Weak detonation wave ignition and sustaining in over CJ-speed flow by means of undercritical microwave discharge

Kirill V. Khodataev

UFSF “Moscow Radiotechnical Institute of RAS”, Russia

K.V.K@home.ptt.ru

Nomenclature

E, H = effective amplitude of electric and magnetic field of microwave radiation
c = light velocity
ω, λ = microwave radiation frequency and wave length
σ = plasma electrical conductivity
ψ = ionization coefficient
ρ = density
T_e, T_g = electron and gas temperature
n_e, n = electron and gas number density
C_e, C_g = electron and gas thermal capacity at constant volume
τ_{eg} = electron-gas relaxation time
τ_h = chemical energy relaxation time
D_e = free electron diffusion coefficient
ν_i = sum of ionization, electron attachment and recombination frequencies
a_s = streamer radius
E_{cr} = critical value of electric field

Introduction

The microwave undercritical high pressure discharges ability to ignite and to sustain combustion in flammable gas mixes in high-speedy flows (up to supersonic flows) is shown theoretically and experimentally. The performed theoretical study predicts that microwave discharges of the same type are able to ignite not only combustion, but detonation too. The filamentary structure of discharge creates the hot active centers like active points in cells in front of CJ detonation wave. It means that artificial active points, created by microwave radiation in definite region of combustible mix flow, will able to provoke the quasi-stationary weak detonation wave in fixed location. The stimulated weak detonation wave can exist at wide diapason of oncoming flow speed, if it is more CJ velocity.

Application of detonation regime of burning in propulsive systems is being discussed during more than half century. The most attractive idea is based on use of standing detonation wave in jet engines. Noted property of microwave undercritical discharge will help to solve some problems concerning to design of propulsive jet engines based on detonation in continuous mode.

Formulation of task

Experiments with MW discharges have shown that the energy release inside streamer channels during quite small time duration (in order of one microsecond and less) arises gas temperature inside the channel up to many thousands Kelvin (three and more). It was demonstrated by observing of evaporation of wolfram wire initiating the streamer undercritical MW discharge. Estimations and modeling on various numerical models have confirmed it too. The many experiments have been performed on ignition of combustion in combustible mixes, particularly in air-propane mix. It was shown that MW discharges are igniting combustion and increasing the speed of combustion[1,2,].

One from noted above simple numerical models has been used for study of possible ignition of detonation in the flammable gas mixes. The modeling had pointed on such principal opportunity[3,4].

The typical value of detonation front velocity in a still gas mix is about couple of km/s. In a flow with speed which is more of this value the ignition center generates the oblique detonation wave. In Ref.[5] as such initiating center the inlet cowl was used. At injection of hydrogen in to the flow before the cowl the change of light in the channel was observed. It was interpreted as oblique detonation wave. Those experimental conditions were studied theoretically and numerical modeling confirms initiation of detonation[6].

The streamer MW discharge representing the complicated net of thermally exploding hot filaments is able to ignite the detonation in many points in transverse cross-section of engine channel. It means that in this case we will have the plane weak (underpressed) detonation wave attached to place of MW initiation. One can suppose that such regime can open the new opportunities for designing of scramjet based on use of standing detonation wave with short zone of combustion.

Here we investigate process of detonation ignition by single streamer channel arising during individual discharge.

Numerical modeling

The model used in this investigation is described in Ref.[4]. Let us repeat the main physical assumptions been laid into basis of this model.

As it is known, discharge plasma generally is thermodynamically no equilibrium medium. Energy of electromagnetic field is absorbed first of all by electrons and then through elastic and not elastic collisions is transferred to a heavy component. Therefore, as a minimum, it is necessary to consider two-temperature model of plasma, distinguishing electron temperature and temperature of heavy component. The electronic temperature determines many constants of reactions. It determines constants in the equation of ionization balance, frequency of ionization, attachment, recombination and so on. Electronic temperature determines time of a relaxation in a power exchange between electronic and heavy components, losses on recombination and bremsstrahlung radiation, active and reactive resistance of plasma. Dissociation of molecular gas depends, basically, from temperature of heavy components and in the developed model it is taken into account through Saha's equation. The description of thermal capacity, viscosity and heat conductivity of heavy components are based on the assumption of its thermodynamic equilibrium, characterized by temperature of gas. In the same assumption the heat conductivity, coefficient of diffusion and a thermal capacity of electronic component are defined. The propane presence at air in stoichiometric proportion changes gas-dynamic characteristics of air a little and its presence is taken into account by presence of chemical potential, relaxing into a heat with characteristic time of a relaxation, dependent on density and temperature of heavy components. After passage of reaction of burning the number of molecules does not vary almost, that allows using the statement equation of air for the description of processes in air-propane mix.

Dependence of time of a relaxation τ_h on the specified parameters is borrowed from Ref. [7]

$$t_{comb} = \frac{1.36 \cdot 10^{-10}}{(p, atm)^{3/2}} \cdot \exp\left(\frac{19000}{T, K}\right) \quad (1).$$

The system of the equations, put in a basis of model, consists from the equations of two-temperature one-speed gas dynamics with taking into account the relaxation of internal chemical energy:

The equation of ionization balance (equation of continuity for electron component) equation of continuity for

$$\frac{d\psi}{dt} = \nu_{iar} \cdot \psi + \nabla \cdot (D_e \nabla \psi) \qquad (2)$$

The equations of power balance for electronic component

$$\frac{dT_e}{dt} = \frac{1}{C_e} \cdot \begin{pmatrix} -T_e \nabla \cdot V + \nabla \cdot (\vartheta_e \nabla T_e) + \\ + \dfrac{T_g - T_e}{\tau_{eg}} + \dfrac{\sigma \cdot |E|^2}{n} \end{pmatrix} \qquad (3)$$

The equation of power balance for heavy components

$$\frac{dT_g}{dt} = \frac{1}{C_g} \cdot \begin{pmatrix} -T_g \nabla \cdot V + \nabla \cdot (\vartheta_g \nabla T_e) + \\ + \dfrac{T_e - T_g}{\tau_{eg}} + \dfrac{h}{\tau_h} \end{pmatrix} \qquad (4)$$

The equation of movement heavy components

$$\frac{dV}{dt} = -\frac{1}{\rho} \cdot \nabla (nT_g + \psi n T_e) \qquad (5)$$

The equation of continuity for heavy components

$$\frac{dn}{dt} = -n \nabla \cdot V \qquad (6)$$

The equation of a relaxation of internal chemical energy *h*

$$\frac{dh}{dt} = -\frac{h}{\tau_h (p, T_g)} \qquad (7)$$

Maxwell equations for electromagnetic field in assumption of monochromaticity

$$\nabla \times H = \left(\frac{4\pi\sigma}{c} - i\frac{\omega}{c}\right) \cdot E \qquad (8)$$

$$\nabla \times E = -i\frac{\omega}{c} \cdot H \qquad (9)$$

The system is completed by Ohm law and statement equations of electron and heavy component.

In those equations are used the following functions:

$$\nu_{iar} = \nu_i (\psi, n, T_e, T_g) + \nu_a (\psi, n, T_e, T_g) + \\ + \beta_r (\psi, n, T_e, T_g) n\psi$$

- sum of ionization, attachment and recombination frequencies,

$$D_e = D_e (\psi, n, T_e, T_g)$$

- electron diffusion coefficient,

$$\vartheta_e = \vartheta_e (\psi, n, T_e, T_g)$$

$$\vartheta_g = \vartheta_g (\psi, n, T_e, T_g)$$

- thermal conductivity of electrons and gas

$$\sigma = \sigma (\psi, n, T_e, T_g)$$

- electrical conductivity,

$$C_g = C_g (\psi, n, T_e, T_g)$$

- gas thermal capacity,

$$\tau_{ch} = \tau_{ch} (p, T_g)$$

- relaxation time of combustion, defined by Eq.(1),

$$\tau_{eg} = \tau_{eg} (n, T_g)$$

- relaxation time of electron in gas,

$$f_{dis} = f_{dis}(n, T_g)$$

- dissociation coefficient,

$$f = \psi\left(1 + f_{dis}(n, T_g)\right)^{-1}$$

- ionization coefficient. All functions are based on real cross-sections of reactions.

Boundary conditions correspond to quite big radius of calculation area for gas perturbations which have not a time for arrive to boundary and are transparent for MW radiation reflected by plasma channel. Initial conditions correspond to insignificantly small ionization and gas density decreased near the axis inside radius a = 0.03 cm up to critical value. The task is solved in 1D axis-symmetric approximation. Wave length of MW radiation λ=8.9 cm equals to value used in real experiments. Air-propane mix is stoichiometric; its initial pressure is 1 atm at room temperature. Chemical potential of stoichiometric air-propane mix normalized on room temperature equals to h_0 = 30.33. Pulse duration of MW radiation is 0.6 μs.

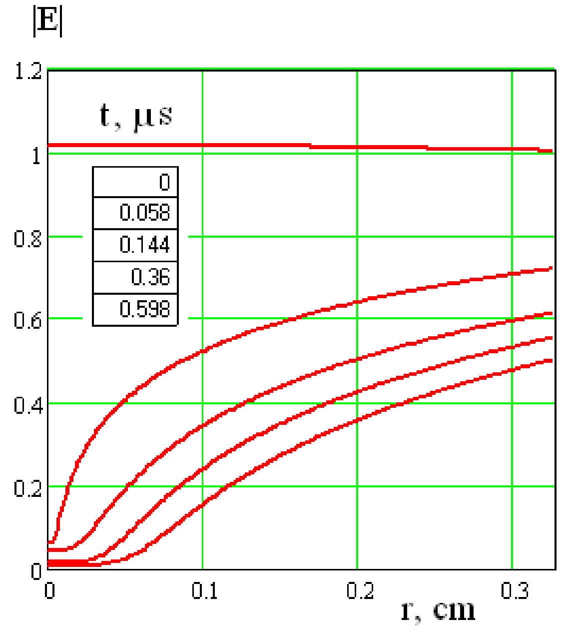

Fig.1. Electric field amplitude distribution at successive moments of time.

The modeling confirms MW streamer discharge ability to ignite detonation in stoichiometric air-propane mix at atmospheric pressure.

In area inside radius a, where initial field amplitude is overcritical the fast ionization starts. Increasing electrical conductivity cause the rising of induced current in channel and decrease electric field with clear displayed skin-effect.

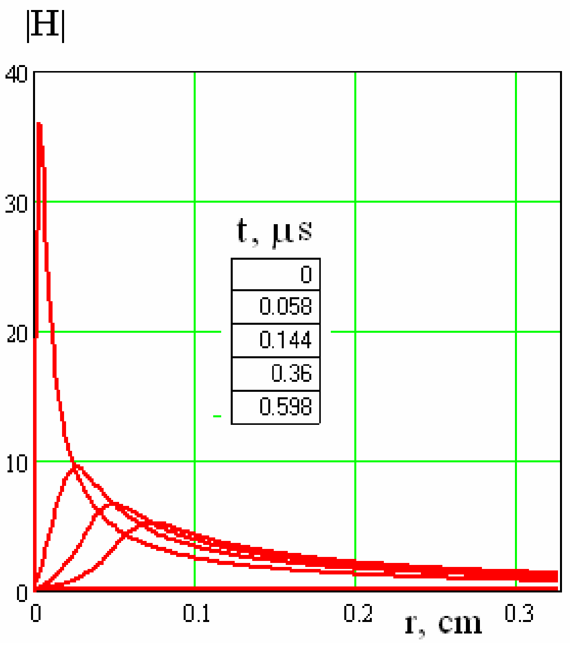

Fig.2. Magnetic field amplitude distribution at successive moments of time.

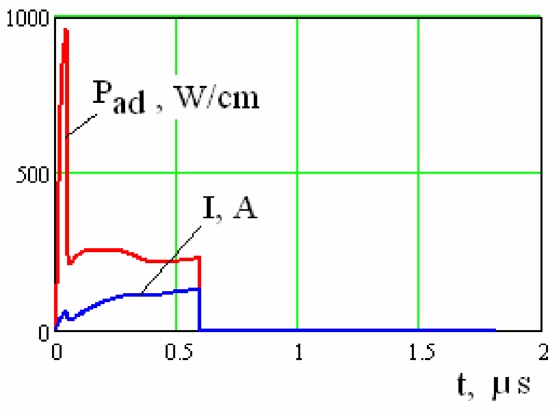

Fig.3. Power of Ohm heating and induced current amplitude in dependence on time.

The Fig.1 shows the electric field distribution at successive moments of time. The skin-effect is seen on Fig.2 too, where magnetic field amplitude distribution is presented. Electric current in gas with finite electric conductivity naturally causes the Ohm heating. Power of Ohm heating in time is shown on Fig.3.

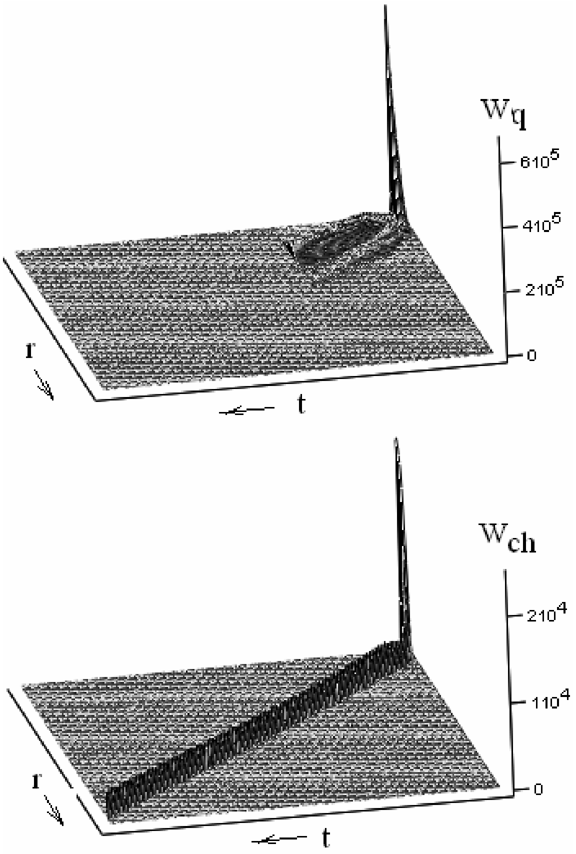

Fig.4. Spatial-temporal distributions of specific power of Ohm heating W_q and burning W_{ch}.

Fast heating of gas generates high temperature and initiate both heat explosion and chemical reaction of combustion. As result the detonation wave with constant radial velocity equaled to Chapman-Jouguet value is appearing.

Spatial-temporal distributions of specific power of Ohm heating and burning are shown on Fig.4. The Ohm heating is stopped when MW pulse is over. But detonation wave is propagating continuously up to boundary of calculated area. It good illustrated by Fig.5 which demonstrates the gas density evolution in time.

The distributions of gas parameters behind the detonation front are typical for theoretical model of Zeldovich et al. as one can see on Fig.6. Temperature behind the front is approximately 3000 K. The observed speed of detonation front is 1.58 km/s. This value well corresponds to theoretical value for CJ wave for adiabatic parameter behind front $\gamma_2 = 1.2$.

$$M_{CJ} = \frac{\left[\sqrt{(\gamma_2 - 1)\left((\gamma_2 - 1)h + \frac{(\gamma_2 + \gamma_1)}{\gamma_1 - 1}\right)} + \sqrt{(\gamma_2 + 1)\left((\gamma_2 - 1)h + \frac{(\gamma_2 - \gamma_1)}{\gamma_1 - 1}\right)}\right]}{\sqrt{2\gamma_1}} \qquad (10)$$

where h is chemical potential, normalized on T_1, indexes 1 and 2 are related to media before and after front.

Indeed the calculated thermal capacity of mix behind front equals to ~5 (see Fig.7). It corresponds to above-mentioned value of γ_2

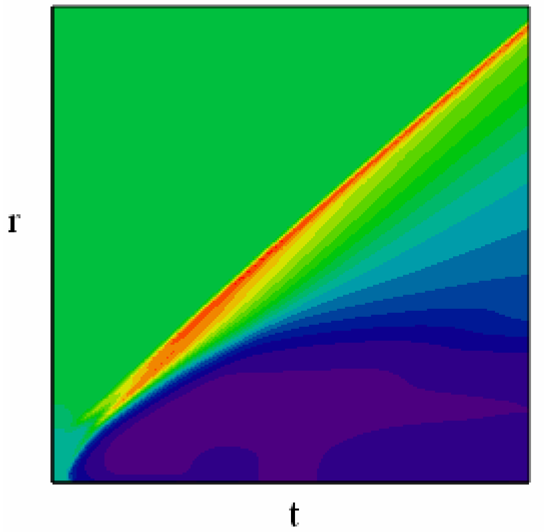

Fig.5. Profile of gas density on plot (r,t)

Increase of thermal capacity is defined by expenditures on dissociation and molecular excitation. Dissociation coefficient behind detonation front equals to ~0.05. Ionization coefficient is near to unite only at first moment on the axis of the channel and later equals approximately to 10-3 in hot channel created by discharge and has a very small value behind the detonation front. Electron temperature differs from gas temperature (much more) only during MW pulse. After end of MW pulse electron temperature equals to gas temperature.

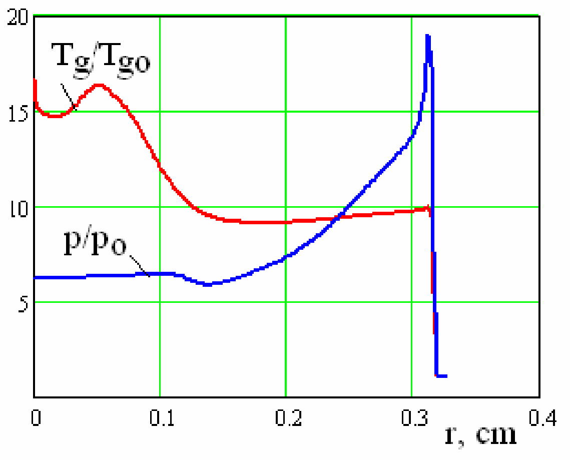

Fig.6. Radial distributions of gas temperature and pressure at last moment of calculation time t_{end} = 1.82 μs.

Discussion

Thus calculations have shown that each elementary filament of a MW streamer discharge is able to ignite detonation in a gas combustible mix. Average distance separating the filaments is of the order of quarter of wavelength (more or less in dependence on discharge conditions). It means that all gas fulfilled the discharge region will have been combusted through approximately 5-10μs and detonated area will increase with CJ speed. Characteristic size of a typical MW streamer discharge is comparable with several wavelength of MW radiation. Earlier it was proved theoretically and experimentally that streamer discharge can be sustained in a high-speed velocity of a gas flow.

It is understandable because the propagation velocity of undercritical streamer MW discharge is of the order of several km/s. Consequently behind the layer of MW discharge all combustible gas mix must be detonated. This forced standing front of forced detonation can be created in the flow velocity, which is more than velocity of Chapmen –Jouguet. This regime can be classified as underpressed or weak detonation wave.

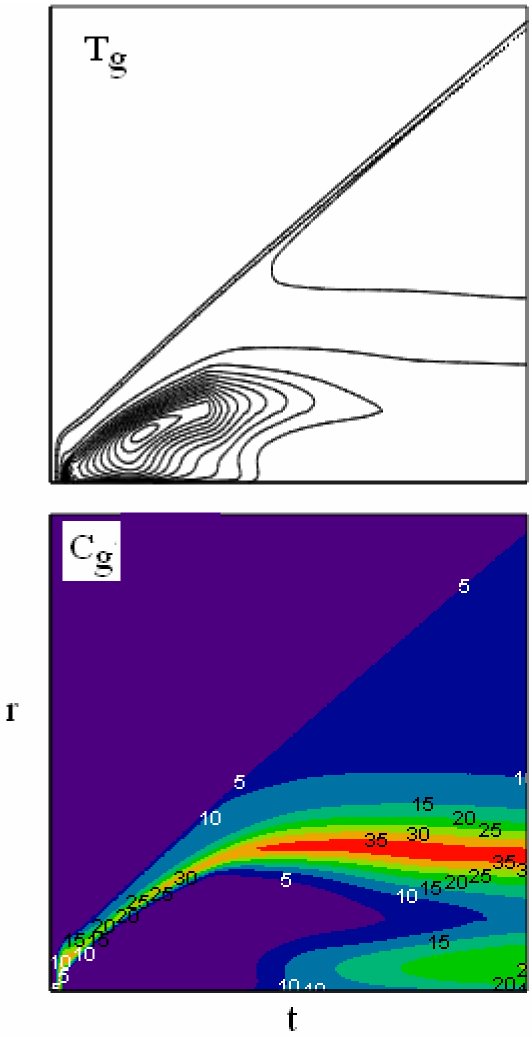

Fig.7. Distributions of mix temperature (above) and gas thermal capacity (below)

It is natural to suppose that the using of such regime of burning can help to design the scheme of scramjet with very high specific impulse. The using of ordinary rates for detonation wave shows that in the simplest scheme of scramjet without inlet diffuser and with outlet nozzle by means of standing weak detonation wave the specific impulse up to 5 km/s can be gotten

Conclusive notes

Further the designed numerical model can be used for define the area of parameters values, such as mix pressure, MW field undecriticality, MW pulse duration and mix content, where the detonation ignition is possible. The calculations will help to formulate program of experimental study of detonation ignition process. Firstly it must be experiments in a still mixes using existing facility. Second step is theoretical and experimental investigations of the standing detonation wave ignition by MW in a hypersonic flow using the corresponding installations, significantly more complicated and expensive.

Acknowledgment

Author sincerely thanks Dr. David M. Van Wie for displayed interest, fruitful discussions and support.

References

---

[1] Igor Esakov, Lev Grachev, Kirill Khodataev and David Van Wie. *Experiments on propane ignition in a high-speed airflow with a help of deeply undercritical microwave discharge.* 42nd AIAA Aerospace Sciences Meeting 5-8 January 2004, Reno, NV. Paper AIAA-2004-0840.

[2] I. Esakov, L. Grachev and K. Khodataev, D. Van Wie. *Efficiency of Energy Put into Initiated Microwave Discharge in High- Speed Air Flow and Propane Level of Combustion in It.* 43nd AIAA Aerospace Sciences Meeting 10-13 January 2005, Reno, NV. Paper AIAA-2005- 0989

[3] K. Khodataev. *The Ignition of the Combustion and Detonation by the Undercritical Microwave Discharge.* AIAA Plasmadynamics and Laser Conference, 32nd, and Weakly Ionized Gases Workshop, 4th, Anaheim, CA. Jun 11-14, 2001. AIAA Paper 2001-2941.

[4] K.Khodataev. *Numerical Modeling of the Combustion, Assisted by the Microwave Undercritical Attached Discharge in Supersonic Flow.* 43rd AIAA Aerospace Sciences Meeting 10-13 January 2005, Reno, NV. Paper AIAA-2005-0985

[5] T. Arai, S.Masuda, F.Sakima. *Intake Injection and Shock Induced Combustion in a Scramjet Engine Model.* 12th AIAA International Space Planes and Hypersonic Systems and Technologies. 15-19 December2003, Norfolk, VA, USA. Paper AIAA 2003-6910.

[6] G.Pusina, J.Sislian, B. Parent. *Computational study of formation and stability of standing oblique detonation wave.* 42nd AIAA Aerospace Sciences Meeting and Exhibit, 5-8 Jan. 2004. Reno, NV, USA. Paper AIAA 2004-1125

[7] M.V.Petrova, B.Varatharjan and F.A.Williams. *Theory of propane autoignition.* 42nd AIAA Aerospace Sciences Meeting 5-8 January 2004, Reno, NV. Paper AIAA-2004 -1325