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Influence of equivalence ratio on plasma assisted detonation initiation by alternating current dielectric barrier discharge under rich burn condition

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A B S T R A C T

In order to study the effect of different equivalence ratios on plasma assisted detonation initiation under a rich burn condition, a loosely coupled method was adopted to simulate the detonation formation by alternating current dielectric barrier discharge in a hydrogen–oxygen gas mixture with different equivalence ratios. The spatial and temporal evolution of discharge products were analyzed first. Then, the species distribution, Mach number, thrust wall pressure, and whole history of detonation formation were examined in detail. Results showed that the shapes of the temporal and spatial distribution of discharge products do not change when equivalence ratio varies in one discharge cycle. However, due to the variation of the percentage of fuel and oxidizer, and its impact on the discharge elementary reactions, the number density of every key active particle declines while the decline amplitude decreases when equivalence ratio rises. Although the magnitudes of species concentration are not altered by the plasma, the reacted region extends towards the downstream flow more quickly. The influence of equivalence ratio on plasma assisted detonation initiation becomes remarkable until late in the subsonic stage of the flowfield evolution process in the combustor under a rich burn condition. Furthermore, a larger equivalence ratio leads to a better accelerating effect of the plasma. Through analyzing the dynamic process of thrust wall pressure, it is also found that the DDT process is expedited more notably under a larger equivalence ratio, yet the magnitude of pressure is independent of the plasma. The provision of active particles for the combustion reaction by the plasma and its dilution effect on the fuel are the two intrinsic reasons for the reduction of DDT time and distance and the increase of this reduction degree, when equivalence ratio rises.

1. Introduction

Equilibrium plasma has been used for the ignition of internal engines for more than 150 years [1]. However, as the development of hypersonic propulsion and the higher demands for fuel utilization and emission control at the end of the 20th century, the traditional spark plug which generates equilibrium plasma no longer meets these requirements, so the idea of using nonequilibrium plasma began to attract people's attention. The effect of gas heating by nonequilibrium plasma is not as impressive as equilibrium plasma, yet the highly thermal nonequilibrium nature of the internal particles of nonequilibrium plasma particularly makes for improving ignition and combustion efficiency. In addition, by choosing certain discharge methods, it may have several merits such as larger ignition volume, longer operation time of the electrodes, and so on [2].

As one of the best candidates for hypersonic propulsion devices, the detonation engine possesses a very high thermal cycle efficiency and releases energy fast. But it is very difficult to initiate detonation steadily and reliably under varying or off-design conditions, which blocks the practical application of detonation engines [3]. Considering the merits of nonequilibrium plasma mentioned above, a series of research aims at shortening the deflagration-to-detonation (DDT) distance and time by using this kind of plasma in detonation engines recently, and it shows that the plasma do have the capability to facilitate the detonation formation [4–7]. In our previous research [8], results also proved that the DDT process is accelerated with the help of an alternating current dielectric barrier discharge (AC DBD) plasma in a stoichiometric mixed hydrogen and oxygen. However, for a realistic application, the detonation engine usually works under off-design and varying conditions, where a most important operating index—equivalence ratio, which re-

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flects the percentage of the fuel and oxidizer in a mixture, can change notably. Thus, studies on the influence of equivalence ratio on plasma assisted detonation initiation are urgently needed.

The words "equivalence ratio" firstly occurs in the combustion field rather than in the gas discharge field, and the ignition time is a function of equivalence ratios. Commonly, it is the optimal value that equivalence ratio equals to 1 and it becomes difficult for a fuel–air mixture to be ignited as equivalence ratio stays away from 1. To improve a laminar lifted flame by the dielectric barrier discharge [9], an O_3 plasma was added into the flame reactions, yet simulation showed that the flame speed is enhanced more for lean and rich equivalence ratios than at stoichiometric. Similar conclusions were obtained by Lefkowitz et al. [6]: they found that the ignition time is reduced more significantly near the lean and rich limits when a nanosecond repetitively pulsed discharge is adopted, especially for aviation gasoline–air mixtures. Different from the conclusions given above, Nagaraja et al. [10] pointed out that the nonequilibrium plasma action on low temperature chemistry is nearly independent of the equivalence ratio through conducting a plane-to-plane DBD simulation, where the discharge gas is composed of *n*-heptane and air. As for flow discharge experiments without combustion [11], under lean conditions, OH number density measured after the nanosecond pulsed discharge burst demonstrated that unlike H_2–air mixture, where OH concentration is almost independent of the equivalence ratio, OH concentration is reduced as the equivalence ratio is reduced for all the three hydrocarbon–air mixtures. Notice than this sensitivity of equivalence ratio on the fuel was also proved in ref. [12]: in the comparative study of plasma assisted ignition for C_2-hydrocarbons, it was found that the equivalence ratio φ action on the delay time is totally different for different fuels, only $\varphi = 1$ and 0.5 were considered here. Meanwhile, some researchers deem that equivalence ratio might have little effect on plasma assisted combustion: swirl-stabilized combustor experiments on the effect of plasma on nitric oxide emissions with equivalence ratios ranging from 0.6 to 0.82 showed that the NO production from nanosecond pulsed discharge is not significantly affected by the equivalence ratio at a frequency of 20 kHz [13]. Moreover, at high pressure discharge environment, Boumehdi et al. [14] found that there is no sharp difference between the productions of active species in the surface-DBD discharge for different equivalence ratios, which are between 0.3 and 1.

Since most of the related studies performed under lean conditions, and the effect of equivalence ratio on plasma assisted combustion may change depending on specific conditions, it is very necessary to understand how equivalence ratio affects the AC DBD plasma assisted detonation initiation process under rich burn conditions. Based on the establishment of a plasma discharge model and a plasma-combustion model, the flowfield characteristics at certain moments, pressure history of thrust wall, and DDT time and distance are all numerically studied under different equivalence ratios.

2. Models and numerical approaches

2.1. Discharge simulation

The one dimensional computational configuration of AC DBD is presented in Fig. 1. A high voltage electrode is located at $y = 0$ mm and a grounded electrode is located at $y = 10$ mm with a dielectric layer covering on its surface (the thickness of the dielectric layer is assumed to be zero). Thus, the discharge gap has a distance of $d_G = 10$ mm. The discharge only varies along the y direction to establish a 1D model (ignore the edge effect and others, then the discharge is uniform in the x direction). The gap is filled with hydrogen–oxygen mixture at an initial pressure of 0.8 atm and a temperature of 500 K.

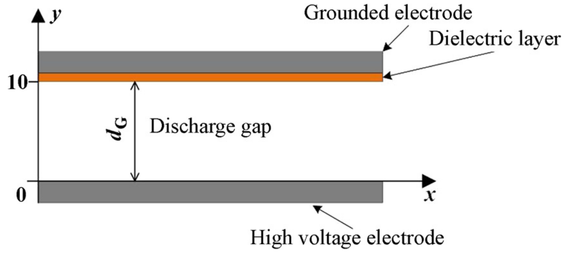

Fig. 1. Schematic of discharge simulation configuration.

The governing equations for discharge simulation incorporate the drift-diffusion equations for positively charged, negatively charged, and neutral particles, and Poisson's equation for the electric field as follows:

$$\frac{\partial n_k}{\partial t} + \nabla(\mu_k n_k \mathbf{E}) - \nabla^2(D_k n_k) = S_k \tag{1}$$

$$\frac{\partial n_k}{\partial t} - \nabla(\mu_k n_k \mathbf{E}) - \nabla^2(D_k n_k) = S_k \tag{2}$$

$$\frac{\partial n_k}{\partial t} - \nabla^2(D_k n_k) = S_k \tag{3}$$

$$\frac{\partial^2 \varphi}{\partial y^2} = -\frac{e}{\varepsilon_0 \varepsilon_d} \sum Z_k n_k \tag{4}$$

where n_k is the number density of particle k; μ_k and D_k denote the mobility and diffusion coefficient respectively, and S_k is the reaction source term. φ, e, ε_0, and ε_d are the electric potential, elementary charge, permittivity of free space, and relative permittivity, respectively; $\varepsilon_d = 3.0$; n_k and Z_k are the number density and charge of particle k, respectively. Then, the strength of electric field is calculated by the following equation:

$$\mathbf{E} = -\nabla\varphi \tag{5}$$

Positively charged particles O^+, O_2^+, H_2^+, H^+, negatively charged particles O^-, O_2^-, O_3^-, OH^-, H^-, and neutral particles O, O_2, O_3, H_2, H, OH, H_2O are taken into account. Discharge related reactions are given in Table 1.

More details about the equations, reaction mechanisms, boundary and initial conditions, and numerical solving schemes can be found in ref. [8]. The DBD actuator is driven by a sinusoidal alternating current power supply with 10 kHz frequency and 14 kV peak-to-peak voltage, and the applied voltage starts from the negative peak. To study the effect of equivalence ratio on plasma assisted detonation initiation under rich burn condition, three equivalence ratios including $\varphi = 1.0, 1.33, 2.0$ are selected.

2.2. Combustion simulation

A loosely-coupled approach [8] is adopted to deal with the simulation of plasma assisted detonation initiation. In this study, the operation sequence is set as follows: the DBD actuator discharges in a defined area first, and then the mixture is ignited by a traditional spark ignition method. In this way, after simulating the AC DBD process, the spatial distributions of the key radicals and molecules at the moment when all the radicals reach their relatively high concentrations, together with a widely used traditional heat ignition (i.e. defining a high temperature domain) [3], are chosen as the initial conditions of the combustion simulation in the discharge zone.

As shown in Fig. 2, the cylinder detonation combustor is 800 mm in length with an inner diameter of 23 mm. The close

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