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Turbulent flame propagation enhancement by application of dielectric barrier discharge to fuel-air mixtures

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ABSTRACT

The promotional effect of non-thermal plasma (NTP) on lean flame propagation in turbulent fuel-air mixtures in a reciprocating engine-like high-temperature and -pressure environment was investigated. A turbulent flow was created by installing a perforated plate with oblique holes in the combustion chamber of a rapid compression and expansion machine (RCEM). Ignition was conducted by conventional spark plug. The NTP was generated by a dielectric-barrier discharge (DBD) device installed in the combustion chamber near the spark plug. A portion of the lean fuel-air mixture ($\phi = 0.5$) in the chamber passed through the NTP and diffused throughout the chamber before spark ignition. To elucidate whether the effect persisted even when the plasma-affected volume was diffused by the flow, two types of experiments with temporal delay were conducted. The fuels evaluated were n-heptane as a representative fuel with a strong low-temperature oxidation reaction, i-octane as a representative fuel with a weak low-temperature reaction, and a primary reference fuel consisting of a mixture of these two fuels. Temporal growth of the flame was observed using a high-speed camera with an image intensifier. The evolution of in-cylinder pressure was also monitored and the characteristic time of the mass fraction burned was evaluated accordingly. It was found that flame propagation was promoted by DBD for n-heptane-containing mixtures at a certain initial temperature while the i-octane-air mixture did not exhibit such enhancement. The results obtained suggest that long-lived intermediate chemical species formed by the plasma diffuse into the cylinder, affecting flame propagation through promotion of a low-temperature oxidation reaction. In addition to these findings, the effect of NTP on burning periods were evaluated.

1. Introduction

Lean combustion of premixed-charge spark-ignition engines is a key energy efficiency technology. The use of turbulent combustion is necessary to promote this in practical situations. A rotating flow, such as a swirl and tumble flow, increases the intensity of turbulence during combustion and reduces the burning time, resulting in increased thermal efficiency. The optimal use of turbulence is required to minimize heat transfer to the wall [1]. Excessively strong turbulence may induce quenching effects, which are greater with leaner hydrocarbon mixtures [2]. Additional combustion-assisting technologies are required to achieve stable leaner combustion.

Plasma-assisted ignition/combustion (PAI/PAC) has been actively studied over the past decade. PAC mainly utilizes non-thermal plasma (NTP), in which the electron temperature is higher than the ion and neutral-molecule temperature [3,4]. In NTP, it is possible to generate radicals and ions that are difficult to form in thermal equilibrium. Extension of the lean ignition limit [5] and stabilization of laminar and turbulent flames [6,7] have been reported.

On the contrary, few studies on the effects of plasma on flame propagation have been reported so far. Ombrello et al. [8] showed that by mixing ozone with a density of several thousand ppm into a C_3H_8 lifted flame, the flame propagation speed was increased by several percent. Similar effects of flame propagation enhancement by ozone were reported by Wang et al. [9]. The presence of ozone molecules in the methane-air combustion system can enhance the flame velocity through chain branching reactions and thermal effects. Recently, the effect of ozone on flame speeds was investigated under elevated pressures [10]. An increase in laminar burning velocity by ozone addition in saturated hydrocarbons and a decrease in the case of unsaturated hydrocarbons were reported. These phenomena were explained in terms of heat loss induced by the exothermic ozonolysis reaction in the mixing process.

Other flame propagation enhancement methods using low-temperature chemistry (LTC) have also been recently reported.

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Ju et al. [11] showed the effects of LTC and transport on flame propagation. They found the existence of six different combustion regimes in their simulations. Pan et al. [12] conducted numerical simulation of flame propagation for n-heptane and showed an increase of flame propagation in the negative temperature coefficient (NTC) region of 750 K to 900 K. Bradley and Morley reported that, since flame propagation speed is usually governed by a high-temperature reaction, the effect of LTC on propagation is small [13]. However, the sensitivity analysis by Pan et al. showed that the flame propagation promotion effect is governed by auto-ignition chemistry.

Concerning the effect of NTP on large hydrocarbon fuels, Nagaraja et al. [14] showed the effect of NTP on auto-ignition for n-heptane. They found a significant effect in the 550–650 K region. They also reported that the abstraction of H from large fuel molecules by plasma application is effective at the beginning of two-stage ignition and promotes chain branching reactions for low-temperature oxidation reactions. Plasma application after the first heat generation produces the effect, mainly through the thermal effect of the plasma. Rousso et al. [15] also investigated the effect of NTP on fuel-air mixtures. Their sampling and tunable diode laser absorption spectroscopy (TDLAS) measurements revealed a discrepancy between the model and experimental results, suggesting that there are missing reaction pathways.

As described above, since NTP can enhance LTC reactions, it is highly likely to have an effect on flame propagation. In our previous report [16], we observed the acceleration of flame propagation velocity by NTP generated by dielectric barrier discharge (DBD) using a rapid compression and expansion machine (RCEM). DBD, which is a type of NTP discharge, was adopted because of the flush-mounting capability and high durability of the DBD device. The dependence of the DBD effect on the initial temperature, fuel, and equivalence ratio were examined and the threshold temperature at which acceleration takes place in the quiescent condition was elucidated.

Only a few studies on the effects of turbulence on plasma-assisted ignition/combustion have been reported. Among these, ignition in a turbulent environment by nanosecond repetitive discharges was investigated numerically by Castela et al. [17]. They found that radicals supplied by the discharges may have been affected by the turbulence due to diffusion of the reactive species, and succeeded in demonstrating ignition up to $Re_t = 395$. Won et al. [18] experimentally demonstrated the enhancement of turbulent burning velocity through the influence of low-temperature oxidation of n-heptane. They observed an increase in turbulent flame velocities by producing intermediate species in the pre-flame zone. Clarification of the effects of turbulence on PAC still remains an important task.

In the present study, the promotional effect of NTP on the acceleration of flame propagation and/or shortening of the flame development time in a turbulent environment was examined to elucidate whether the effect persists even when the plasma-affected volume diffuses. The DBD was generated at the inner surface of the combustion chamber of the RCEM prior to the discharge of the spark plug for ignition. The dependence of flame development on the type of fuel and the temperature was examined. In the following sections, we describe the experimental setup and procedure, including the RCEM and DBD, and explain the results obtained on the effect of DBD on flame propagation from the measurement of pressure histories. The results are then discussed in relation to their dependence on the fuel and temperature.

2. Experimental setup and procedure

In this study, to examine the effect of DBD on flame propagation in an engine-like environment, a flow was generated in the combustion chamber of an RCEM. The barrier and spark discharge were generated in the chamber, and flame propagation was visualized using a high-speed camera. The barrier discharge was formed prior to the spark discharge, which was dedicated to ignition. The experimental equipment and procedure are described in detail below.

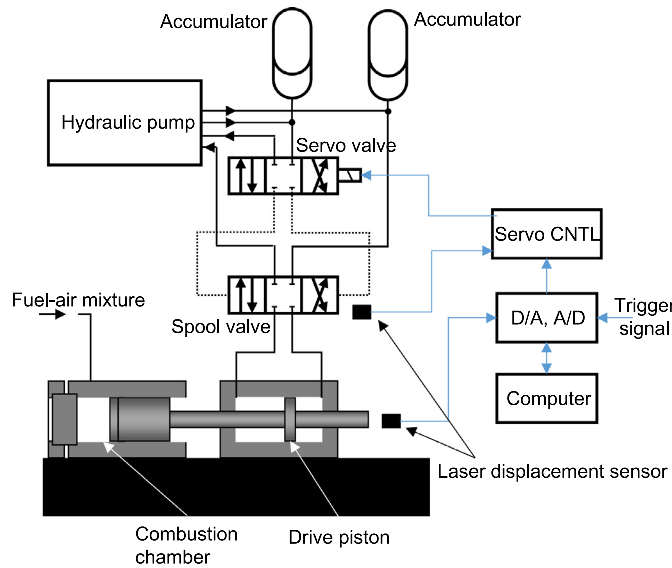

Fig. 1. Schematic of the RCEM.

A schematic of the RCEM is shown in Fig. 1. The RCEM we used is same as that described in reference [19]. The piston of the RCEM is driven by hydraulic pressure with feedback control by computer according to the measurements of laser displacement sensors. It can generate a maximum pressure of 15 MPa with a maximum compression velocity of 8 m/s. The combustion chamber is heated by a circulating oil heater to achieve a homogeneous initial temperature distribution. The bore and stroke are 10 cm and 12 cm, respectively.

The DBD device and spark plug are located in the upper wall of the combustion chamber. A cross-sectional view of the plate and details of the DBD plasma reactor are shown in Fig. 2. Another cylinder supporting the perforated plate was inserted into the cylinder. The perforated plate had 40 holes of 4 mm in diameter, positioned diagonally at 45° and in a staggered orientation to form turbulence. At the top dead center, the piston was stopped at 0.5 mm in front of this plate. During the compression stroke, the fuel-air mixture blown out from each hole interacted to form a turbulent flow. An outline of the DBD plasma reactor and spark plug in the chamber wall is shown in Fig. 2(a) and 2(b). The metal part used for affixing this ceramic piece served as an exposed electrode. Fig. 2(c) shows a photograph of the alumina ceramic piece that was used, which was equipped with an embedded electrode and had a hole at the center for the spark plug. The depth of the embedded electrode from the surface was 300 µm. Surface DBD was generated around the spark plug by applying an AC sinusoidal high voltage with a frequency of 15 kHz. A portion of the fuel-air mixture that passed through the DBD plasma was diffused by the in-cylinder flow. Flow would also be expected to be induced by the DBD plasma's electrohydrodynamic (EHD) effect, but since the velocity of the EHD effect was only approximately 1 m/s, it was considered to be negligible.

Since the premixed gas is charged over a period of about 1 minute, no noticeable turbulent flow is usually formed in the cylinder by the induction process. In addition, it was confirmed that the flow generated by the piston movement is less than 1 m/s.