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Research Paper

Research on the impacts of air temperature on the evolution of nanosecond pulse discharge products

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HIGHLIGHTS

- Most of the O_2 particles become O_2(V1) in high temperature.
- The O_3 molecules are produced mainly by decayed O atoms.
- NO molecules are obtained by decayed N_2(A3), N(2D) and N(2P) at the first stage, NO molecules are obtained by decayed N atoms at last.

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ABSTRACT

Based on nonequilibrium plasma dynamics of air discharge, the kinetic model simulating plasma discharge products induced by nanosecond pulse discharge in air is presented in this work. Then the paper compares the calculation of model with experimental results of references, and verifies the accuracy of the model. The evolution characteristics of nanosecond pulse discharge plasma under different air temperatures are obtained. Because the O, O_3 and NO have close relationship with the combustion, their formation mechanisms are discussed especially. With increasing temperature, there is no significant addition in O atoms and O_3 molecules. It is found that most of the O_2 molecules become O_2(V1) in higher temperature. The decreasing time of the O atoms is in accordance with the increasing time of O_3 molecules. Thus, the O_3 molecules are produced mainly by decayed O atoms. Increased air temperature will not produce more active particles which could assist the combustion. With the increasing temperature, the particle number density of NO increases fast. At last, they have reached an equilibrium value of the same.

1. Introduction

Plasma, which is the fourth state of the matter, provides an unprecedented opportunity for combustion [1,2] and emission control owing to its unique capability in producing active species, heat and modifying transport processes [3,4]. In the past two decades, particular interests in applications of plasma to the problem of assisted ignition and combustion have been observed [5,6]. The plasma ignition has been shown to have a property of shorting the ignition delay time, extending the ignition limit, improving the reliability, reducing the NO_x emissions [6,7]. Until now, the plasma-assisted combustion has been explored for applications on various engines such as internal combustion engine, turbo engine, pulse detonation engine [8,9] and scramjet [10,11].

There are several plasma discharge modes to assist combustion, such as nanosecond pulse discharge, microsecond discharge, millisecond discharge and microwave discharge, etc. Those discharge modes will form a variety of plasma, such as arc plasma, glow plasma, corona plasma, microwave plasma, spark plasma and dielectric barrier discharge plasma. Recently, the use of nanosecond pulse discharge (NPD) to assist the combustion has been received extensive attention and study. The NPD has been demonstrated to be a promising technology to assist the combustion and improve the engine's performance. A typical plasma ignitor [12] and discharge under the NPD is shown in Fig. 1.

There have been a large number of streamers beyond the plasma igniter. Electronics collision and molecular decomposition will occur in the streamer channels. There will be a lot of hydrocarbon-based fragments (CH_i) in the mixed gas which will assist the combustion. With a large number of streamers, the ignition energy can fully interact with the mixture. This will ignite the combustible mixture in a wide range rapidly.

Although a big progress has been made in NPD to assist the combustion, there also is a large gap in understanding the kinetics of nanosecond pulse discharge plasma to assist the combustion.

Classic Townsend mechanism and stream theory are the basis of researches on gas discharge, but they have some defects when used to explain nanosecond pulse gas discharge. Under normal

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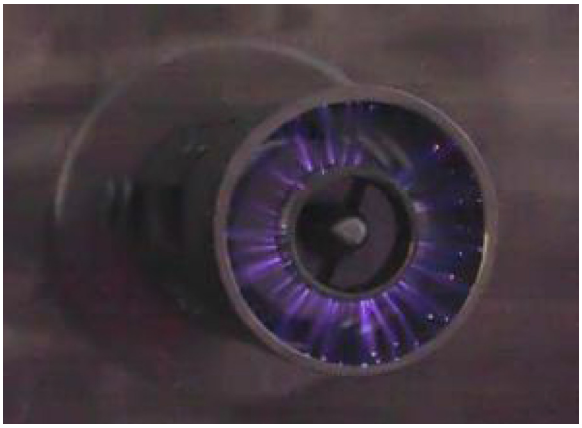

Fig. 1. A toroidal plasma ignitor discharge under nanosecond pulse discharge.

pressure and high pressure, many low-pressure plasma diagnostic methods, like Langmuir probe, are useless. Some diagnostic approaches, such as the spectral line broadening of Stark effect and Thomson scattering, are limited by the precision of instruments and by the manufacture cost of equipments, so that they cannot be used for common laboratory diagnosis and industry diagnosis. This makes many basic features and time characteristics of atmosphere and high-pressure plasmas inaccessible to experimental measurements. Therefore, mathematical modeling and computer numerical simulation become major methods of exploring and optimizing the gas discharge process.

Nagaraja et al. [13] studied the $H_2/O_2/N_2$ premixed flat flames which is enhanced by nanosecond plasma discharge. Burnette et al. [14] studied the kinetics of NO formation and decay in nanosecond pulse discharges in Air-Fuel Mixtures. Yin et al. [15] present new results of a kinetic study of radical reactions using a stable and diffuse ns pulse discharge. Niessen et al. [16] put forward a temporal evolution model of the chemical process for dielectric barrier discharge, in which a gas mixture including N_2, O_2, H_2O, NO, NO_2 and C_2H_4 was concerned. He also compared the calculated results with experimental results. Mintusov et al. [17] studied the intensified combustion effect and the dynamic computation model for high-voltage nanosecond repeated pulse discharge. Mruthunjaya Uddi [18,19] investigated the chemical reaction rate for repeated discharge. Kosarev et al. [20] studied the ignition mechanism for $CH_4/O_2/Ar$ mixture in nanosecond pulse discharge by means of experiments and numerical simulations, which shows that the ignition of nanosecond pulse discharge plasmas can shorten the ignition delay time effectively.

Although there have been some achievements in researches on the discharge characteristics of nanosecond pulse discharge to assist the combustion, it is necessary for researchers to learn the nature of nanosecond pulse discharge sufficiently so that it can be applied in industry better. Currently, the investigations on nanosecond gas discharge are still in the exploratory stage. Therefore, the research on nanosecond pulse discharge to understand the kinetic of NPD plasma to assist the combustion is necessary.

This paper studies the evolution of discharge particle number density in the air with the changing initial air temperature. The active particles related to combustion are discussed especially. The calculated results in this paper can be used as reference for research on the assisted combustion and parameter control of plasma.

2. Dynamical model of air discharge

The plasma dynamic model consists of elastic collision, excitation, ionization, electron adsorption/de-adsorption, and recombination etc. For convenience of calculations, space processes like diffusion and drifting are neglected.

The numerical simulations have been built basing on ZDPlasKin [21] and BOLSIG+ [22]. The ZDPlasKin is a zero dimensional plasma kinetics solver. The BOLSIG+ is a electron Boltzmann equation solver.

The dynamic of species density $[N_i]$ is described by kinetic equation:

$$\frac{dN_i}{dt} = \sum_{j=1}^{j_{\max}} Q_{ij}(t) \tag{1}$$

where N_i is the species density in cm^{-3}, t is the time in s, $j_{\max}$ is the maximum value of product component, the Q_{ij} is the total rate of species production and destruction in various processes (The unit is cm^{-3}). For example, the above-mentioned rates corresponding to the reaction:

$$aA + bB \to a'A + cC \tag{2}$$

can be expressed for A, B and C species as:

$$Q_A = (a' - a)R, \quad Q_B = -bR, \quad Q_C = cR \tag{3}$$

using R as the reaction rate and k as the constant rate of the reaction:

$$R_j = k_j [A]^a [N]^b \tag{4}$$

All of the species and reactions are converted automatically to the system of kinetic equations and solved numerically by ZDPlasKin tool.

The energy equation describing temperature variations in the system can be approximated by the adiabatic isochoric equation, that is:

$$\frac{N}{\gamma - 1} \cdot \frac{dT_g}{dt} = \sum_{j=1}^{j_{\max}} \pm \delta\varepsilon_j \cdot R_j + P_{elast} \cdot [N_e] \tag{5}$$

where the N is the species density in cm^{-3}, the γ is the adiabatic index of the gas, T_g is the temperature in K, $\delta\varepsilon_j$ is the jth reaction exothermic chemical reactions in K, P_{elast} is the energy of electron collision in K, N_e is the electron density in cm^{-3}. The first item on the right stands for the heat release in chemical reactions, and the second item represents Joule heat resulted from electron current and from elastic collisions between electron and heavy particles. As the transfer rates of positive ion and anion are relatively slow compared with that of electrons, Joule heat caused by ion current is neglected.

The rate constants of reactions between heavy species from this list are calculated from the thermodynamic gas temperature T_g. This temperature is frequently assumed to be equal for all ions and neutrals even in non-thermal plasma. This is no more true for electrons. Their energy is usually much higher, as well as their temperature (T_e). The rate constant for electron impact reactions must be calculated from electron energy distribution function (EEDF). The EEDF is usually obtained by solving Boltzmann equation for free electrons. Transport parameters and constant rates for electron-neutral interactions are calculated using build-in into the package BOLSIG+ solver.

Chemical reactions of plasma discharge include 49 excitation-ionized air components (Table 1) and 454 equations [23–31].

3. Model validation

In order to verify the accuracy of the air nanosecond pulsed plasma dynamics calculation model, the results of O atoms and NO molecules are compared with the experimental results in Refs. 18 and 32.