable combustion can be accomplished through the formation and propagation of a stable flame kernel. In a lean combustion region, however, greater flame instability, a longer ignition delay time and an extended main combustion period can cause combustion to become unstable, thereby limiting the region where stable lean combustion is possible. Accordingly, it is thought that innovation in the ignition system is one important factor for expanding the limits of stable lean combustion. In contrast to the single-point ignition of a conventional spark plug system, if volumetric ignition could be accomplished to form multiple flame kernels over a wide area, it could be expected to achieve more stable ignition under adverse combustion environments.

Various studies have been conducted on different ways of improving ignition, including the concept noted above. Research has been done on methods of increasing spark ignition energy, such as by improving plug materials, applying multiple-point or multiple-pulse ignition and lengthening the spark discharge duration. Many of these techniques have applied to production engines. Apart from spark plugs, there are also reports in the literature about a railplug igniter [2] and a plasma jet igniter [3] that inject a high level of energy to disperse thermal plasma over a wide area. Another report [4] describes a method of accomplishing volumetric ignition by discharging combustion gas containing radicals as a result of burning a rich mixture in the plasma cavity of a

plasma jet igniter. However, because all of these approaches are fundamentally based on the formation of high-temperature (thermal) plasma similar to spark ignition, they can result in thermal loss to the electrodes due to an increase in the surrounding gas temperature. The use of high energy injection has revealed the problem of electrode durability, which is currently a major issue blocking practical application of these methods. In place of a combustion gas discharge, another method [5] proposes discharging diesel fuel as the source of ignition. However, this approach requires the addition of a diesel fuel injection system and the construction of two fuel supply systems, which would invariably increase the cost substantially. Laser ignition offers the advantages that there is no thermal damage to the electrodes and that non-contact ignition is possible at any arbitrary position in the combustion chamber. However, a number of issues remain to be addressed, including grime on the laser irradiation port and the efficiency, durability and cost of the laser itself. [6]

This paper focuses on low-temperature (non-thermal) plasma ignition achieved with high-speed pulsed plasma and describes an attempt to apply this technique to an automotive engine which requires ignition under a high ambient pressure condition. This method allows the controllability needed for ignition and offers the possibility of accomplishing volumetric ignition at a low level of energy consumption. The results of analyses are presented that focused specifically on low-temperature plasma characteristics under a high ambient pressure and ignition characteristics in the lean combustion region.

HIGH-SPEED PULSED PLASMA IGNITION

FEATURES OF HIGH-SPEED PULSED PLASMA

High-speed pulsed plasma falls in the category of low-temperature plasma, in contrast to the thermal plasma typified by the arc discharge of a spark plug. Figure 1 outlines the differences between low- and high-temperature plasmas. In the case of thermal plasma, there are sufficient exchanges of kinetic energy among the electrons, ions and molecules such that their temperatures are in a thermal equilibrium state. For that reason, approximately 50% of the energy injected is lost in the form of thermal damage to the electrodes as a result of a rise in the gas temperature. [7] Moreover, because there is only one discharge path, a lot of energy is consumed per discharge volume. In contrast, low-temperature plasma is in a non-thermal equilibrium state in which only the electron temperature is markedly high. High-energy electrons collide with the molecules of fuel and oxygen, generating highly reactive radicals that promote oxidation chain reactions. Low-temperature plasma offers several advantages, including little thermal damage because the gas temperature is not elevated, creation of a volumetric discharge space due to the formation of multiple discharge paths called streamers, and low energy consumption per discharge volume.

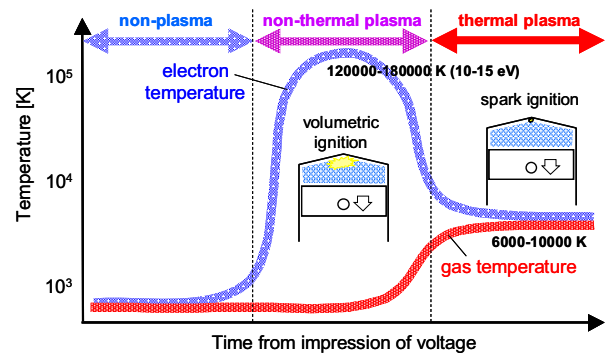


Figure 1: Schematic diagram of two kinds of plasma

There have been reports [8-10] in recent years of research on low-temperature plasma ignition under atmospheric pressure using cylindrical fixed-capacity combustors to examine the possibility of applying this ignition method for rapid combustion in a pulsed denotation engine. The aim of those studies was to achieve volumetric ignition by applying short-pulsed voltage between the electrodes for around 50-100 nsec in order to form low-temperature plasma by blocking the electric field before the arc transition. The electron temperature in such low-temperature plasma reaches more than 10 eV (equivalent to a temperature of approximately 120,000 K), resulting in markedly high electron kinetic energy. [9] In the following discussion, such plasma is referred to as high-speed plasma (HSP) since it is formed by applying ultra-short pulsed voltage.

HIGH-SPEED PULSE GENERATOR

A high-voltage short-pulse generator is needed to form HSP. Figure 2 shows the circuit diagram of the high-voltage short-pulse generator used in this study.

This generator is a lumped Blumlein pulse generator based on the use of a commercial pseudospark switch. The pseudospark switch is a fast gas discharge switch for high power application (model FS 2000) that manufactured by ALSTOM. The basic principle is that the high voltage supplied from a high-voltage DC power source charges a Blumlein path and is switched by means of a pseudospark switch; the voltage is then raised by a ratio of 1:2 by a pulse transformer in the final stage and a short high-voltage pulse is generated between the electrodes. [11]

Figure 3 shows typical waveforms of the output voltage generated by this pulse generator. The pulse has a full width at half maximum (FWHM) of approximately 80 nsec. In this study, a voltage range of 10-50 kV was used in both the discharge and combustion experiments.

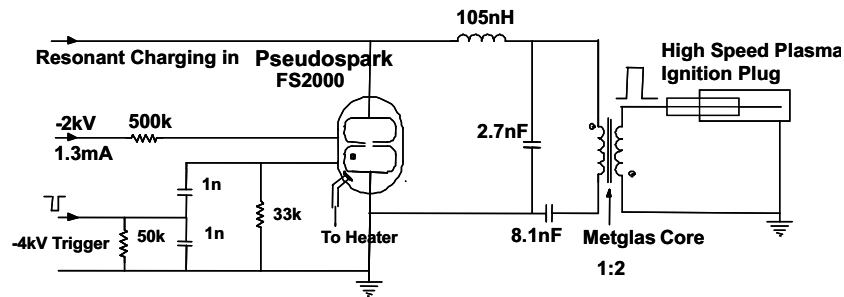


Figure 2: Circuit schematic of high-speed plasma ignition

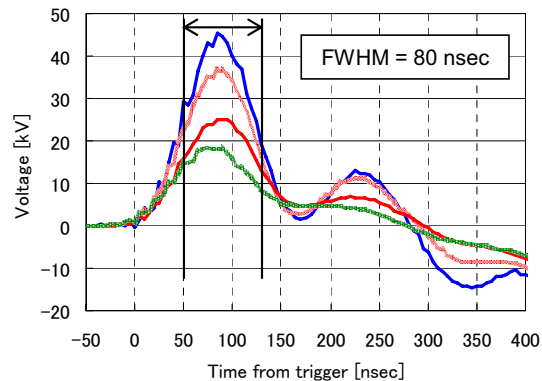


Figure 3: Several output voltage waveforms from HSP circuit

ELECTRODE SPECIFICATIONS FOR HSP IGNITION

Figure 4 is a schematic diagram of the electrode geometry for HSP ignition. A coaxial electrode system was used to produce a volumetric discharge. To obtain the desired discharge volume, the electrode gap was set at 6.4 mm and the central electrode length (L) at either 6 mm or 12 mm. A screw thread with a thread diameter of 2.2 mm and pitch of 0.45 mm was provided on the surface of the central electrode. That served to increase the field strength near the central electrode, making it possible to form more uniform streamers in the circumferential

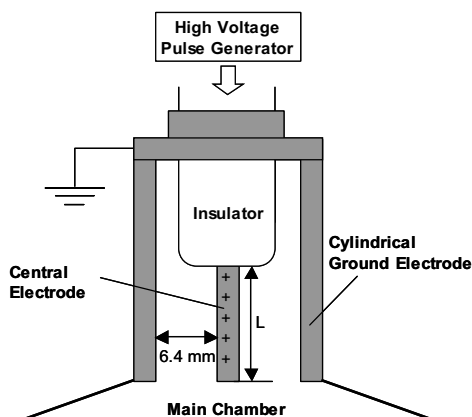


Figure 4: Schematic of high-speed plasma ignition plug

direction of the cylindrical ground electrode. In order to withstand the high voltage, the thickness of the insulator was increased and the corrugated portion was made longer compared with an ordinary spark plug.

TEST ENGINE AND EXPERIMENTAL SETUP

The experimental setup used in this research is shown schematically in Fig. 5, and the specifications of the test engine are given in Table 1. A four-valve single-cylinder engine with a pentroof combustion chamber was used as the test engine. A fuel injector was installed in the intake port, and the electrode system for HSP ignition was provided in the top center of the combustion chamber. The short high-voltage pulse generated by the high-speed pulse generator was applied to the central electrode in response to the ignition trigger. The discharge condition was confirmed by monitoring the output voltage and current waveforms in each cycle with a digital oscilloscope. The cylinder pressure was measured with a pressure sensor and transferred via a charge amplifier and data recorder to a PC terminal for analysis. The heat release rate was calculated on the basis of the recorded cylinder pressure data. In addition to the performance experiments, the discharge phenomena inside the coaxial electrode system and the combustion flame were photographed with an image-intensified charge-coupled device (ICCD) camera or high speed video camera using an optical access engine that facilitated visualization.

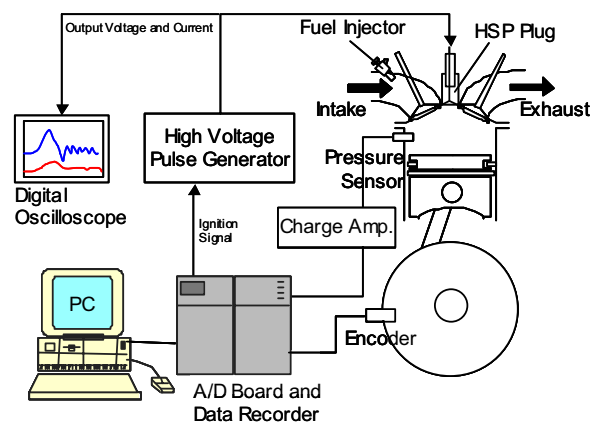


Figure 5: Experimental setup