

FLAME PROPAGATION THROUGH THE MIXTURES EXCITED BY NANOSECOND BARRIER DISCHARGE

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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 degrees of freedom, one should use short-duration (nanosecond) pulses with high values

of 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 set-up

Detailed description of the setup you can find in [3]. Three different quartz nozzles with rectangular cross-section, with 2.2, 2.5 and 4.3 mm in width and the same length of 30 mm, were used. 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.

To fix the point of streamer's start and the number of streamers as well, the high-voltage electrode has a number of pins on its upper

edge. Three electrodes were used - with 8, 15 or 28 pins, so the number of streamers could be 16, 30 or 56 respectively. The nozzle and images of discharge and flame are presented in fig.1. To measure the combustion rate increase, an emission spectroscopic system was used as well as flowmeters.

In the present work we used three differ-

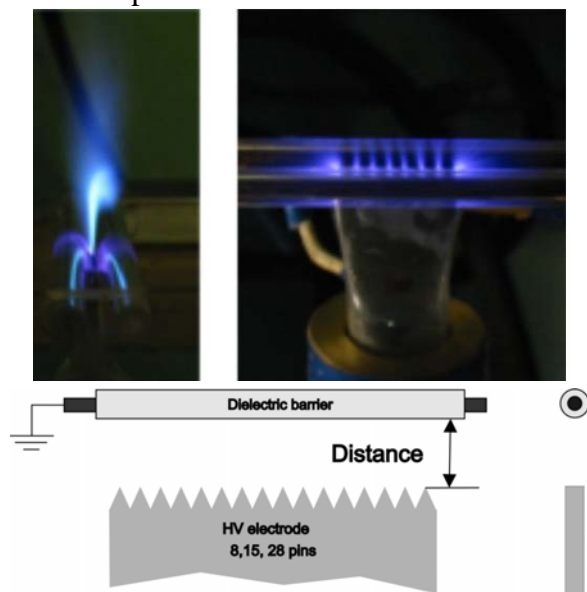


Fig. 1.

ent 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.

For determining of spatial and temporal characteristics of a streamer the PicoStar HR12 camera (LaVision) with a spectral range of sensitivity 300÷700 nm and time resolution up to 200 ps was used. Photos of streamer discharge were received in two modes of operation of the high-speed camera: integral and stroboscopic mode. When working in integral mode the amplifier of the high-speed camera was switching on simultaneously with coming of high-voltage pulse on electrode. Time of exposure was 50 ns and was longer than the duration of a high-voltage impulse. For working in stroboscopic mode, on the amplifier of the camera a triggering sine signal is set with frequency of 300 MHz.

To investigate formation of OH radicals in a ground state we have adjusted laser induced fluorescence technique. Experimental setup and details of adjustment procedure is represented in Fig.2 (a, b). We moved laser emission to $Q_1(5)$ or $Q_1(6)$ line to obtain fluorescence of OH. The emission was produced by laser system concerning NdYAG laser at second harmonics and dye laser with doubling system. System with cylindrical lenses was used to get 2D map of fluorescence. Laser wavelength was adjusted with the help of simultaneous registration of laser wavelength and rotational system of OH emission from propane-air premixed flame (typical plot used for adjustment is demonstrated in Fig.2a). The fluorescence was registered by with a PicoStar camera with interference filter (315 nm with width 1.8 nm at the half-height). Camera gate was 30 ns. Camera was synchronized with NdYAG laser operation.

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), which are responsible for chain branching. These results are confirmed by experimental data. In particular, additional OH* production (in $A^2\Sigma$ - state) under discharge influence in methane-air and propane-air premixed flames was observed. The similarity of the results is the evidence of likeness between mechanisms of flame acceleration. This result is confirmed by numerical simulation as well. Combustion intensification shows itself in an emission peak shift and narrowing of area of growth of OH* concentration. The results for temperature – both experimental and calculated – was obtained and in a good agreement as well. Using spectroscopic data, we also can conclude that flame blow-off velocity increase is closely connected with combustion rate increase.

Comparison of 2D OH fluorescence and PLIF-image of OH (obtained with the same in-

terference filter) (Fig.2c and 2d respectively) demonstrates significant difference in a spatial distribution of excited OH radicals and OH in the ground state even at absence of the discharge. So, an additional analysis is needed to elucidate the role of OH in a ground state and OH($A^2\Sigma$) in artificial ignition.

way of influence in this case is changes in flow pattern and heat-removing processes. Another mechanism for flame stabilizing is creation of zones with near-zero flow rate, where ignition occurs, and then flame moves upward the stream.

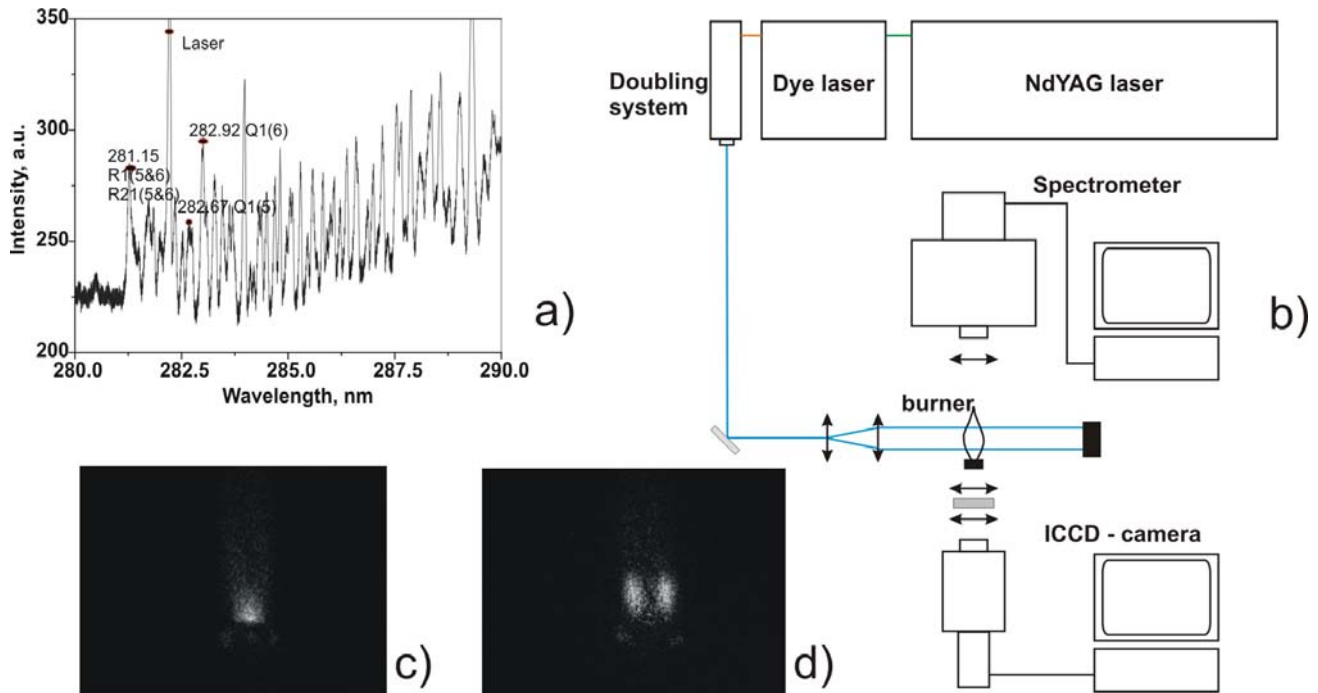


Fig. 2.

The formation of secondary OH* peak in the discharge zone corresponds with the statement that place where the active particles are put is important. It's useless to produce radicals in the reaction zone, where temperature is high enough and radical production in discharge is negligible with that one in chain reactions. On the other hand, if radicals are produced before reaction zone at a large distance, they probably recombine and just heat the gas for a few decades of K. So, an optimal place exists, where radical production is most effective in terms of flame blow-off increase.

It worth mention that geometry of burner and discharge cell are of great importance. Electrodes, if placed near the burner, serve as additional stabilizers and allow to increase blow-off velocity even without discharge. The

So, there are two types of discharge application in combustion tasks. The first is to ignite mixture in areas with low flow speed with combustion rate remaining constant, i.e., by heating, as in [4], and the second is to increase combustion rate by uniform treatment of mixture in the discharge. We think that the second way is more perspective and that's why one should use relative flame velocity increase as the main parameter of discharge effectiveness, instead of absolute values of flow speed. We should compare the discharge power to relative burner power increase, taking into account that completeness of combustion could change.

Our results show that flame propagation velocity can be increased more than twice, depending on the way we organize discharge as

well as discharge parameters (duration, pulse repetition rate, voltage etc) with energy input less than 0.5 % of the burner power. To verify the statement that our discharge doesn't heat the gas, we performed spectroscopic investigations and found that the widening of the lines of emission of molecular nitrogen corresponds to the additional heating about a few decades of K. Moreover, a number of experiments with different HV electrodes – with 8 and 16 pins – has been done. Estimates show that the local overheating is greater for the case of 8 pins, while the intensification ratio ((blow-off rates ratio with and without discharge) is significantly greater in the case of 16 pins (fig. 3).

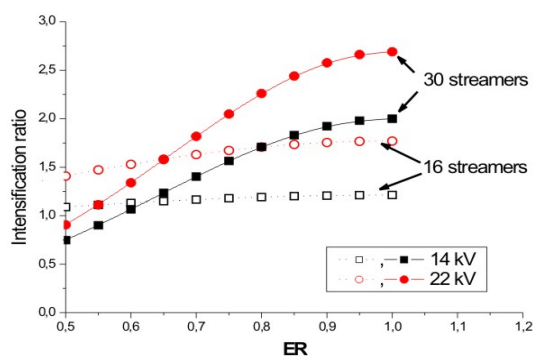


Fig.3.

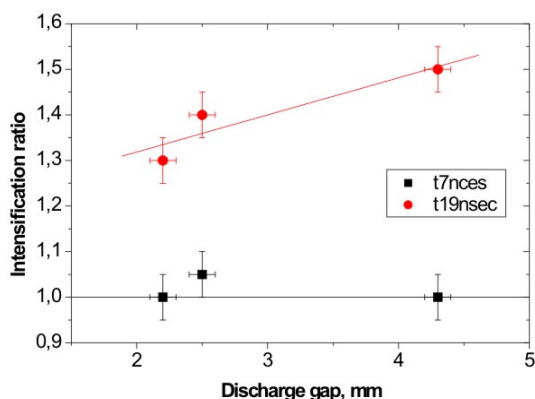


Fig.4.

Different pulse durations were investigated. It was found that with effect of flame blow-off velocity increase is significantly greater for the pulse length of 19 ns than for 7

ns, and corresponds to energy input. But further pulse length increase results in shifting of the main zone of energy release out of the flow gap, so discharge doesn't influence on the mixture any more, concentrating near dielectric barrier.

The investigation of discharge frequency influence on flame blow-off velocity showed that with frequency growth the effect significantly increases (fig.5) – we can sustain combustion with the same burner power using lean mixtures. Based on this result a conclusion could be drawn that with ER (equivalence ratio) reducing it's necessary to input larger amount of discharge energy to provide the same burner chemical power.

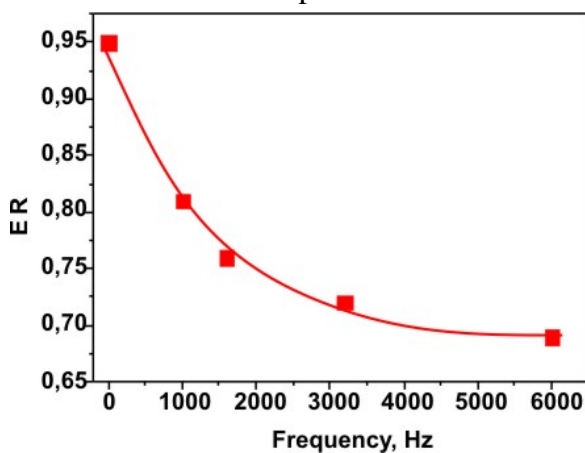


Fig.5

So, the effect of blow-off increase is explained by active particles production. The larger the number of active particles, up to some limit, the greater blow-off rate increase. To determine optimal discharge parameters, which give us maximum efficiency of radical production at minimum energy input, streamers development and their interaction were investigated.

It was found that two different regimes of streamer propagation exist. When we use term "streamer", we mean a self-sustained cold discharge, with ion temperature close to room temperature. We want to underline this fact to exclude the hypothesis about thermal effect of the discharge. Using of barrier discharge allows to translate this technique of flame acceleration to the higher pressures. When the discharge gap



Fig 6a



Fig 6b

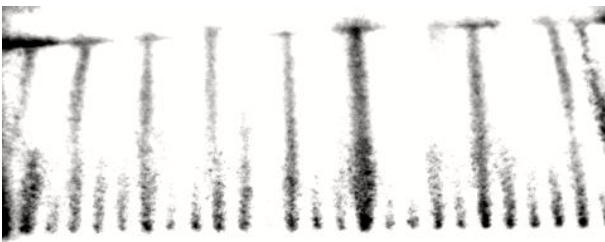


Fig 6c

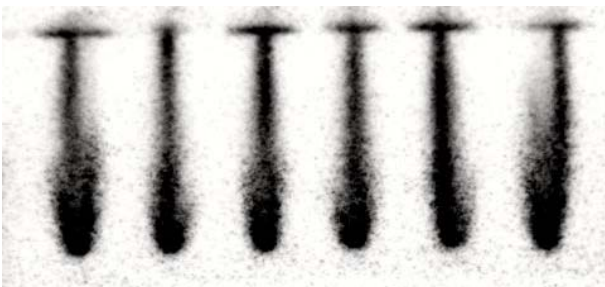


Fig 6d

is small enough, the reduced electric field exceeds breakdown field in the air both in the streamer head and in the channel, so active particles are produced inside the gap. At larger distances the main active particles production takes place only in the streamer head, so the effectiveness does not depend on the pulse duration. So, an optimal gap exists, where active particles production is maximal. This gap is depended on applied voltage. When gap is long enough, the streamer couldn't propagate and only a corona develops near the pin, so the larger part of the gap is not treated by the

discharge. On the contrary, at short gaps values of reduced electric field exceed optimal.

The comparison of cathode-directed streamer and anode-directed streamer showed that the emission from the cathode-directed one is more intensive (see fig. 6, a-cathode-directed streamer, 28 pins, b – cathode-directed streamer, 8 pins, c-anode-directed streamer, 28 pins, d-anode-directed streamer, 8 pins). It is known that the emission intensity is proportional to the density of excited species. This fact explains and confirms results obtained earlier in [1], where flame blow-off increase was compared for both cases and it was found that the effect is greater for positive (cathode-directed) streamer. It's also seen quite well that anode-directed streamer doesn't branching. Starting from a certain number of pins, the number of streamer stops to grow and become fixed. So, streamers if situated near each other, strongly interfere. More detailed investigation of streamer properties and other results by this topic you can find in [5].

An additional proof to the suggested theory and model of radical influence lies in the results of experiments with $\text{Ar}/\text{O}_2/\text{C}_3\text{H}_8$ mixture. According to this theory ([1]), the main channel of active particles production (O, H, OH) in nitrogen/oxygen mixture is the following:

- Nitrogen excitation by electronic impact, with production of electronically-excited molecules.
- Kinetic of excited states, primarily quenching of excited nitrogen on oxygen molecules with atomic oxygen formation.
- Combustion of a new mixture with highly non-equilibrium radicals concentration and production of new radicals (OH).

So, in experiment we have changed the nitrogen in the mixture to argon in order to remove main channel of active particles formation and decelerate flame in comparison with $\text{N}_2/\text{O}_2/\text{C}_3\text{H}_8$ mixture. Indeed, the results of ex-

periments showed that the phenomenon in argon mixture is much weaker. This is an evidence for our flame acceleration model.

Conclusions

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. The acceleration mechanisms are similar in both cases.

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. Development of the streamer in different regimes was studied, optimal regimes were found.

It was found that active particles (O and OH primarily), which are produced under the discharge 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 spectroscopic investigations and experiments with Ar/O₂/C₃H₈ mixture, where discharge influence is small because of the excluding of the main mechanism of active particles production – oxygen dissociation by excited nitrogen quenching.

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