

Very Lean and Diluted SI Combustion Using a Novel Ignition System with Repetitive Pulse Discharges

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ABSTRACT

A newly developed small-sized IES (inductive energy storage) circuit with semiconductor switch at turn-off action is successfully applied to an ignition system of a small gasoline internal combustion engine. This IES circuit can generate repetitive nanosecond pulse discharges. An ignition system using repetitive nanosecond pulse discharges is investigated as an alternative to a conventional spark ignition system. The present study focuses on the extension of the operational limits for lean and diluted combustion using the repetitive nanosecond pulse discharges.

First, in order to investigate the flame kernel formation process when the repetitive nanosecond pulse discharges are used, the initial flame kernel is observed using Schlieren photography with a high speed camera. As a result, the flame kernel generated by repetitive pulse discharges is larger than by a conventional ignition system. Then, an application of repetitive nanosecond pulse discharges to a single cylinder SI engine is conducted and the operational limit of lean combustion is investigated. The result shows that the lean limit is extended from 20 to 23 in A/F at IMEP 440 kPa by replacing the ignition system from a conventional one. Also, the diluted limit is investigated. The result shows that the diluted limit is extended from 17.5 % to 22.5 % in EGR ratio at IMEP 630 kPa and that thermal efficiency is improved by 5%. The ignition delay and the combustion duration are decreased and the cycle-to-cycle variation of the ignition timing and IMEP are decreased.

INTRODUCTION

An improvement of thermal efficiency without increasing cost much is an urgent issue for small

gasoline engines. Some of the most effective ways to improve thermal efficiency and to reduce the pollutant emissions are lean-burn technique and diluted combustion using EGR (Exhaust gas recirculation) [1]. 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 unstable combustion in the lean or diluted mixture region. Generally speaking, the minimum ignition energy tends to increase and the burning velocity tends to decrease on the fuel leaner side or by diluting with inert gases [2][3]. To solve the problems, new enhanced ignition systems have been proposed, for example, plasma jet igniters [4], laser ignition [5], rail plug [6], etc. There is, however, still more work to be done for commercial use [7].

As a new promising ignition system, nonequilibrium plasmas are attracting considerable attention. Thereby, some fundamental studies have been carried out, such as transient plasma discharges by Ronney et al. [8], and high voltage repetitively pulsed nanosecond gas discharge by Pancheshnyi et al. [9], etc.

In the previous paper [10], 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, Static Induction Thyristor (SiThy), 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 allows to set various conditions, such as pulse duration, frequency, number of pulses.

In the previous research [10], the authors had shown that repetitive short pulses with several nanoseconds

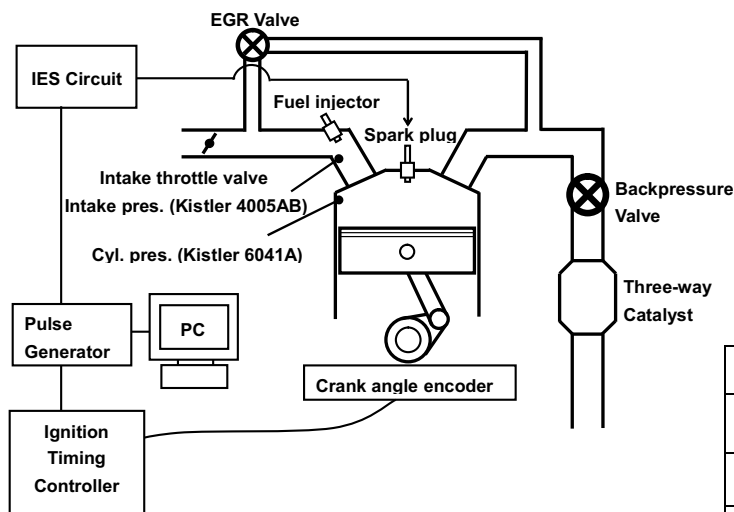


Fig.1 Schematics of test engine and ignition system

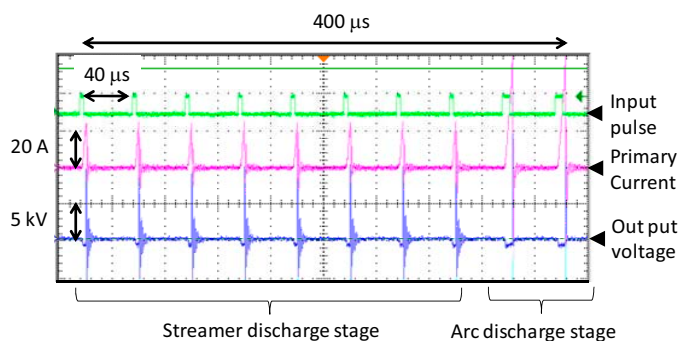


Fig.2 Typical traces of input pulse, current and voltage of repetitive pulse discharges

realized by newly developed IES circuit cause streamer discharges and improve the combustion stability of lean mixture compared to a conventional ignition system using a constant-volume chamber and also an internal combustion engine. In this paper, this ignition system is adopted for a small gasoline engine using both lean and diluted mixtures with much EGR (Exhaust Gas Recirculation) gas to see how much the combustion characteristics can be improved.

EXPERIMENTAL SET UP

IGNITION SYSTEM - A pulse electric power source using IES circuit was used for the ignition high-voltage power source [2]. Using this electric power source, two kinds of discharges of arc and streamer can be realized. The streamer discharge is a nonequilibrium low-temperature plasma where many electric paths appear within a volumetric discharging space. Once this ignition system is used for a spark ignition engine, chemically reactive species are formed with low power consumption and volumetric ignition may be realized. Thereby, the combustion stability with lean or diluted mixture should be improved. Figure 1 shows the schematics of the experimental apparatus with the repetitive pulse ignition system. The crank-angle and TDC of a single-cylinder test engine are detected to determine the ignition timing.

Table 1 Specifications of test engine

Engine type	4-stroke single cylinder
Bore × Stroke	$\phi 75 \times 60$ mm
Compression ratio	10.5
Displacement vol.	265 cc
Fuel supply	Port injection

Table.2 Experimental conditions

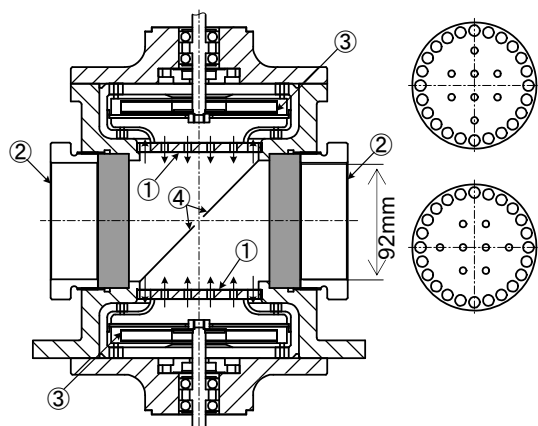
	Lean limit test	EGR limit test
Engine speed	1000 rpm	1000 rpm
IMEP	440 kPa	630 kPa
A/F	14.6 ~ 27	14.6
EGR ratio	0 %	13 % ~ 23 %
Fuel	Gasoline (RON91)	Gasoline (RON91)

To set the repetitive pulses, a pulse-generator that can generate optional signals is used. As the pulse signal is in "High" state, electric energy is charged in the circuit and the charged energy will be discharged in a short duration with high voltage temporal gradient of dV/dt . High voltage acts between the two electrodes. In this experiment, eight pulses for streamer discharges and two pulses for arc discharges are used as shown in Fig. 2. The time period from the pulse onset to the next pulse onset is fixed at 40 μ s, leading to 400 μ s for total discharge duration. The first eight pulses do not consume much electric power because the streamer discharge does not have a large current.

It is worth mentioning that the time period for a single discharge of the IES circuit is much shorter than that of the conventional ignition circuit (CIC). The discharge duration for even single pulse discharge of conventional ignition circuit (CIC) lasts for about 400 μ s, while the total discharge period for 10 pulses of IES circuit is 400 μ s.

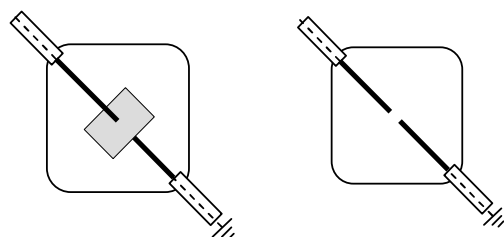
TEST ENGINE AND CONDITIONS - A single-cylinder port-injected gasoline engine with a small displacement of 265 cc is used for tests. The specifications are listed in Table 1. An EGR system is equipped as shown in Fig. 1. EGR ratio is determined by measuring both the CO_2 concentrations of the exhaust gas and the suction gas. Exhaust gas emissions are measured using a portable analyzer (HORIBA MEXA-554J). As this analyzer uses NDIR, the accuracy of THC is not so good. A/F and NO concentration are measured using a Zirconia sensor (HORIBA MEXA-720NOx). In-cylinder pressure is measured using a water cooled piezoelectric sensor (Kistler 6041A).

Table 2 shows experimental conditions. Two systematic experiments are conducted to examine both the limits of lean and diluted combustion. For the lean limit testing, IMEP is constant at 440 kPa with varying A/F without EGR while IMEP is constant at 630



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

(a) Combustion Chamber



(1) needle-to-plate type

(2) needle-to-needle

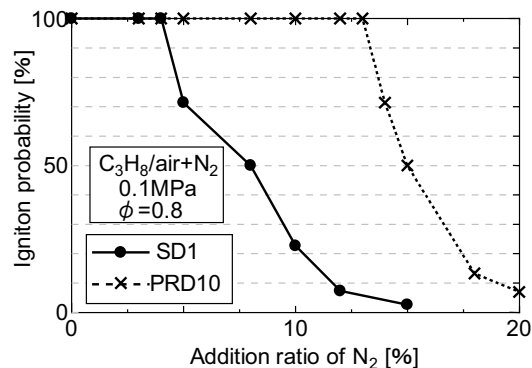
(b) Ignition plug

Fig. 3 Experimental setup using constant-volume chamber and ignition plug

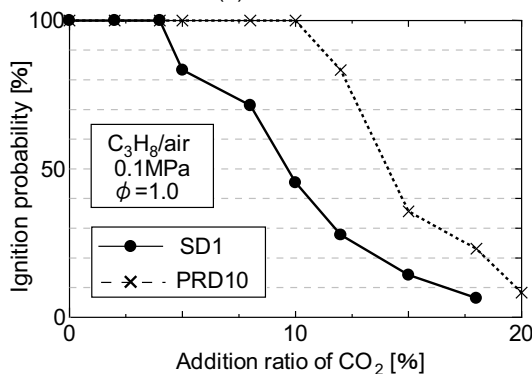
kPa with varying EGR ratio in stoichiometric A/F for the dilution limit testing.

RESULTS AND DISCUSSION

IGNITION CHARACTERISTICS OF DILUTED COMBUSTION IN A CONSTANT-VOLUME CHAMBER - At first, the dilution limit is examined using a constant-volume chamber with inert gases. Figure 3(a) shows a structure of the chamber; the combustion chamber is a nearly spherical vessel with a mean inner diameter of about 100 mm and a total volume of about 2000 cc. Four transparent windows of 92 mm in diameter at four sides are equipped for flame observation, and two perforated plates of 92 mm in diameter are at two opposite sides. The cross-sectional view of the combustion chamber observed from the transparent window is shown in Fig. 3(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 an ignition plug. Once combustion is completed, the chamber is vented and flushed with air to remove condensed water vapor and to cool the system to the allowable initial temperature range of the experiment($298 \pm 3K$).



(a) N₂ dilution



(b) CO₂ dilution

Fig.4 Ignition probability for N₂ and CO₂ dilution

A semiconductor pressure transducer is used for the measurement of the dynamic system pressure. In this study, a needle-to-plate (N-P) type ignition plug is mainly used to enhance the streamer discharge as shown in Fig. 3 (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 x 28 mm. In addition, a needle-to-needle (N-N) type ignition plug is also used for comparison, as shown in Fig. 3 (b)(2). As for fuel, C₃H₈-air mixtures are used. Initial pressure is set at 0.1 MPa.

The effect of repetitive pulse discharges on the inflammability under diluted condition was examined. Figures 4(a), (b) show the ignition probability as a function of the addition ratio of inert gas (which is defined as the volume ratio of inert gas to the C₃H₈-air mixture with $\phi=0.8$ and 1.0) at 0.1 MPa for N₂ dilution and CO₂ dilution, respectively. Here, N-P type plug with 2.5mm spark gap was used. In Fig. 4(a) for N₂ dilution, the amount of N₂ addition corresponding to 100% ignition probability was found to be 4% for single pulse, while 13% for repetitive 10 pulses, respectively, suggesting that repetitive pulse discharges extended the dilution limit for N₂ dilution mixtures. On the other hand, in Fig. 4 (b) for CO₂ dilution, the amount of CO₂ addition corresponding to 100% ignition probability was found to be 4% for single pulse, while 10% for repetitive 10 pulses, respectively, suggesting that repetitive pulse discharges also extended the dilution limit for CO₂ dilution mixtures.