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Acceleration of DDT by non-thermal plasma in a single-trial detonation tube

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Abstract This paper compares the flame acceleration in single-trial dual-detonation tubes triggered by a spark plug and non-thermal plasma igniter. The low-temperature plasma was generated by an in-house novel AC-driven dielectric barrier discharge igniter, which reduces the power supply requirements and was applied in the quiescent ignition of a single-trial detonation tube. Three different types of detonation mixtures were tested with flame propagation tracked by ion probes and pressure waves recorded by high-frequency pressure transducers. The flame propagation speeds were calculated and compared based on signals from the ion probes. The detonation combustion succeeded in the dual tubes, but the deflagration-to-detonation transition could be significantly accelerated by the plasma for all mixtures, as it was shortened by more than 50% compared to that of the spark plug. The present study provides a suitable technological approach for igniters of PDEs.

1. Introduction

In practical applications, it is important to shorten the Deflagration-to-Detonation Transition (DDT) to increase the operating frequency of Pulse Detonation Engines (PDEs). Therefore, different approaches are employed either to intensify the ignition success by high-energy injection or to increase the turbulence with spoilers inside the detonation tube, by either using shock wave interactions or a pre-detonation tube.[1–5]

An electric spark plug is commonly used to ignite the mixture in the detonation tube because it is easy and cheap. However, long-duration DDTs usually occur and are quite dependent on the ignition energy and position of the spark plug even for appropriate air–fuel ratios. One can realize independent DDT, but one must increase the spark plug ignition energy, for instance, to higher than 0.5 J,[6,7] though this is quite expensive. The dead weight of such a spark plug is also very heavy. It has been found that low-temperature plasma can enhance ignition and assist in combustion.[8,9] Thus, plasma-assisted flow control, ignition, and combustion have been further studied for application in PDEs.[10–12]

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Nanosecond pulsed high-voltage discharge technology has been validated for its capability in igniting different detonation mixtures. Wang et al.[13,14] used the 80 kV voltage and 50 ns pulsed discharge to ignite a C_2H_4/air mixture and found that the ignition delay time was significantly reduced compared with that by electric spark plug ignition. Singleton et al.[15,16] used a 90 kV voltage and 85 ns pulsed discharge or 60 kV and 54 ns pulsed discharge to ignite a C_2H_4/air mixture with wide equivalent ratios and indicated that the DDT distance was much shortened. Busby et al.[17] employed high voltages ranging between 55 and 62 kV and 50–75 ns pulsed discharge for the equivalent premixed gasoline/air mixture in single-trial detonation experiments. Brophy and his coworkers[18,19] and Hackard[20] used nanosecond pulsed discharge ignition to achieve the coordinated operation of a PDE with an 80 Hz working frequency. Brophy et al. validated C_2H_4 and air, while Hackard tested gasoline/air. Starikovskii[21] validated the enhancement of ignition and the combustion of propane using a 10–20 kV and 77 ns nanosecond pulsed discharger. The validated experiments showed that the ions released by the transient plasma could shorten the DDT.[22]

Both the miniaturization and low cost of high-voltage power supplies makes this goal in engineering applications more challenging in PDEs. Instead of the nanosecond pulsed high-voltage discharge approach, non-equilibrium, low-temperature plasma can also be generated by Alternating Current(AC)-driven Dielectric Barrier Discharge (DBD) technology, such as that described in works by Rosochaet al.,[23] Hu et al.,[24] Kim et al.[25] and others.[26,9] However, the above research was conducted to improve the combustion or start-up characteristics of industrial burners. Compared with high cost of nanosecond high-voltage pulsed discharge, an AC-driven DBD lowers the requirements of the power supply and holds a better control of the gas heating. Nano-pulsed DBD technology is widely used to generate low-temperature plasma for flow control,[27] such as in separation control for an airfoil, compressors or even in adjusting shock waves. However, in the direct initiation of detonation in PDEs, most of the nanosecond pulsed discharge is performed without a dielectric barrier between the two electrodes. To the best knowledge of the present authors, no such research has been performed to examine the effectiveness of non-equilibrium, low-temperature plasma generated by an AC-driven DBD on the shortening of DDT and triggering detonation combustion in PDEs.

In this paper, we pursue an experimental study on a lab-scale platform and validate the effectiveness of non-thermal plasma for accelerating DDT in a single-trial PDE tube, based on the novel plasma generator proposed by the present authors. Three types of detonation mixtures of hydrogen, acetylene, and propane are tested in the experiments. The flame development, propagation speed, and pressure distributions are compared in the present study.

2. Description of the experiment system

2.1. Experiment setup

A photograph of the experimental system is shown in Fig. 1(a), which consists of dual detonation tubes with the spark plug and plasma igniter installed, respectively. In each tube, a gas charging system, ignition system, vacuum system, and data recording system are included. The outlet of each detonation tube is sealed with a Poly Tetra Fluoro Ethylene (PTFE)film.

The rectangular detonation tube, enlarged in the Fig. 1(b), is 1500 mm in length and 60 mm × 60 mm in the cross-section. There are 10 rectangular-ambulatory plane-type spoilers installed inside each tube. The first one is located 150 mm from the tube head, with an interval of 60 mm between two spoilers. The total blockage ratio of the spoilers is about 43%. The front plane of the detonation tube is made of PTFE at 1450 mm × 60 mm to visualize the flame development. Four in-house built ion probes are located at equal intervals of 300 mm along the detonation tube, starting 200 mm from the tube head. Two dynamic pressure transducers are fixed on the detonation tube at 800 and 1250 mm.

The plasma generator or the electric spark plug is installed close to the head of each detonation tube. The spark plug is fixed 30 mm away from the tube head and the center of the plasma generator is also 30 mm away from the tube head. This means that the ignition kernel forms at the same position inside the two tubes.

Three types of detonation mixture are tested in the experiment, the species of which are shown in Table 1. To obtain detonation easily, additional oxygen is added to the mixture of propane and air. The mass fraction is used in the table. All the experiments are conducted under conditions of 298 K and 1 atm (1 atm = 101,325 Pa). The theoretical C–J velocity of the detonation combustion is also shown in Table 1.

2.2. Low-temperature plasma generator

The configuration of the non-thermal plasma generator is shown in Fig. 2(a), consisting of a plasma igniter, AC power supply, and (Automatic Frequency Control)AFC system.

The novel plasma generator consists of (1) ceramic tube, (2) High Voltage (HV) electrode, (3) Low Voltage (LV) electrode with (4) gas holes, and (5) insulator in Fig. 2(b). The HV electrode and the insulator are joined by screws, while the ceramic tube is glued to the HV electrode. Different configurations of the plasma generator by DBD are proposed and compared. The scheme described below is specified and used in all the experiments. The HV electrode is 20 mm in diameter and 40 mm in length (L_L), and the barrier medium is made of a corundum tube with an outer diameter of 25 mm and 50 mm in length. There are 24 gas holes in the LV electrode with a diameter of Φ = 4 mm. The diameter of the LV electrode is 33 mm, which means that the discharging gap between the LV and HV electrodes is 4 mm.

The AC power can supply 0–40 kV output voltage and 30 kHz frequency sinusoidal waves. Controlled by the synchronous controller, the discharge of the plasma igniter can be continually adjusted up to a maximum frequency of 500 Hz, and the single discharging duration can be controlled from 0.1 to 1000 ms. Thus, the required discharging waveforms can be obtained by the AFC system.

Both the spark plug and plasma igniter are operated at 1 Hz in the present experiment. The work mode can be regarded as the single trigger mode, because the combustion process in the single-trial detonation tube is finished well before 1 s.

The electric power of the spark plug and plasma igniter can be compared to each other. The discharge duration of the