13. EFFECT OF AN OPTICALLY INITIATED PLASMA ON THE COMBUSTION OF HOMOGENEOUS AIR-FUEL MIXTURES

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Abstract. The influence of a plasma initiated by an optical pulsed-mode discharge on the propagation velocity and stability intervals of turbulent flames in homogeneous air-fuel mixtures (hydrogen and hydrocarbons) is experimentally studied for various intensities of the initiating laser beam. Traditional means (formation of flow-separation regions) were used to stabilize the combustion. Burning characteristics were compared with those obtained during initiation of the process with the optical discharge, all other experimental conditions being identical.

It is found that, during the burning initiated by the laser beam, the burning rate increases and flame stability intervals (with respect to the velocity and chemical composition of the mixture) become wider. The effect is predominantly caused by gas-dynamic factors (turbulization of flow) and by high energy added to the flow. It is established that there are two mechanisms underlying the ignition and combustion processes. For hydrogen-air and methane-air mixtures, a thermal mechanism is operating. For complex hydrocarbon fuels, a transition from one mechanism to another is possible under the action of the laser-beam energy. In the latter case, pre-flame chemical reaction proceed, and the burning may develop without any optical break-down.

Data on the effect of flow parameters, chemical properties of the combustible mixtures, and the repetition frequency of laser-irradiation pulses on the flame velocity are reported.

Introduction

Nowadays research of the optical pulsed discharge (OPD) in supersonic gas flow [1–3] shows the possibility to apply new methods of stabilizing the flame and control the combustion in gaseous flows. OPD formation in the reactive flow can cause new effects conditioned by the influence of the gasdynamic and kinetic factors on this flow. Non-stationary gasdynamic disturbances appear at optical breakdown which forms quasistationary wave structure consisting of a shock wave and thermal wake under certain conditions [3]. Besides, an optical breakdown plasma, emitting in a wide spectral range can considerably change pre-flame processes in the reactive medium, leading mechanisms of kinetic processes, respectively, the rate of heat release in the flow till ultimate determining the explosive character of the process.

Experimental study of a combustion initiation by laser radiation (laser spark) started with a laser technique development. A large number of works were fulfilled (by the end of 70-th) in a field of a IR-photochemistry. Pulsed and cw laser sources with relatively high power were used.

The possibility of various fuel/air mixtures combustion control in flows by focused radiation of a pulsating CO₂-laser was studied in present paper. Such possibility may occur when radiation energy, absorbed effectively by reactive medium, initiates pre-flame reactions and changes leading mechanisms of a combustion.

Application of the optical pulsed discharge for a flame initiating and stabilization in homogeneous hydrogen/air and hydrocarbon/air flows was studied for the first time. To provide a medium’s optical breakdown an argon was injected into the focused laser beam region along the axis of the main flow. Inert gases have a breakdown threshold several times lower than used mixtures. However, this additional factor of an optical discharge stabilization (by argon injection) is not a matter of principle and can be excluded using laser power increased by several times.

Experimental set-up and registration methods

Gasdynamic section of the set-up (Fig.1) provides the formation of subsonic jet of the working mixture by confusers and the argon wake (through the hole of 3mm in a tube of 4mm) along the flow axis. Hydrogen/air exit diameter confuser was 8mm, and 20mm for different mixtures. Air and hydrogen are mixed in the working chamber 1, air and hydrocarbons are mixed before it in gas supply system. Argon is supplied from the plenum chamber 2. Laser radiation is focused by the lens 3 in the argon jet at a distance of 10mm from the outlet section and blocked up by absorber 4. The pulse-periodic CO₂-laser LOK-3MSI developed in ILP SB RAS and applied in the previous our experiments was used.

Optical scheme of flow visualization is presented in Fig.1 too. The flow region with OPD 5 was lighted using He-Ne – laser 6. The spherical
wave front (converging beam) with the demanded aperture of the object under investigation was formed by micro-lens 7 and large focusing distance (450mm) lens 8. The application of the spherical wave front allowed one to use interferometer 9 with the inlet aperture 16mm, which is less than the visualization field’s dimension (50mm). Interferometer was set up at a certain distance from the object. The applied scheme of interferometer with the separated regulation of the fringe’s width and sensitivity allowed one to determine reliably the boundaries of the turbulent combustion zone. Information was registered through light filter 10 and objective 12 by television camera of technical vision 11 with the exposure time 0.1ms. It was recorded by video-player 13 and displayed by monitor 14 during process in study. After experiment the selected frames were numbered and processed by the standard graphic methods.

Experimental results for hydrogen

All experiments were conducted with the homogeneous mixture hydrogen/air jet at subsonic exhaustion into ambient atmosphere. The range of air consumption varied within 1.5–8g/s, hydrogen 0.045–0.1g/s. Argon consumption varied little and made up 2.3–2.5g/s. Velocities of the mixture and the argon flows were determined by known data about gas consumption and throat areas of the outlet holes. Equivalence ratios was determined by the relation of air and hydrogen consumption taking into account stochiometric coefficient, equal to 34.5.

Experiments were performed in two stages. At the first stage without supply of laser power (OPD) and argon supply two regimes of combustion were established: (1) – “attached” flame stabilized at the outlet confuser hole, which at increasing of the flow velocity was transferred into (2) – “detached” from the hole’s edge flame with the following it’s breakdown. Argon supply decreases the breakdown parameters, this effect depends on the argon consumption. In average according to the total measurements conducted in the range of the argon velocities 150–210m/s the characteristics of breakdown were: mixture velocity 60–70m/s and equivalence ratio 0.6–0.8. Thus, the first regime of combustion was realized at argon supply without OPD.

The second stage of the experiments was performed with the OPD formation in the flow. Argon exhaustion velocity was 190m/s. This parameter determines the choice of pulse repetition frequency \( f \) of the laser. As it is shown in [3] the upper limit of this parameter is determined by the value \( f = \frac{u}{l} \) (where \( l \) is the optical break-down plasma extension), which is not more than 30kHz for the conditions of the experiment. The experiments were performed also for the frequency of 8kHz.

Figure 2,b–f shows the results of visualization of hydrogen/air mixture combustion supported by OPD when the flow velocity (from 60m/s till 200m/s) and equivalence ratio (from 0.5 till 1.9) increase. Interferometer is adjusted to the fringes of the unlimited width. OPD plasma is registered as the great lighting region showing the length 8–10mm and diameter two times smaller, whereas the diameter of the focused laser beam was not more than 0.3mm. Figure 2,a shows mixture combustion flow without OPD at low velocity and equivalence ratio values (60m/s and 0.5 respectively) and argon supply, i.e. in the regime of the “attached” flame. Argon jet in the axis part of the flow is traced poorly. The feature of this flow is

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**Fig. 1.** Experimental set-up and optical scheme.


Hydrocarbons/air flame boundaries in a flow were determined by light emission visualization of a spectrum region for CH radicals.

Parameters for reactive flow (velocity, equivalence ratio), laser radiation (pulse repetition frequency and power), also argon velocity (consumption) in the case of optical breakdown were varied in experiments.

Experimental results for the flame, stabilized by separation zone behind argon supply tube (4mm of outer diameter, in a center of confuser exit), were used as the basic ones in a comparative analysis.
that the interference fringes vary regularly at a
distance not less than two diameters of the
confuser. Density and other parameters in the
considered flow vary regularly, that characterizes
the laminar flow and combustion process.
Downstream parameters vary not regularly which
indicates transition to the turbulent regime.
Therefore the determination of the Reynolds
numbers range at which the experiments were
performed is of particular importance. This
parameter varied in the range of \( \text{Re}=\left(0.5–3\right)\times10^4 \) (at
\( \alpha>1 \), considering the characteristic scale of 2mm –
the circular slot which forms the mixture flow).

Thus, the optical pulsed discharge effects
considerably the reactive flow and stabilizes the
flame near the place of radiation focusing. The
variation of the parameters of the flow at
combustion in the whole range of the Reynolds
numbers corresponds to the turbulent one even at
low Re (see Fig.2,a and 2,b). Besides, combustion
was performed even at the highest flow velocities.
The ultimate values of the parameters of it’s
breakdown were not reached. Figure 2.b in which
there is not plasma lighting should be paid attention
to. It is caused by the fact that at the given laser’s
pulses repetition frequency of 8kHz the time
interval between them (0.12ms with the frame
frequency 25s\(^{-1}\)) exceeds a little the exposition time
(0.10ms). That is why in some (not frequent) cases
the optical breakdown is not registered (when the
opening of the lock is during the time interval
between pulses). Poor lighting is conditioned by
after lighting of the discharged plasma.
Nevertheless the combustion process is registered
which shows that it is sustained even during the
period between pulses. The angle of inclination of
the flame decreases monotonously when the
velocity and the equivalence ratio increase. Thus,
one can make a conclusion that quasistationary
process of combustion is formed by pulsed optical
discharge at used frequencies of radiation 8 and
30kHz.

### Propagation velocity of the turbulent hydrogen/air flame

Measured flame velocities \( u_f \) in the
reactive flow hydrogen/air is considerably greater
than the velocity of the laminar flame propagation
whose quantity does not exceed 2.6m/s, that is
evidence of a turbulent combustion also.

A number of physical models were
proposed to describe the propagation velocity of
turbulent flames in various mixtures [4]. As a rule,
all of them boil to establishing a relation between
the turbulent flame velocity and mixture parameters
(normal flame velocity \( U_H \), or characteristic time of
particle residence in the laminar flame front \( \tau_G \)), on
the one hand, and turbulence parameters of the flow
(mean value of turbulent velocity pulsation \( U' \), or
turbulence-exchange coefficient \( D \)), on the other.
Experimental data favoring this or that model are
always available. For instance, in [5], a one-to-one
experimentally measured dependence of the
dimensionless turbulent velocity \( \left(U/U_H\right) \) on \( U'/U_H \)
was reported for flame propagation in a channel in
which the mixture flow was ignited near the channel
exit.

To analyze the obtained data on \( U_f \), one
may invoke a turbulent-combustion model based
on the assumption about some limiting conditions of
flame propagation [6].

Since, for turbulent flows, occurrence of
arbitrary values of local velocity gradients
grad\(U=U'/\lambda\) are typical (where \(\lambda\) is the turbulence scale), it is apparent that only some fraction of all pulsation is capable of promoting flame propagation. Pulsation to which velocity gradients above a certain critical value correspond do not help the flame move. Adopting, as a characteristic time of combustion, the reciprocal of the critical velocity gradient, we may write that \(U_*/\lambda_* = 1/\tau_\Gamma\).

With the maximum value of \(U'_*/\lambda_\ast\) for which the turbulent-assisted flame propagation is still possible taken as a characteristic flame propagation velocity (i.e., \(U_f=U'_*/\lambda_\ast\)), one may determine \(U_f\) assuming that a certain definite relation between \(U'_*\) (RMS value), integral turbulence scale \(\lambda_\ast\), on the one hand, and \(U_*/\lambda_*\) on the other, exists which can be written in the form \(D=U_*/\lambda_\ast=U_*/\lambda_\ast\); then \(U_f=(D/\tau_\Gamma)^{1/2}\).

This model used for description of integral characteristics of turbulent combustion in leading and trailing flame edges, intervals of parameters in which burning is possible (flame-stall characteristics) and flame front oscillation frequency (see [6-8]) showed a good agreement with experimental results obtained for various operating conditions of technical apparatus. With no stilling devices (e.g., grids) provided for changing turbulence parameters, one may assume that the turbulence-exchange coefficient is proportional to the product of flow velocity and jet cross-sectional area: \(D=ud\) [9].

Fig.3. The data on hydrogen/air combustion – 1,2 – experiment; 3,4 – calculations

The data obtained in this study are shown in Fig.3. Various reasons can be invoked to explain the observed scatter of the measured values (within a factor of 1.3). The main one is the registration technique used. In our experiments, the oscillation frequency of the flame front amounted to several tens of Hz, while the exposure time was \(10^{-4}\)sec; therefore, instantaneous (random) positions of the flame front between two extreme positions were probably registered. The visualization method could also add some detrimental contribution. Data obtained by two methods of registration are shown in Fig.3. The extreme positions of the flame front were determined either from infinite-thickness fringes in flow interferograms (dots 1) and from finite-thickness fringes (dots 2). As follows from the figure, the extracted data differ appreciably from each other. It should be noted that no appreciable effect of the pulse repetition frequency on \(U_f\) was found. The latter is likely caused by the fact that the characteristic time of particle combustion in our experiments was longer than the period between pulses \((\tau_\Gamma\geq10^{-3}\)sec\), although at frequencies below \(8kHz\) one may expect the quasistationary regime of the development of the process to be violated.

Thus, stable combustion occurs for a wider range of initial conditions. The appearance of the obtained dependence of \(U_f\) on the flow velocity and \(\tau_\Gamma\) is indicative of the fact that one and the same mechanism of flame propagation is operating under conditions of flame initiation with an optical discharge and with traditional means.

**Experimental results for hydrocarbons**

The first experiments is devoted to reveal the main mechanisms of combustion development effected by pulsed laser radiation (with and without optical breakdown). Its have a qualitative character.

**Methane/air mixture**

All experiments were conducted with the homogeneous methane/air mixture jet (with 20mm diameter) at subsonic exhaustion into ambient atmosphere. The range of air consumption was within \(0.3-1.7g/s\), methane \(0.01-0.09g/s\). Velocity of a reactive mixture varied within limits \(1.8-5.4m/s\). Argon consumption was \(0.2m/s\) and was increased two times in some experiments. Equivalence ratios was determined by the relation of air and methane consumption taking into account stechiometric coefficient, equal to 17.24.

Presented in Fig.4 pictures of combustion zone at laser energy supply but without optical breakdown (a) and with it (b) in a flow shows, that the velocity of a flame propagation is higher in the second case, also an argon was used to get the condition for breakdown. Despite of dilution of the reactive mixture by inert gas a flame front angle increase in a value and is close to \(90^\circ\). Range of a
mixture composition, where stable combustion take a place, is widened. Range of values of $\alpha$ changed from 0.85–1.16 (without radiation energy supply) up to 0.61–1.35 in a presence of the OPD with frequency 17kHz and absorbed power 1.2kW. It worth to notice that an argon jet effects sufficiently (in comparison with hydrogen/air mixture) these parameters. The argon velocity increased the initiation of stable combustion had became worse. Probably, this effect is caused by dilution of the reactive mixture and decreasing of the energy, heating this fuel mixture.

Fig.4. Combustion in a flow of a methane/air mixture. a) – without OPD, $\alpha$=1.05; b) – with OPD, $\alpha$=1.10.

Preliminary analysis of the obtained results shows, that velocity of a flame propagation has the same conformity as for hydrogen/air mixture.

Propane/air mixture

The range of methane consumption varied between 0.046–0.09g/s, and air between 0.77–1.5g/s. Velocity of a reactive mixture was 2.2–4.5m/s. An argon consumption had the same values, mainly 0.2m/s as in experiments with a methane. Velocity of an argon jet was no less than 17m/s and exceeded the mixture velocity. Equivalence ratios was determined by the relation of an air and propane consumption taking into account stochiometric coefficient, equal to 15.67. One can mark the same character of combustion process which was founded out in experiments with methane. The range of mixture composition and velocity for a stable combustion was widened in a comparison with the basic regimes. For example, for velocity value 3 m/s range of $\alpha$ 1.02–1.18 widened to 0.95–1.5.

But in contrast to a methane/air mixture the effect of a propane/air combustion initiated by focused CO2-laser radiation without an optical breakdown (discharge) was revealed. The same effect of a flame initiation by focused laser beam without an optical discharge was found out for evaporated alcohol/air mixtures. Typical results of the visualization of these combustion regimes supported by laser radiation (17kHz, 1.3kW) but without optical discharge are presented in Fig.5a,b. The range of mixture composition for a stable combustion was widened in a comparison with the basic regimes also. Despite of the limited data on turbulent flame velocity for these regimes obtained one can say with certainty about changing of conformity to the natural law for flame propagation in comparison to combustion supported by optical pulsating discharge.

Fig.5. Combustion of propane (a) $\alpha$=1.18 and vaporized alcohol (b) supported by laser radiation but without OPD.

Conclusions

Experimental results on homogeneous mixtures of a hydrogen/air and hydrocarbon/air combustion initiated by OPD showed that pulsating optical discharge effects considerably the reactive flows. It was proved by measurements in the whole range of Reynolds numbers Re=(0.5–3)×10^5 that stable hydrogen/air combustion is supported in a wider range of initial conditions; scale of a density fluctuation sufficiently changes also. High flame propagation velocities testify to development the process of a turbulent combustion.

Under conditions of an optical pulsating discharge, the flame for all used fuels was found to
be stable in a wider range of initial conditions in comparison with traditional method of stabilization (separation zone in flow). For hydrogen/air mixture the general appearance of the obtained dependence of $U_T$ on the physical and chemical properties ($\tau_\Gamma$) and hydrodynamic parameters ($u,d$) is the same under conditions of flame initiation with an optical pulsating discharge and with traditional means. Probably, the same conclusion one can say about methane/air mixture with lesser reactivity and, consequently, sufficiently affected by argon’s dilution.

The effect of a flame initiation and supporting by focused CO$_2$-laser pulsating radiation without an optical breakdown (discharge) was founded out. Probably, the mechanism of this process is connected with pre-flame reactions initiated by absorbed laser radiation.

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References


