Control of combustion processes at pulse-periodic effect
of laser radiation and electric field

A.V. Tupikin, P.K. Tretyakov

Khristianovich Institute of Theoretical and Applied Mechanics SB RAS,
Novosibirsk, Russia
Aim of investigations

The study in pulse-periodic regime of:

1) the influence on processes of burning by laser radiation;

2) the effect of electric field on combustion.
Advance of pulse-periodic regime:

1) Significant capacities of a supply of energy are easier for realizing in an impulse, than in a continuous mode

2) Opportunity of studying of dynamics of influence of a source of energy supply

3) The variation time characteristics allows to influence the certain processes of burning selectively
Laser-induced ignition

First – Laser-induced photochemical ignition
Second – Laser-induced spark ignition
Third – Laser-induced thermal ignition
Fourth – Laser-induced excitation of reactive molecules
Laser-induced photochemical ignition

1) $h\nu > E_c$

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Ionisation Pot. (eV)</th>
<th>$\lambda_{\text{max}}$ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O$_2$</td>
<td>12.07</td>
<td>102.73</td>
</tr>
<tr>
<td>H$_2$</td>
<td>15.425</td>
<td>99.12</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>12.51</td>
<td>80.39</td>
</tr>
</tbody>
</table>
Laser-induced photochemical ignition

2) $h\nu < E_c$

$f_{col} << W_{abc}/(h\nu)$

**P=0.1 atm**

**T=300K**

Stoichiometric $\text{H}_2-\text{O}_2$ mixture with $\text{NO}_2$ addition of 20%

The photo-dissociation of $\text{NO}_2 + h\nu \rightarrow \text{NO} + \text{O}$ is the dominant elementary reaction generating the free radicals of oxygen atoms.

S. Mori and N. Yoshikawa
Laser-induced spark ignition

Resonant laser-induced ignition

Nonresonant laser-induced ignition
Engine with the q-switched Nd:YAG laser system

Significant reductions in fuel consumption as well as reductions of exhaust gases show the potential of the laser ignition process

Laser induced ignition
G. Liedl*a, D. Schuöcker*a, B. Geringer*b, J. Graf*b, D. Klawatsch*b, H.P. Lenz*b, W.F. Piock*c, M.Jetzinger*c, P. Kapus*c
*aInstitute for Forming and High Power Laser Technology, TU Vienna, Arsenal Obj. 207, 1030 Vienna, Austria
*bInstitute for Internal Combustion Engines and Automotive Engineering, TU Vienna, Getreidemarkt 9, 1060 Vienna, Austria
*cAVL List GmbH, Graz, Austria
HiPoLas: miniaturised Nd:YAG Laser

Military applications
(Laser fire control armament system for the Paladin, NLOS-C Lightweight, and FCS 155mm cannons)

Laser ignition for automotive engines
(United States Patent 6514069)
Laser spark ignition

Energy of impulse < 1мJ;
Duration of impulse ~ 110 – 130ns;
Frequency of pulse repetition -20kHz;
Length of a wave -1060nm.
Fuel – H₂+O₂ (CH₄+O₂)

А.В.Иванов, С.Г.Ребров, А.Н.Голиков, Гутерман В.Ю. Лазерное зажигание ракетных топлив кислород-водород, кислород-метан. «Авиакосмическая техника и технология». №2, 2008.
Laser-induced spark ignition

Structure of supersonic jet with optical discharge

Ignition and stabilization methane/air flame by optical discharge

optical discharge in supersonic air jet

M = 2.2, n ≈ 0.5, α = 0.9, f=30kHz

ITAM SD RAS & ILPh SD RAS (13.07.2011)
Leading mechanism is thermal self-ignition with the presence of excited molecules.
Dynamics of ignition

The first interval $\Delta \tau_{1,2}$ from the leading front of the ignition pulse to the emergence of the glow (200 $\mu$sec)
Second interval ($\Delta \tau_{2,3}$), the emission intensity slowly increases, showing that, at this stage, active radicals grow in number and hot regions appear in the mixture (the time delay of ignition)
At the third stage ($\Delta \tau_{3,4}$) a flame front develops

Conditions of quasi steady-state process:
$\tau_r = a / U_n^2 > 1/f$
($a$ – factor of thermal carry, $U_n$ - normal component of speed of flame propagation, $f$ – frequency of pulse repetition)

Experimental scheme (for propane)
Dynamics of ignition (*Alcohol/air mixture*)

Experimental scheme (for alcohol and petrol)

Alcohol/air mixture. Unlike the case of propane, here the action due to radiation is more pronounced at each laser pulse.
Dynamics of ignition (*petrol/air mixture*)

\[ u = 4.75 \text{ m/s (Re } \sim 3000) \]
\[ \alpha = 1.8 \quad T = 400 \text{K} \]

\[ u = 5.5 \text{ m/s (Re } \sim 2800) \]
\[ \alpha = 1.8 \quad T = 470 \text{K} \]

The increase in initial temperature of a mix can lead to growth of velocity, and reduction of time of stay in a zone of absorption of radiation.
The calorific method was used to measure the absorption of laser-radiation energy in propane/air mixtures. The upper and lower curve was taken at a focal length of 100 and 50 cm, respectively.

The estimated temperature of the mixture at combustion initiation regimes turned out to be close to the ignition temperature.
Delay time ignition, characteristic time of burning

\[ C_3H_8 + \text{air} \]

Comparison of experimental and calculated delay time ignition

Correlation of experimental data with characteristic time of burning:
- measured time of flame front development

\[ \tau_r = \frac{a}{U_n^2} \]

\[ \alpha = \frac{1}{\varphi} \quad \text{air equivalent ratio} \]
1. Laser-induced photochemical ignition is effected, if $h\nu$ more energy of coupling, or frequency of collation is less the relation of the absorb power to ($h\nu$).

2. Laser-induced spark ignition may be more used in technical application.

3. Laser-induced thermal ignition don’t right to consider without excitation of reactive molecules
Influence on combustion by pulse-periodic laser radiation

nozzle diameter 20 mm, flow velocities U=2.0–3.5 m/s, equivalence ratio α=1/φ=0.8–1.3.

The activated plasma ensured quasi-stationary flame propagation regime since the characteristic time of combustion, or the time of residence of reacting species in the laminar flame front (about 10^{-3} sec) was greater than the time between successive energy pulses (about 10^{-4} sec).
The increased rate of combustion can be explained by local heating of the mixture due to resonance absorption of the laser radiation.
Integral flame emission intensity

Dependence of emission from air equivalent ratio (for different temperature)

The emission intensity was not affected by the laser radiation
Influence on combustion by pulse-periodic laser radiation

\[ \Delta E_{\text{pulse}} = \int_{T_0}^{T} \Delta m C_p dT \]

Flame velocity:
1 – continuous, 2 – \( f = 50 \text{ kHz} \), +– \( f = 5 \text{ kHz} \),
\( \times – f = 70 \text{ kHz} \), 3 – without laser, line – data from the literature

Form of a flame \((\alpha = 1.4, \ N = 1.8 \text{ kW})\):
\( a – \) continuous, \( b – f = 50 \text{ kHz} \), \( c – f = 5 \text{ kHz} \)
Lifting flame

a - without laser radiation, $U_0 = 11.5$ m/s;
b - with radiation, $W = 1$ kW, $f = 1.5$ kHz, $n = 3$,
$U_0 = 11.5$ m/s;
c - without radiation, $U_0 = 20.5$ m/s;
d - with radiation, $W = 850$ W, $f = 0.7$ kHz, $n = 3$,
$U_0 = 20.5$ m/s
Brief summary

1) Absorption of laser radiation conducts to improvement of conditions of burning: velocity of flame propagation, limits of stabilization increases;

2) The leading mechanism of influence of radiation on a flame is local increase of translational temperature of a mix.
Influence of weak electric field on a flame

The weak electric field does not lead to breakdown of environment.

Mechanism of influence:
1) Ohmic heating of a mix
2) Change kinetic of reactions
3) Ionic wind
D. Dunn-Rankin “Characterization of Ionic Winds from Flames and Corona Discharges”
Results of numerical modelling

(D. Dunn-Rankin)
H.K. Kammler, S.E. Pratsinis, P.W. Morrison

Application of an electric field for the control of temperature over reception a microscale powder TiO$_2$
Влияние электрического поля на горение
(несколько ссылок)


Кидин Н.И. Влияние внешних электромагнитных полей на процессы горения. http://www.ism.ac.ru/sgv/rtf/121.rtf

Influence of weak electric field on combustion

Lifting flame

DC electric field

\[ u = 15 \text{ m/s} \]

\[ U = 0 \quad U = 1 \text{kV} \quad U = 2 \text{kV} \quad U = 4 \text{kV} \]

Pulse-periodic electric field

\[ u = 11.5 \text{ m/s} \]

\[ U = 0 \quad f = 20 \text{ Hz} \quad f = 50 \text{ Hz} \quad f = 100 \text{ Hz} \quad U = 3.6 \text{kV} \quad f = 0 \]

H – height of a raising of a torch;
Diameter of nozzle – \( d = 2.3 \text{ mm} \)

\( U = 500 – 4500 \text{ V} \)
Influence of weak electric field on combustion

The limiting height of a raising of a torch does not depend on velocity. 

\( \frac{H}{d} = \text{max by } f=0. \)
Influence of weak electric field on combustion

Homogeneous combustion

V = 2 \text{kV}

Laminar flame
U_0 = 0.8 \text{ m/s};
t = 20^\circ \text{C};
\alpha = 1.34

Flame velocity increase by 20-30%
Influence of weak electric field on combustion

Homogeneous combustion

Dependence of flame velocity from duration of an impulse (f=50 Hz)

Dependence of flame velocity from frequency (τ =1 ms)

With growth of frequency speed of distribution of front of a flame grows, thus the effect depends on a pressure
There are modes at which influence an pulse-periodic electric field is more effective than imposing a constant field.
Influence of weak electric field on a flame

Homogeneous combustion

Turbulent mode

Laminar mode

On a transitive mode there are fluctuations of front of a flame
At $U=0.5$ kV the amplitude of fluctuations of front of a flame decreases

At $U>0.5$ kV the amplitude of fluctuations of front of a flame increases. Noise from a flame considerably amplifies.

$u_{cp}=1.15$ m/s; $\alpha=1.35$;
$Re=1500$
Influence of weak electric field on a flame

Tomographic reconstruction of structures of intensity radiations of intermediate radicals

The image of a flame on registration of radiation OH

Integral intensity of radiation OH

Intensity of radiation OH on radius
Influence of weak electric field on a flame

Tomographic reconstruction of structures of intensity radiations of intermediate radicals

The image of a flame on registration of radiation CH

Intensity of radiation CH on radius
1 - without electric field
2 – with electric field
Influence of weak electric field on a flame

Dynamics of flame displacement

Experimental scheme

Displacement of front:
- From a negative electrode;
- From positive electrode.
Influence of weak electric field on a flame

Homogeneous combustion

X-component of velocity
Y-component of velocity

Change of velocity at inclusion of an electric field

Experimental scheme
Conclusions

- Electric fields are an effective control facility integrated characteristics of burning

- The range of stable burning can be expanded in area of poor mixes

- Pulse-periodic influences expands opportunities of management with process of burning
Спасибо за внимание!

Thank you!

Работа выполнена при финансовой поддержке Программой фундаментальных исследований «Отделение энергетики, машиностроения, механики и процессов управления» РАН № 1 «Фундаментальные проблемы горения и детонации в энергетике» (проект 1.2) и РФФИ (грант № 11-01-00158-а).