

Development of a Novel Ignition System Using Repetitive Pulse Discharges: Application to a SI Engine

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ABSTRACT

A newly developed small-sized IES (inductive energy storage) circuit with semiconductor switch at turn-off action was successfully applied to an ignition system. This IES circuit can generate repetitive nanosecond pulse discharges. An ignition system using repetitive nanosecond pulse discharges was investigated as an alternative to conventional spark ignition systems. Experiments were conducted using spherically expanding flame configuration for CH_4 and C_3H_8 -air mixtures under various conditions. The ignition system using repetitive nanosecond pulse discharges was found to improve inflammability of lean combustible mixtures, such as extended flammability limits, shortened ignition delay time, with increasing the number of pulses. The authors seek for the mechanisms for improving the inflammability in more detail to optimize ignition system, and verify the effectiveness of IES circuit in EGR condition, for real engine use. Moreover, an application of this ignition system to a SI engine was conducted. As a result, the lean limit was extended from 20 to 23 in A/F

at IMEP 440 kPa by replacing the ignition system from a conventional one, and indicated thermal efficiency was improved by 11%.

INTRODUCTION

Recently many issues related to automotive engineering, such as the environment and energy problems have gained attention. These social-related issues are giving impetus to the adoption of urgent measures such as alternative fuels and new combustion techniques for the internal combustion engines. Some of the most effective ways to improve the thermal efficiency and to reduce the pollutant emissions of undesirable combustion products, such as nitrogen oxides, are lean-burn technique and EGR (Exhaust gas recirculation) [2]. Although these methods have already been in practical use, there are still many technical problems, such as the substantial decrease in the burning velocity and the large increase in the misfire probability in the lean mixture region. Generally speaking, the minimum ignition energy tends to increase and the burning velocity tends to decrease

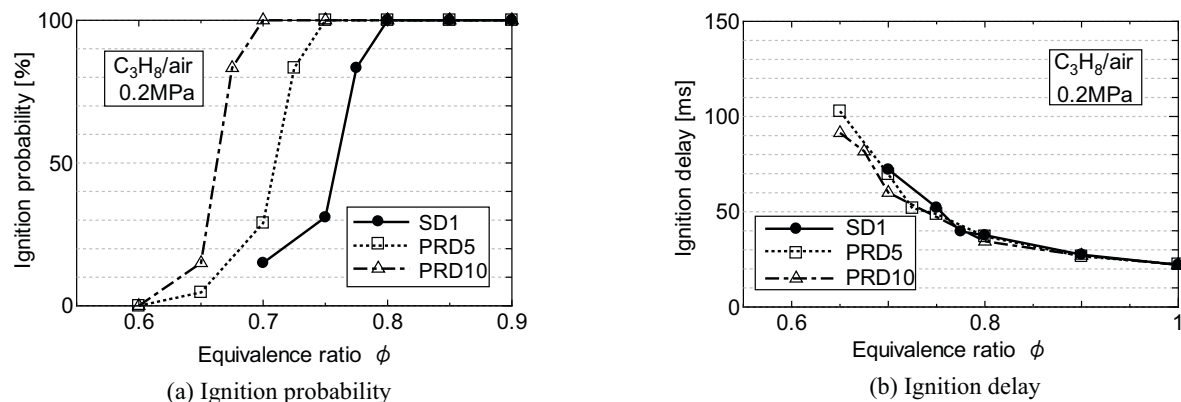


Fig.1 the effect of the discharge types of IES circuit on the inflammability for C₃H₈-air mixtures at 0.2 MPa.

rapidly on the fuel leaner side or by diluting with inert gases [3][4]. To solve the problems, new enhanced ignition systems have been proposed, for example, plasma jet igniters [5], laser ignition [6], rail plug [7], etc. There is, however, still more work to be done on commercial use [8].

As for the new promising ignition systems, ignition systems using nonequilibrium plasmas are recently attracting considerable attention. And some fundamental studies have been already carried out, such as transient plasma discharges by Ronney et al. [9], and high voltage repetitively pulsed nanosecond gas discharge by Pancheshnyi et al. [10], etc.

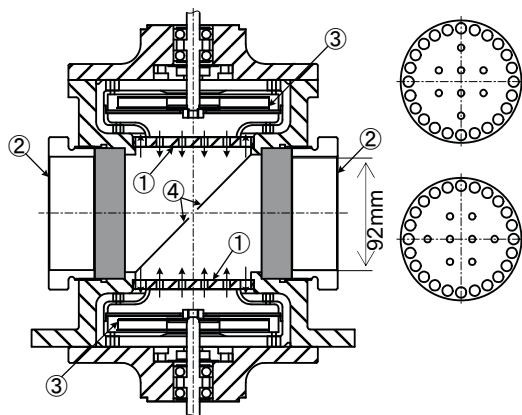
In the previous paper [1], the authors investigated ignition properties of combustible mixtures under various conditions using repetitive pulse discharges generated by a newly developed small-sized IES (inductive energy storage) circuit with semiconductor switch at turn-off action [11]. The IES circuit with semiconductor switch has been developed recently for pulsed power applications, such as plasma surface treatment, plasma sterilization [12] and so on. The study was the first case where this circuit was applied to an ignition system. This IES circuit enables us to set various conditions, such as pulse duration, frequency, number of pulses, easily and strictly. Typical examples of the results mainly obtained by the previous paper [1], which also include the updated data, are shown in Figs.1. Here, SD1 (single pulse) was set to consist only of arc discharge, while PR5 (5 pulses) consist of 2 streamer discharges and 3 arc discharges, and PR10 (10 pulses) consist of 5 streamer discharges and 5 arc discharges (5 kV, 10 ns - 200 ns, 30 kHz). In addition, total ignition energies supplied were estimated to be about 30mJ for all the cases.

Figure 1(a) shows the ignition probability (which was defined as the ratio of number of igniting the whole flame to total number of experiments for each condition) as a function of equivalence ratio at 0.2 MPa for C₃H₈. In Fig.1(a), the equivalence ratios corresponding to 100% ignition probability are found to be 0.8 for SD1, while 0.75 for PRD5 (5 pulses), and 0.7 for PRD10 (10 pulses),

respectively, suggesting that repetitive pulse discharges extend lean flammability limit.

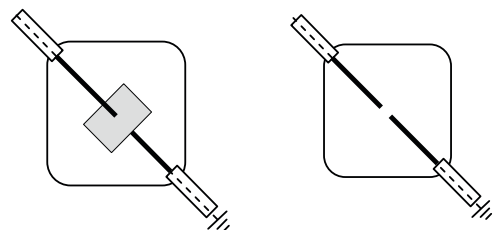
Figure 1(b) shows the ignition delay (which was defined as the interval between the ignition current trigger and the time at which the pressure rose to 10% of its maximum pressure) as a function of equivalence ratio at 0.2 MPa for C₃H₈. In Fig.1(b), there seems to be almost no significant difference near stoichiometric conditions, while differences can be seen on the fuel lean region. At $\phi = 0.8$, the ignition delay time is 38 ms for SD1 (single pulse), while 37 ms for PRD5 (5 pulses), 34 ms for PRD10 (10 pulses), suggesting ignition delay time decreases with increasing the number of pulse. At $\phi = 0.7$, the ignition delay time is 72 ms for SD1, while 70 ms for PRD5, 60 ms for PRD10, suggesting ignition delay time also decreases with increasing the number of pulses. These concluded that repetitive pulse discharges can extend the flammability limit and reduce the ignition delay time (that is, improving the initial combustion phase) in the fuel lean region, as the number of pulses increases. The estimated mechanisms of improving the inflammability using repetitive nanosecond pulse discharges are as follows; streamer discharges occur several times from the beginning, whose pulse duration of 10 ns to 200 ns employed here is expected to generate active species related to combustion process efficiently. After that, nanosecond arc discharges occur also several times, which can create higher energy density and temperature gradient. This leads to transferring generated energy into a combustible mixture with smaller heat loss. These were expected to cause improving ignition properties in fuel lean region. The detailed mechanisms, however, are still unknown.

In this paper, the authors investigate the improving mechanisms, compared with conventional ignition system to optimize the pulse settings for real engine use. Also, the effect of repetitive pulse discharges on the inflammability under diluent condition is examined, considering the application of EGR condition. In addition, this system was applied for a SI (Spark Ignition) engine to indicate the quantitative data superior to a conventional system.



- ① Perforated Plate
- ② Observation Window
- ③ Fan
- ④ Ignition plug

(a) Combustion Chamber



- (1) needle-to-plate type
- (2) needle-to-needle

(b) Ignition plug

Fig.2 Experimental setup

EXPERIMENTAL SETUP

COMBUSTION CHAMBER

The combustion chamber [1] [13] used in this study is a nearly spherical vessel with a mean inner diameter of about 100 mm and a total volume of about 2000 cm³. It is fixed with four transparent windows of 92 mm in diameter at four sides for flame observation, and two perforated plates of 92 mm in diameter at two opposite sides. The cross-sectional view of the combustion chamber observed from the transparent window is shown in Fig.2 (a). Behind each perforated plate, a fan is installed to mix gases. Combustible mixture with a desired composition is ignited at the center region of the chamber using ignition plug. Once combustion was completed, the chamber was vented and the flushed with air to remove condensed water vapor and to cool the system to the allowable initial temperature range of the experiment (298±3K). A TOYODA PMS-5M-10H semiconductor pressure transducer was used with a TOYODA AA3004 amplifier for the measurement of the dynamic system pressure. Both units were calibrated

together using a deadweight calibration system. A YOKOGAWA DL708E digital scope was used to record the pressure and ignition signals for subsequent analysis on a PC.

In this study, needle-to-plate (N-P) type ignition plug was mainly used to enhance the streamer discharge as shown in Fig.2(b)(1), which has high voltage electrode of 1 mm radius with acute needle tip and low voltage electrode with a grounded square disk of 22 mm×28 mm. In addition, needle-to-needle (N-N) type ignition plug was also used for comparison, as shown in Fig.2(b)(2). As for fuel, C₃H₈-air mixtures were used. Initial pressure was set at 0.1 MPa or 0.2 MPa.

IGNITION SYSTEMS

A newly developed small-sized IES (inductive energy storage) circuit with semiconductor switch at turn-off action [1] [11] was used to generate repetitive nanosecond pulse discharges. This IES circuit enables the turn-off voltage rise-up rate (dv/dt) limit of semiconductor switch to be over several 10 times higher than that of the conventional inverter use switching circuit technology, leading to generate the high rise-up voltage pulse. Actually, this IES circuit generated the high dv/dt pulse of over 55kV/μs, to which 4 kV / 30 A semiconductor was applied. In addition, this circuit can operate with low-voltage power supply as low as car battery. The more detail of this circuit and switching mechanism can be obtained in [11]. Electrical parameters were recorded by Hewlett Packard 5450A oscilloscope with the help of Tektronix P6015A high-voltage probe and Pearson Model 2872 current monitor. Examples of voltage trace across the gap and the corresponding current pulse and energy deposition for IES circuit (10 pulses) and conventional ignition system (CIC) are shown in Figs.3 and Figs.4, respectively, for C₃H₈-air with $\phi = 0.7$ at 0.1 MPa. The energy supplied was calculated by time integration of the product of voltage and current. In both figures, IES circuit is found to be able to generate repetitive pulses with by far shorter duration. Total discharge period for 10 pulses of IES circuit is found to be about 400 μs, while even single pulse discharge for CIC lasts for about 400 μs.

Examining the characteristics of IES circuit in detail, in Figs.3, two types of discharges can be identified, that is, high voltage and low current discharges (pulse 1-5 in Figs.3), which have small energy deposition to the plasma (less than 0.1 mJ per pulse), and low voltage and high current discharges (pulse 6-10 in Figs.3), which have higher energy deposition (typically 2 mJ - 30 mJ). The former can be characterized as streamer discharge and the latter can be characterized as arc discharge. The place of the first breakdown pulse in the train (pulse 6 in this case) depends mainly on the composition of mixture, pressure, temperature and interelectrode distance.

Firstly, the authors investigate the ignition properties of IES circuit, by comparing it with conventional ignition system. Then the authors examine the mechanisms for