STUDYING OF GASCYDYNAMICS AND COMBUSTION MECHANISMS UNDER PULSED-PERIODIC LASER RADIATION AND ELECTRIC FIELD.

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Introduction

Of particular scientific and practical interest are the ways to control chemical reactions of combustion by means of external energy deposition (electric field (EF), laser and microwave radiation), causing the increase of translational, vibrational or electronic energy of reacting molecules and, as a consequence, resulting in reducing energy barriers of chemical reactions, decrease of induction periods and increase of combustion velocity (see for example [1-6]). Processes of interacting of energy sources with formed flames, as well as initiation of combustion are investigated. Until now, one can find in published works the descriptions of at least four mechanisms of the combustion initiation by laser radiation (LR). The first one is the laser-induced thermal ignition. The energy absorbed by mixture is spent for increasing the mixture translational temperature, and the mixture is ignited upon achieving a certain temperature [1,2]. The second mechanism is the laser-induced photochemical ignition, in this case the emission absorption by the medium leads to a dissociation of some sort of molecules, and this initiates the combustion process [3,4]. The third mechanism is the laser-induced spark ignition, the power density of the supplied laser energy is enough to ensure a spark in the medium (10⁹–10¹⁰ W/cm²), and the laser spark plasma initiates the combustion [5]. And the last variant is the laser-induced excitation of reactive molecules. In this case, the vibrational degrees of freedom are excited by a part of the LR energy, which contributes to a reduction of the reactions threshold [6]. In cases of the LR effect on the formed flame, there are usually distinguished the influence of heating of a mixture (thermal mechanism) and change in the chemical reaction kinetics (kinetic mechanism). The effects related to the action of EF on combustion are not less interesting also.

In this work, we review the results obtained in Laboratory No. 2 of ITAM SB RAS on studying the influence of focused pulsed-periodic CO₂ laser radiation on forming and development of a flame propagation process in a flow of homogeneous fuel-air mixtures and a constant and pulsed-periodic electric field on homogeneous and diffusion combustion.

The ignition of combustion by LR

At the consideration of ignition processes under different initial conditions, one of the above listed mechanisms can be determining. The thermal mechanisms is the most probable under the atmospheric pressure.

In [7], the effects arising in the ignition of a propane-air flow with pulsed-periodic CO₂ laser radiation are investigated. The dynamics of the process was compared to calculation of quiescent mixture ignition at identical excess air ratio values and various initiation temperatures.

In the performed experiments, the fuel was propane since this gas, on the one hand, has an absorption line that falls in the interval of working frequencies of the CO₂-laser (λ = 10.2 µm) and, on the other hand, propane is most widely used as a gaseous fuel. At a mean LR power of 1.5 kW the amount of the energy absorbed in the mixture is sufficient for igniting the mixture.

Figure 1 shows the block diagram of the experimental setup. The mixture, premixed in system 9, entered the quartz tube 3, 13.5 mm in diameter and 90 cm long. At the exit from the tube, a laminar flow formed, with a parabolic profile of flow velocity. The CO₂-laser radiation was focused

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by lens 2 (focal length $F = 50$ cm) in the region over the tube outlet, igniting the mixture entering this region.

The space-integral emission from the flame was cut by an optical filter to subsequently fall onto the photocathode of a photomultiplier 7. The signals were registered with the help of a digital double-beam oscilloscope 8, whose sweep was triggered by the photomultiplier signal at the time the mixture took fire. The signal from the photodetector 6, which registered the laser radiation, was supplied to the second channel. This measurement scheme allowed us to register the emission dynamics of the emerging flame and its relation to the characteristics of LR pulses.

In a special experiment, calorimetric measurements of LR absorption in the propane-air mixture were performed. These data were used to determine the absorption coefficient $\mu$ versus the excess air ratio $\alpha$ (Fig. 2), which dependence was subsequently used to evaluate the energy absorbed by the mixture in the experiment. For the adopted conditions the delay times of mixture self-ignition were calculated on the assumption that the physical process occurs under adiabatic, constant-pressure conditions. The duration of the induction period is known to strongly depend on the initial temperature of the mixture. The duration of induction period is known to strongly depend on the temperature. The comparison of experimental and predicted delay times (Fig. 3) revealed that the initial temperature of the mixture would be significantly higher, and the estimated energy characteristics of involved processes (the absorption frequency) probably indicate the presence of excited molecules in the reacting zone. I.e. a substantial difference between mixture self-ignition and the laser-initiated process has been shown, that is related to the heating of the mixture.
mixture in the focusing zone to temperatures above ignition point, and also with the reduction of the induction period due to the presence of excited molecules in the reacting zone.

**LR effect on the formed flame**

In [8], the results of studying the effect of focused pulsed-periodic CO₂ laser radiation on combustion of hydrocarbon mixtures are presented. The stabilization schemes and flame photographs are presented in Fig. 4, where a), b) is the stabilization by plasma; c), d) is the stabilization in the spark absence. The flame image at the radiation lines of intermediate reaction products (CH, C₂, OH) was fixed by a technical vision camera. The turbulent velocity of flame propagation was determined versus the flow and radiation parameters. A generalization of obtained results proved to be possible at the use of a model for the description of a turbulent flame velocity, in which the residence time in the flame laminar front (the typical combustion time) is a physical-chemical characteristic of the fuel/air mixture. The results are presented in Fig. 5. Here: U₀ is the mixture flow velocity, d is the jet outlet size, τ is the reference combustion time. The dots 1 were obtained at the flame stabilization without radiation. Curve 8 and dots 2 correspond to the combustion stabilization by an optic pulsed discharge – f=17 kHz; 3 – f=30 kHz; 4 – f=45 kHz. Curve 9 and dots 5 correspond to combustion stabilization by a focused radiation – f=17 kHz; 6 – f=30 kHz; 7– f=45 kHz. In these experiments, the typical combustion time exceeded the time between laser pulses by more than an order of magnitude. An increase in the combustion velocity for the case of the flame initiation and stabilization by a focused laser radiation may be explained by a local mixture heating at the expense of a resonance (λ=10.2 µm) absorption of a part of the laser radiation by propane.

To simplify the investigations of flames with combustion initiation by laser radiation (by eliminating the influence of hydrodynamic peculiarities of the flow) a series of experiments was carried out with the laminar flame of the Bunsen type. The main purposes were the obtaining of information on the effect mechanism. It was supposed that the data on the stable combustion limits, normal flame rate, and the integral emission of intermediate products of chemical reactions may contribute to the establishment of a relation to the laser radiation (LR) parameters.

![Figure 3](image1.png)

**Fig. 3. Ignition delay time versus α**

Lower – experimental
Upper – calculated

![Figure 4](image2.png)

**Fig. 4. Experimental scheme and photograph of the flames.**
In fact, the laser-power fraction absorbed by the propane caused local heating of the mixture, which was confirmed by direct measurement of temperature in the thermal wake over the laser beam [9]. The presence of the laser radiation resulted in substantial widening of flame stabilization limits at the edge of the tube (increase in the excess air ratio at $U = \text{Const}$). For instance, for $T = 20^\circ \text{C}$ and $U = 0.9 \text{ m/s}$ the flameout excess air ratio in the absence and in the presence of the laser radiation was found to equal $\alpha = 1.3$ and $\alpha = 2.2$, respectively. It is known that, with this flame stabilization method, the flameout conditions are determined by the critical wall velocity gradient and by the normal flame-propagation velocity. A local heating increases the normal flame-propagation velocity, thus promoting an increase in $\alpha$ under flameout conditions.

We examined the influence of LR characteristics on the flame shape. The LR absorption leads to the LR energy change by which one can evaluate the degree of the LR action.

Fig. 6 illustrates effect of the mean LR power at constant flow velocity values ($u_m = 1.1 \text{ m/s}$) and excess air ratio ($\alpha = 1.04$). A beam axis is located in 9 mm from the tube edge (perpendicular to the picture plane), pulse repetition rate of LR $f = 50 \text{ kHz}$. As shown in the pictures one can see an increase of front deformation along with increase of incident LR power.

![Fig. 5. Generalized $U_r$ vs $U_{od}/\tau$ curves.](image)

1 – without LR,
   with optic pulsed discharge:
   2 – $f=17 \text{ kHz}$; 3 – $f=30 \text{ kHz}$; 4 – $f=45 \text{ kHz}$.
   8 – Generalized curve

with LR
   5 – $f=17 \text{ kHz}$; 6 – $f=30 \text{ kHz}$; 7 – $f=45 \text{ kHz}$
   9 – Generalized curve

Fig. 6. Flame shapes depending on power input
(a – $N=0$; b – $N=0.8 \text{ kW}$; c – $N=1.2 \text{ kW}$)
The following group of pictures (Fig. 7.) shows the influence of LR pulse repetition rate. The LR power input $N=1.8$ kW, excess air ratio $\alpha = 1.4$, mean velocity $u_m = 1.1$ m/s. The maximum effect matches to the continuous mode, in which case in some flow areas it is possible to locally determine the combustion rate value. Fig. 7d presents the scheme of the combustion fronts observed. On interval $(1-2)$, the combustion rate defined by absorbed LR energy exceeds the flow rate, and a stabilization on LR absorption zone (stabilization on a beam) occurs. At point 2, the combustion rate (flame-propagation velocity) is equal to the flow rate, i.e. by means of coordinate of point 2 it is possible to determine the value of local combustion rate at this point.

The amount of absorbed LR is increased with mixture enrichment, and hence the temperature in the absorption zone increases which leads to the growth of combustion rate. This fact is confirmed by the relationship of flame velocity to excess air ratio (Fig. 8).
The experimental results have shown that the flame-propagation velocity increases in 5–7 times, for example, for $\alpha = 1.4$, $f = 50$ kHz and $N = 1.8$ kW from $u_n = 0.24$ m/s to $u_n = 1.3$ m/s, i.e. in 5.5 times.

It is known, that $u_n \sim T^2$ [11]. The velocity increase matches to temperature rise in the focusing area by $\Delta T \approx 400–500^\circ$. For these conditions it is possible to evaluate the temperature rise at LR absorption, if to consider that the absorption process is isobaric ($\Delta E_a = \int_0^T \Delta m C_p d\Delta m$ – mass of a radiation-absorbing mixture, $C_p$ – heat capacity at constant pressure). Using data of Fig. 2 and assuming that LR is absorbed uniformly along a beam, we will receive the temperature change (at point 2): for continuous radiation $\Delta T \approx 400^\circ$, for periodic $\Delta T \approx 500^\circ$. As we can see, it is possible to explain the combustion rate increase by the rise of translational temperature of a mixture, the effects of change in kinetics of the processes at LR action play less of a role.

The analysis of experimental data shows that in the conditions of exhausting of a fuel-air mixture into the free atmosphere the effect of LR on the formed flame has mainly "thermal" character (i.e. the combustion rate increases and flame stabilization conditions improve as a result of temperature rise). At initiation of combustion by LR, in the same conditions, along with mixture heating the important role plays reduction of induction time by means of presence of exited molecules in the reacting zone (i.e. a change in kinetics of pre-ignition processes).

**EF effect on combustion**

To date, there are a number of fundamental directions in the study of external energy effect on reacting flows. One of such directions is the study of the EF effect. Various mechanisms of interacting are known: ohmic heating of a mixture, the “ionic wind” effect on hydrodynamics of a process and the change in reaction kinetics. Which of them will be determining under given conditions?
gasdynamic conditions, known geometry, intensity and frequency values of the EF? The answer to this question makes it possible to use the EF for effective fuel combustion. Study of the effect of constant and pulsed-periodic EF on combustion in laminar and turbulent flames is carried out within the framework of scientific programs in ITAM SB RAS.

Some results of these investigations are presented in [12]. The experiments were conducted for a homogeneous propane-air mixture. As the flame-propagation velocity the normal component of the mean velocity of exhausting to the combustion-front surface in the jet core was taken, on which change the EF effect was determined. The data for a constant EF are plotted in Fig. 9. In the laminar mode \((U_0 = 0.5 \text{ m/s}, \alpha = 1.3)\), the flame-propagation velocity increases by about 20\% as the voltage is increased to \(V = 3.4 \text{ kV}\). In the turbulent mode \((U_0 = 2.0 \text{ m/s}, \alpha = 1.3)\), the form of relationship between flame-propagation velocity and voltage becomes different. The effect of voltage is more pronounced, and the flame velocity in the same variation range of \(V (1 – 3.4 \text{ kV})\) increases by about 30\%. Similar results have been obtained for a methane-air mix. A difference in propagation velocity relations for laminar and turbulent flame is connected with the hydrodynamic properties of flows.

During examination of the effect of constant and pulsed-periodic EF, it was found that the burning rate in the laminar combustion mode might be higher under the action of a pulsed-periodic EF than a constant EF. Also, the propagation velocity of the laminar and turbulent flame as a function of voltage, frequency and electric pulse duration was determined. The effect of relation between the pulse duration and the characteristic combustion time on the behavior of the laminar flame-front propagation velocity versus voltage is revealed. Thus, at the mixture exhausting velocity of 0.5 m/s and close values of these times, the effect of a voltage change on a flame propagation velocity is diminished (see Fig. 10, combustion time \(\tau \approx 4.1 \text{ mc}, \alpha = 1.3\)).

The experiments revealed that a constant EF affects flame stability in the transition from the laminar to the turbulent flow \((U_0 = 1.15 \text{ m/s}, \alpha = 1.35; \text{Re} = 1500)\). Thus, application of the voltage \(V = 0.5 \text{ kV}\) substantially reduced the amplitude of flame-front oscillations; a further increase in voltage led to an increase in flame-propagation velocity without the loss of flame stability. At \(V \sim 2 \text{ kV}\), the regime changed: there appeared “noise” and front oscillations increasing with a further increase in \(V\).

Thus, it is possible to confirm that:

- The difference in propagation velocity relations for laminar and turbulent flame is connected with the hydrodynamic properties of flows;
- There are regimes in which the burning rate in the laminar combustion mode might be higher under the action of a pulsed-periodic EF than a constant EF;
- There is an effect of relation between the pulse duration and the characteristic combustion time on the behavior of the laminar flame-front propagation velocity versus voltage.
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