20aF-2

Numerical Simulation on Plasma Assisted Ignition by Nanosecond Pulsed Discharge in Internal Combustion Engines

ナノパルス放電による内燃機関プラズマ着火に関する数値シミュレーション

Hidemasa Takana, Igor V. Adamovich and Hideya Nishiyama
高奈秀匡[1]，Igor V. Adamovich[2]，西山秀哉[1]

[1]*Institute of Fluid Science, Tohoku University*
2-1-1, Katahira, Aoba-ku, Sendai 980-8577, Japan
東北大学流体科学研究所 〒980-8577 仙台市青葉区片平2-1-1
[2]*Department of Mechanical and Aerospace Engineering, The Ohio State University*
Columbus, Ohio 43210, USA

Detailed two dimensional numerical simulations of a nanosecond pulsed pin-to-pin discharge in a lean methane/air mixture were conducted under 10 atm and 600 K for plasma assisted combustion in internal combustion engines. It was clarified from this study that the produced radicals were locally higher in the vicinity of electrodes, and high density radicals are more widely distributed on the anode side rather than the cathode side which the streamer is propagating toward. Pronounced enhancement of ignition delay has been verified by nanosecond pulsed discharge.

1. Introduction

Recently, nanosecond pulsed discharge has been paid special attentions for plasma assisted ignition or combustion as an innovative technology to bring breakthrough in the lean combustion.

In this study, detailed two dimensional computational simulations of nanosecond pulsed pin-to-pin discharge in a lean methane/air mixture were conducted at 10 atm and 600 K for plasma assisted ignition in an internal combustion engine. The fundamental characteristics of the nanosecond pulsed discharge and the radical production processes are clarified. Furthermore, the effect of plasma produced radicals on enhancement of ignition delay has been discussed.

2. Governing Equations

Axisymmetric *r-z* two dimensional simulations are conducted for the pin-to-pin nanosecond pulsed discharge. The discharge is initiated between two spherical bare electrodes with the gap spacing of 1.2 mm. The diameter of the bare sphere electrode is 7.5 mm and the maximum of 26 kV is applied in 23 ns with cathode grounded [1].

The governing equations are consist of following continuity equations for electrons and ions with drift-diffusion approximation and Poisson's equation for electric potential,

$$\frac{\partial n_k}{\partial t} + \nabla \cdot \boldsymbol{\Gamma}_k = S_k, \qquad (1)$$
$$\boldsymbol{\Gamma}_k = \mathrm{sgn}(q_k)\mu_k \boldsymbol{E} n_k - D_k \nabla n_k,$$

$$\nabla \cdot (\varepsilon \nabla \phi) = -\sum_k q_k n_k. \qquad (2)$$

The charge continuity equation shown in eq. (1) is solved by VSIAM3 method (volume/surface integrated average based multi-moment method). The electron mean energy, transport properties and rate coefficients are given as a function of reduced electric field with local field approximation.

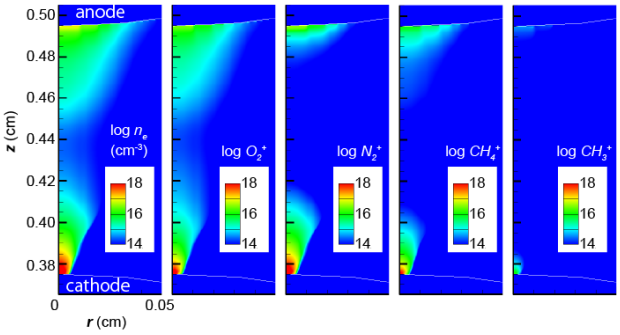
The composition volume ratio of air/methane mixture is N_2:O_2:CH_4 = 0.75:0.20:0.05, which corresponds to the equivalent ratio of 0.5. The initial electron and O_2^+ number densities are uniformly set to be 1.0 x 10^8 1/cm^3.

The rate of photoionization in a gas volume is included in the source term in equation (1). In this study, two-exponential Helmholtz model was employed for photoionization of oxygen. The chemical kinetics of methane/air mixture studied in this work is summarized in the reference [2]. With addition to the reactions shown in [2], the formation of complex positive ions such as O_4^+ and N_4^+ and the production and decay of O_2^- are also incorporated.

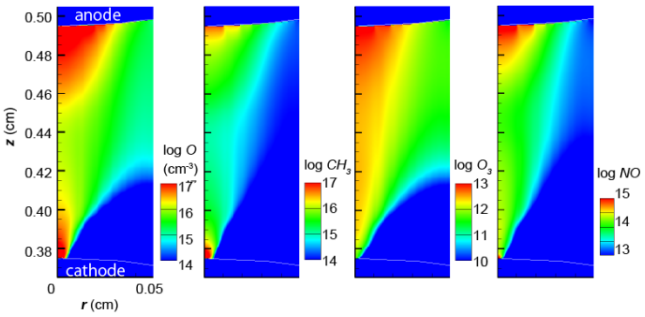
The gas heating process during positive streamer propagation in the pin-to-pin geometry has been conducted by considering the enthalpies of reactions and fast gas heating mechanism [3].

3. Results and Discussion

Figure 1 (a) and (b) show distributions of electron and ions, and O(^{3}P), CH_3, O_3 and NO at *t* = 24.6 ns. Oxygen atom is produced at the streamer head due to high energy electron impact

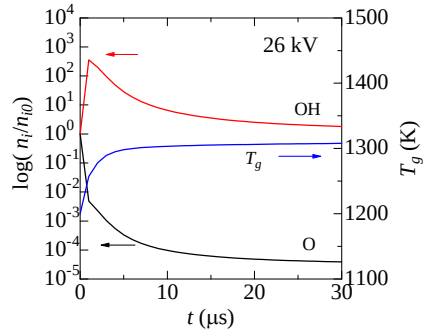


(a)

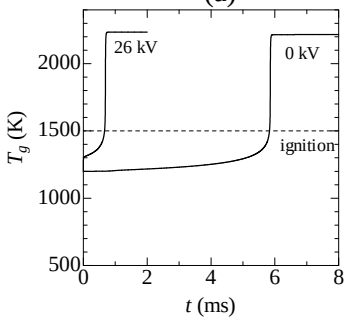


(b)

Fig. 1. Distributions of (a) electron and ions, and (b) O(^{3}P), CH_3, O_3 and NO at t = 24.6 ns.



(a)



(b)

Fig. 2. (a) Normalized number densities of OH and O radicals by their plasma produced number density, (b) time evolutions of gas temperature with or without nanosecond pulsed discharge.

dissociation and also in the vicinity of anode where reduced electric field is sufficiently high. Oxygen atoms of over 10^{17} 1/cm^3 are produced near electrodes during positive streamer propagation. The produced radicals are locally higher near the electrodes and high concentrations of radicals are more widely distributed in the vicinity of anode.

In order to clarify the effect of plasma produced radicals on ignition enhancement, zero-dimensional combustion simulation has been conducted with coupling plasma chemical reactions. In this simulation, simplified methane combustion mechanism of GRI-Mech 3.0 with 325 reactions and 53 chemical species is considered. The initial number densities of the chemical species are taken from the results obtained from the nanosecond pulsed discharge at 24.6 ns in the vicinity of anode at r = 0 mm and z = 4.9 mm shown in Fig. 1.

Figure 2 (a) shows number densities of OH and O radicals normalized by their initial number density for combustion simulation and (b) shows the time evolutions of gas temperature with or without nanosecond pulsed discharge, respectively. In figure 2, the initial state for the combustion simulation is set to t = 0 s. Initial gas temperature of 1200 K is given at t = 0 s, assuming external heat source such as spark plug. The reduced electric field is set to 0 Td at t = 0 s. As shown in Fig. 9 (a), oxygen atom exponentially decreases with time, on the other hand, OH radical increases within several micro seconds and then decreases. The sudden increase of OH is due to the reaction of plasma produced oxygen atom with methane; O + CH_4 = OH + CH_3. Then OH and O radicals are consumed for the oxidation reactions with increase in gas temperature from 1200 K to 1300 K in 10 micro seconds. When defining 1500 K as the ignition temperature, the ignition occurs at 0.66 ms and the ignition delay time is shortened by 88 % by plasma assisted ignition.

4. Conclusions

The obtained results from this study can be summarized as follows.

(1) The concentrations of produced radicals are locally higher near the electrodes and high density radicals are more widely distributed in the vicinity of anode, rather than the cathode toward which streamer is propagating.

(2) Pronounced improvement of ignition delay has been verified by nanosecond pulsed discharge.

References

[1] D. Burnette, I. Shkurenkov, I. V. Adamovich and W. R. Lempert: AIAA 2014-1034 (2014).

[2] H. Takana and H. Nishiyama: Plasma Sources Sci. Technol. **23** (2014) 034001.

[3] N. A. Popov: J. Phys. D: Appl. Phys. **44** (2011) 285201.