Plasma-Assisted Combustion of Propane-Air and Methane-Air Mixtures. Kinetics of Flame Acceleration

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Abstract

The study of nanosecond barrier discharge influence on flame propagation and flame blow-off velocity was carried out. With energy input negligible in comparison with burner's chemical power, a double flame blow-off velocity increase was obtained. The present paper shows that, besides proper form of energy input, proper organization of discharge is of great importance. It was found that active particles (O and OH primarily), which are produced in the streamer head under its action, play the most significant role in the effect of combustion acceleration. The model of flame acceleration, suggested in the previous work, was confirmed by the new experimental data.

Introduction

The interaction of electric fields and discharges with flames has been studied widely and extensively all over the world. The main idea of these researches is the use of electric fields and discharges to affect the flame propagation velocity. This field of research is quite challenging for practical applications, such as aircraft engines, in which combustion should be as rapid and full as possible. More rapid combustion makes it possible to use more lean mixtures, which results in a decrease in the temperature of the combustion products and a reduction in the amount of the harmful NO impurities produced.
Nowadays it seems that the most challenging method for accelerating combustion is the non-equilibrium excitation of the gas mixture components, which allows one to affect the chemical reaction kinetics. To enable more efficient excitation of the electronic and vibrational degrees of freedom, one should use short-duration (nanosecond) pulses with a high reduced electric field [1]. In pulsed discharges, the reduced electric field at the front of an ionization wave (e.g., in the streamer head) attains hundreds of Td, whereas the electric field in the streamer channel is significantly lower and certainly insufficient for the production of active particles. The experiments of [2] demonstrated that it is the region with a strong field in the streamer head in which the active particles are mainly produced.

Experimental setup

The main part of the experimental setup is a quartz nozzle with rectangular cross-section. Three different nozzles, with 2.2, 2.5 and 4.3 mm in width and the same length of 30 mm were investigated. Stainless steel 0,8~mm thick high-voltage electrode was placed inside the nozzle and the grounded electrodes were set tightly into quartz tubes and placed near the nozzle edges, parallel to them. You can find more detailed description of the setup in [3].

To fix the point of the streamer start and the number of streamers as well, the high-voltage electrode has a number of pins on its upper edge. Two electrodes were used - with 8 and 15 pins, so the number of streamers could be 16 or 30 streamers respectively. The nozzle and images of discharge and flame are presented in fig.1.

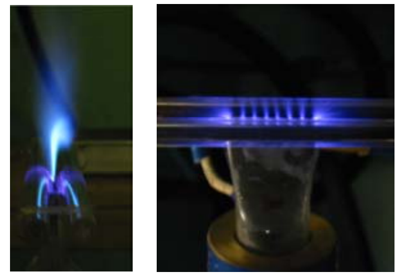

Fig.1. Overall view of the nozzle with discharge.

In the present work we used three different types of nanosecond pulses: with FWHM 7, 19 and 24 ns. The voltage on the discharge gap could be 14 kV or 22 kV, pulse polarity was positive. Pulse repetition rate could be varied within the range of 400-1000Hz.

Results and discussion

It was shown in [1], that in processes of combustion acceleration and flame velocity increase the main role is played by active particles (such as O, H, OH and so on), which are responsible for chain branching. The production of additional centers results in acceleration of chemical kinetic processes. Another important feature is the proper organization of energy input. The energy should be put inside the gap and lead to radical production (instead of gas ionization or thermal heating). Streamer type of discharge totally corresponds to these condition. The main area, where active particles appears, is the streamer head.

We used two different high-voltage electrodes - with 8 and 15 pins. It was found that both types of electrodes leads to flame acceleration for the cases of 14 kV and 22kV. But the effectiveness of such influence is different - the effect is greater for 15-pin electrode (fig.2), because of the larger quantity of streamer. So, the flame stabilization occurs due to the plasma action and hardly depends on the local overheating near the steel plate pins, because estimations shows that overheating is greater in case of 8-pin electrode. The energy input in both cases was the same and was equal approximately to 2-5 mJ per pulse (2-5 W of total power). This value corresponds to 0.5 % of the chemical power of the burner. The equivalent value of gad heating by this energy is 10-20 K. This fact confirms the thesis about the importance of the way we put energy in the mixture.

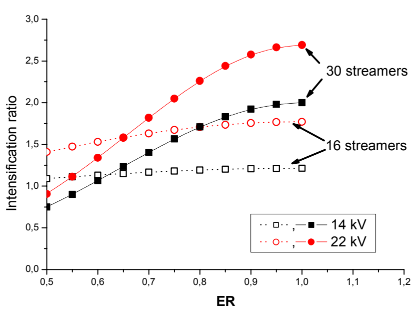

Fig.2. The comparison of the effectiveness of discharge influence. 8-pin versus 15-pin HV electrode

We just have showed that if we are making pulse shorter (24 ns vs 77 ns in the previous work [1]) we can increase the efficiency of energy input (we reduce energy input more than 2 times, and still have the same increase in flame blow-off velocity). But the duration of pulse should be greater than the time of streamer propagation through the gap where mixture flows, to provide full overlapping of the nozzle by the streamer. The streamer velocity was calculated in [2], and is equal to 0.6 mm/ns under the voltage of 22 kV. Calculations were made for the time of the gap overlapping, and the result is approx. 8 ns in the case of 2 mm nozzle (track length is 5 mm, see fig.1), and even greater in the case of 4.3 mm nozzle.

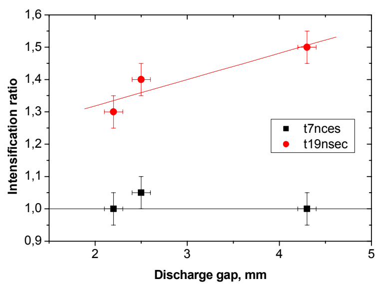

Fig.3. The discharge influence on flame blow-off velocity for different pulse durations

To confirm these arguments, a number of experiments has been performed. Two types of additional line pieces were used to provide different pulse duration (FWHM 7 ns and 19ns). It was found that at frequency 500 Hz and ER=0.8 19ns pulse is much more efficient than 7ns one for all three nozzles, and the advantage of using 19 ns grows with nozzle widening (fig.3), as it was predicted earlier.

A series of experiments were made to prove the correctness of the model of flame acceleration and kinetic scheme, suggested in the previous work [1]. That result was based on the non-resolved spectrum of excited OH at 306.4 nm with quite a large apparatus function of monochromator (2.4 nm). This caused a question, is the first peak of the typical "two-humped" spectrum connected with N2 production in the discharge (second positive system of nitrogen has intense lines on the wavelengths of 315.9 nm, 313.6 nm and 311.6)? In the present work, using CCD-line with signal accumulation mode, it became possible to obtain rotationally resolved spectrum of OH radical in methane-air flame. The result is presented in fig.4, and this figure confirms the previously obtained one for propane-air mixture as well as the importance of OH radical in flame and the similarity of kinetic processes, which leads to flame blow-off velocity increase, for the vast majority of premixed hydrocarbon-air flames. The results for methane-air flame blow-off velocity increase also confirm this theory.

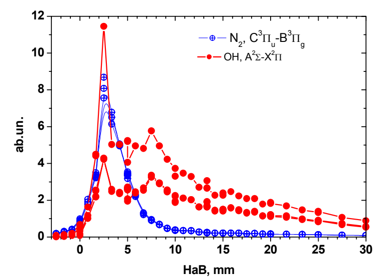

Fig.4. OH* profile along the HaB in methane-air flame.

Using OH rotationally resolved spectra, the rotational temperature was calculated. The technique of temperature determination is described in [4]. We used the ratio of R1(9) Q1(4) lines. In the case of equilibrium flame, the rotational temperature, obtained in a such way, is close to the translational one. Experimental rotational temperature profiles along the height above burner in methane-air flame are presented in fig.5. The comparison of experimental profile with calculated one shows a good data agreement. The theoretical model for temperature calculation is based on initial mixture composition changing under the discharge action.

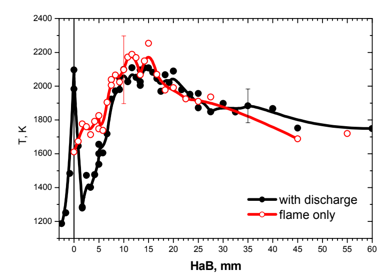

Fig.5. Experimental OH rotational temperature profile along the HaB in methane-air flame.

An additional proof to the suggested theory and model of radical influence lies in the results of experiments with Ar/O2/C3H8 mixture. We have changed the nitrogen in the mixture to argon in order to prevent active particles formation. According to the model, the main channel of O and OH production is the quenching of electronically-exited triplet states of N2 on the oxygen molecules, or dissociation of oxygen molecule, which can proceed via its electronically excited states. So, the substitute of nitrogen to argon should reduce the atomic oxygen and decelerate flame in comparison with N2/O2/C3H8 mixture. Indeed, the results of experiments showed that the phenomenon in argon mixture is much more weaker. This is an evidence for our flame acceleration model.

Conclusion

The study of nanosecond barrier discharge influence on flame propagation and flame blow-off velocity was carried out. The following conclusions could be made:

- With energy input negligible in comparison with burner's chemical power, a double propane-air flame blow-off velocity increase was obtained. It was shown experimentally that results for methane-air flame are similar with propane-air one.
- Besides proper form of energy input, proper organization of discharge is of great importance. It was found that the effectiveness of plasma-assisted combustion depends on type of discharge, pulse duration, pulse repetition rate and other parameters, which are responsible for active particles production.
- It was found that active particles (O and OH primarily), which are produced in the streamer head under its action, play the most significant role in the effect of combustion acceleration. The model of flame acceleration, based on nitrogen quenching on oxygen molecules, with production of O and OH radicals, was confirmed by the new spectroscopic investigations and experiments with Ar/O2/C3H8 mixture, where discharge influence is small because of the absence of mechanism of active particles production.

Acknowledgments

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Referenses

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