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Experimental Study of Detonation in Propane-Air Mix Initiated by Pulse Microwave Discharge

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The work is devoted to experimental check-up of idea about detonation ignition by means of microwave subcritical discharge in gaseous combustible mix on example of a propane-air mix. Performed experiments surely have shown that microwave subcritical pulse discharge is able to initiate the detonation or combustion in dependence on mix composition and microwave specific power at fixed radiation pulse duration 40 µs. The detonation initiation is possible not only in a case of stoichiometric mix, but at lean fuel mix, at equivalence ratio for fuel less 0.5. Detonation ignition is investigated under action of a deeply subcritical (attached) discharge and of subcritical (streamer) discharge. Character values, at which the detonation has been realized, have been defined.

Nomenclature

Φ	=	equivalence ratio for fuel
α	=	completeness of combustion
M	=	mass of inflatable ball envelop
R_0	=	initial radius of inflatable ball envelop
p_1	=	pressure of atmosphere air
ρ_1	=	density of atmosphere air
v	=	dimensionless velocity of inflatable ball envelop
t	=	dimensionless time
r	=	dimensionless radius of inflatable ball envelop

I. Introduction

THE combustion by microwave (MW) discharges have studied experimentally in many works[1,2,3.], which surely confirmed this ability. In theoretical works[4,5,6] have pointed on possibility not only combustion initiation but of detonation ignition in gaseous fuel mixes by means of pulse streamer MW discharges. This work is devoted to experimental check-up of this idea. Experiments, performed in a still propane-air mix at fixed MW pulse duration 40µs, surely showed that MW subcritical pulse discharge is able to initiate the detonation in dependence on mix composition and MW specific power. The detonation initiation is possible not only in a case of stoichiometric mix, but at lean fuel mix, at equivalence ratio for fuel less 0.5. Detonation ignition is investigated under action of a deeply subcritical (attached) MW discharge and of subcritical (streamer) MW discharge[7]. Deeply subcritical MW discharge transforms energy of radiation into mix in a small spherical area attached to top of initiator. Character size of the area is about 0.1cm. Subcritical MW discharge has developed streamer structure, occupied the area with character size of several centimeters. At last case the initiation is performed along all streamer channels almost simultaneously. Power of MW absorption in discharges is estimated as maximal using the measured value of MW electric field amplitude and calculated effective cross

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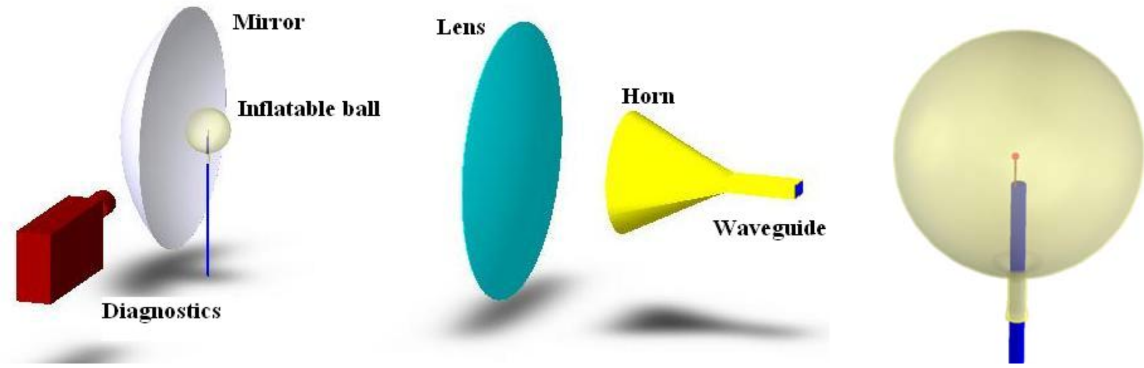
section of electromagnetic vibrator loaded by discharge with optimal resistance[8] (the vibrator serves as discharge initiator). At fixed pulse durance of MW radiation and measured values of total length of all streamer channels it is possible to calculate values both total, and longitudinal absorbed energy, at which the detonation was created. Character values, at which the detonation has been realized, are 1.2 J for attached deeply subcritical discharge and 0.2 J/cm for streamer subcritical discharge.

II. Experimental approach on detonation ignition study

Experiment with studying an opportunity remote detonation ignition in a combustible gas mix with the help of the MW radiation was carried out as follows. The inflate ball made of high quality latex was located on the installation with focused radiation on wavelength 8.9 cm in a focal zone, inflated with a working gas mix up to volume 1 liter, how it is shown in **Fig.1a**. In this figure all basic elements are shown with observance of real proportions. Radiation from the generator acts through a horn and a dielectric radiotransparent lens on focusing spherical mirror. The inflated ball located in focus of MW radiation, is shown in **Fig.1b** in stage before ignition. The gas mix acts in a ball through a tubule on which end it is mounted half wavelength vibrator which is carrying out function of initiator[9]. On its end it is conditionally shown attached deeply subcritical discharge. Aside of system axes the means of optical diagnostics are located. As a combustible gas mix the mix household propane with air was used.



(a) **(b)**

Figure 1. (a) - Schematic of experimental setup. (b) - Inflatable ball with feeding tubule and initiator.

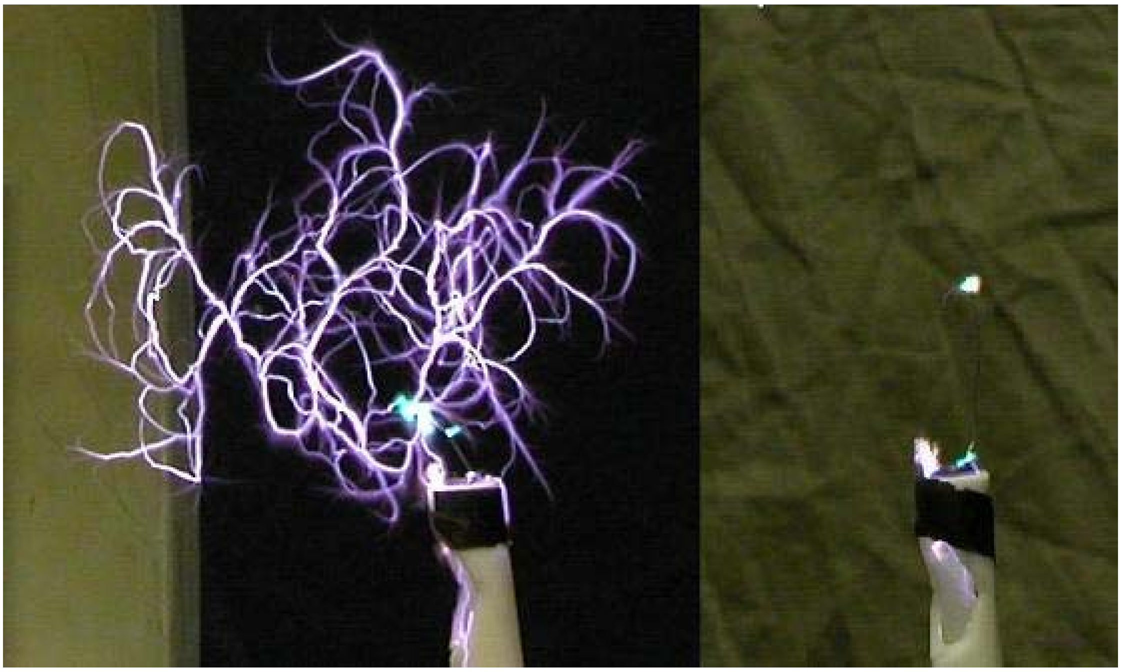
The structure of a mix was determined by a ratio of full pressure and partial pressure of propane P_{prop}/ P_{tot}.
After preparation of a mix were simultaneously started the generator and means of diagnostics.
As means of diagnostics were used: radio-engineering means of measurement of a level of MW radiation, photographing of process by the digital device with second exposure, filming by a digital video-camera with frequency of change of the frames 16 Hz, time-lapse shooting by the high-speed electron-optical chamber «K-011 framing camera » (9 frames, an exposure oт2 up to 100μs, a pause from 2 up to 100μs, Russia).

III. Observation result

The basic experiments were carried out at atmospheric pressure of propane-air mix and two positions of attenuator in waveguide gauge connecting MW generator with antenna system: open and closed.

Regime of streamer subcritical discharge

At open attenuator intensity of an electric field in focus where the initiator settled down, is equal to 4.7kV/cm. The discharge initiated by the half-wave vibrator, located in focus of radiation, is classified[10] as streamer subcritical discharge. Its photo in conditions of experiment with air is shown in **Fig.2a**. The full length of all streamer channels is estimated by size 100cm. At capacity of the generator ~0.5MW and duration of a pulse 40μs running energy in the streamer channels, added due to absorption of energy of the MW radiation, equals to ~0.2 J/cm. It is necessary, however to take into account, that heating of streamer channels occurs not simultaneously. Everyone streamer, developing up to length ~ λ/2, accepts the share of energy during the time of order 2μs. The streamers arising and exploding one after other create sequence in time and developed in space net of hot channels. Temperature of channels is high enough for initiation combustion and it is confirmed experimentally earlier. But parameters of streamer explosion can be too enough for generation of detonation wave by every streamer. In this regime the practically simultaneous generation of detonation wave net must be observed. Interference of detonation wave multitude must result the phenomena like volume explosion in area occupied by streamer discharge.



(a) (b)

Figure 2. Photo of MW pulse discharge at room air initiated by vibrator in focus of radiation: (a) – streamer subcritical discharge, (b) – attached deeply subcritical discharge. Vibrator is mounted on tubule, inflatable ball is absent

Regime of attached deeply subcritical discharge

At closed attenuator the intensity of electric field in focus where the initiator settled down, is equal 1.4kV/cm. The discharge initiated by the half-wave vibrator, located in focus of radiation, is classified as deeply subcritical, attached, discharge. Its photo in conditions of experiments, but with air, is shown in **Fig.2b**. Using ratio given in Ref.[8], it is possible to estimate the energy selected during of MW pulse 40µs 1.2 J. In difference to streamer discharge the attached discharge acts as point source of initiation.

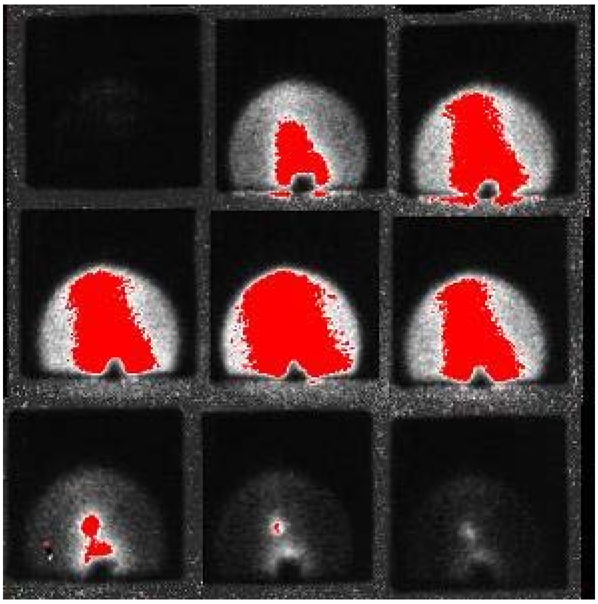


Figure 3. Typical view of time-lapse display in case of detonation. Exposure – 5 µs, pause –– 5 µs, delay - 0 µs, Φ ≈ 1

In both modes in result of discharge initiation and chemical reactions the ball with flash was inflated and then burst. Exception was made with limiting cases of a poor and rich mix. Integrated photos have allowed determining the energy of reaction.

The main attention was given to a problem of ascertaining of a detonation as such, separating it from burning. The basic means of ascertaining of the detonation initiated by discharge, time-lapse display of process with the high time resolution served.

If the luminescence in a ball was finished in time, not exceeding transit time from the centre of initiation up to an envelop of a ball with speed, characteristic for a detonation wave, that is, about 1.5 km/s (the transit time ~40μs), and was not seen later, we classified process as a detonation. Characteristic time-lapse displays for both modes (streamer and attached discharges) are given in **Fig.3**. Absence of a luminescence at the subsequent stages was supervised by increase of exposure and pause up to limiting sizes 100μs (full time of display thus made 1.8.ms) and by delays of the beginning of display up to 10-20ms.

The detonation is observed most clearly at Φ ≈ 1. Cases of a detonation in a poor mix however were observed at Φ ≈ 0.6 and even Φ ≈ 0.5 both with the attached discharge, and with streamer discharge.

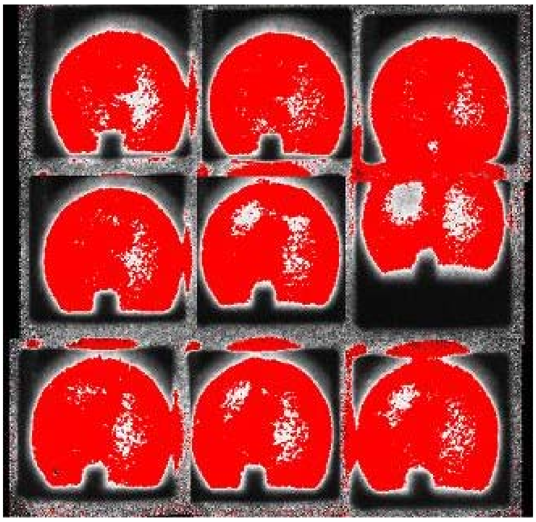
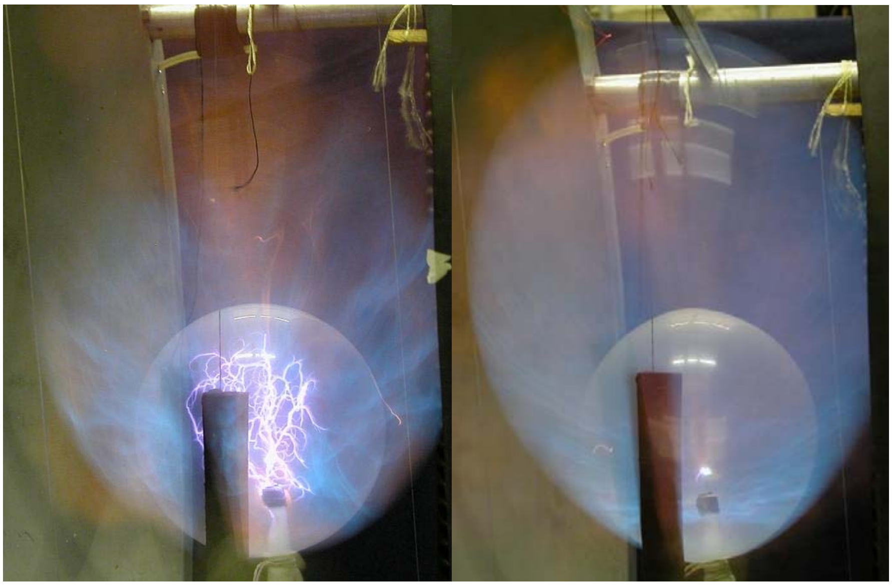


Figure 4. Typical view of time-lapse display in case of burning. Exposure – 100μs, pause –– 100μs, delay - 25ms, Φ ≈ 1



(a) (b)

Figure 5. Integral in time (exposure - 0.5s) photos of inflating ball in case of detonation. (a)- initiation by streamer subcritical discharge, (b) – initiation by attached deeply subcritical discharge

The detonation is observed not always. Rather frequently process accepts character of burning. In this case the ball is inflated and shines with the big delay. In **Fig.4** the time-lapse display made with delay 20 ms is given. It is visible, as the ball extends with speed about 10m/s.

Sharp difference of modes is visible also in integrated photos of initiation process. In **Fig.5** photos in a case of detonation are given initiated both streamer MW discharge and attached MW discharge. Discharges both an initial and final stages of a ball are clearly visible. Under action of hot gas the ball then bursts, scattering on small slices. The pale blue luminescence fills in all volume inflated ball. For comparison in **Fig.6** are given a similar photo for case of burning initiation by attached discharge. The luminescence of orange tone is characterized by a flame.

Features of process of burning initiation appeared possible to look with the help of a digital video-camera. If in case of a detonation in the taken off video film it is possible to see only one frame with a luminescence which fills in all inflated ball **(Fig.6)** in case of slow burning all basic stages of process of ignition are visible (**Fig.7**).

(a) (b)

Figure 6. Frame from video-film in case of detonation. (a) - Φ=1, (b) - Φ=1.5

Figure 7. Sequence of frames from video-film in case of burning initiated by attached MW discharge (from the left to the right and from the top downward through 1/16 s)

In **Fig.7** the sequence of the frames with the period of their change appropriate to speed of shooting of 16 frames per second is given.

Prominent feature of burning initiation is occurrence at an initial stage of spherical area with the blue luminescence, filling only a part of volume. Separately this stage is shown in **Fig.8**.

At this stage heating has not taken place yet as the ball has not increased almost in diameter (no more, than on 5 %). This bright sphere exists long enough time, so the image was not greased during time of an exposition of one frame. As this phenomenon repeats with small variations each time in a case of burning initiation, and its origin is for us not clear in our opinion it deserves separate studying.

Figure 8. Frame from vide-film in case of burning initiation. The nature of long-living bright sphere is not clear.

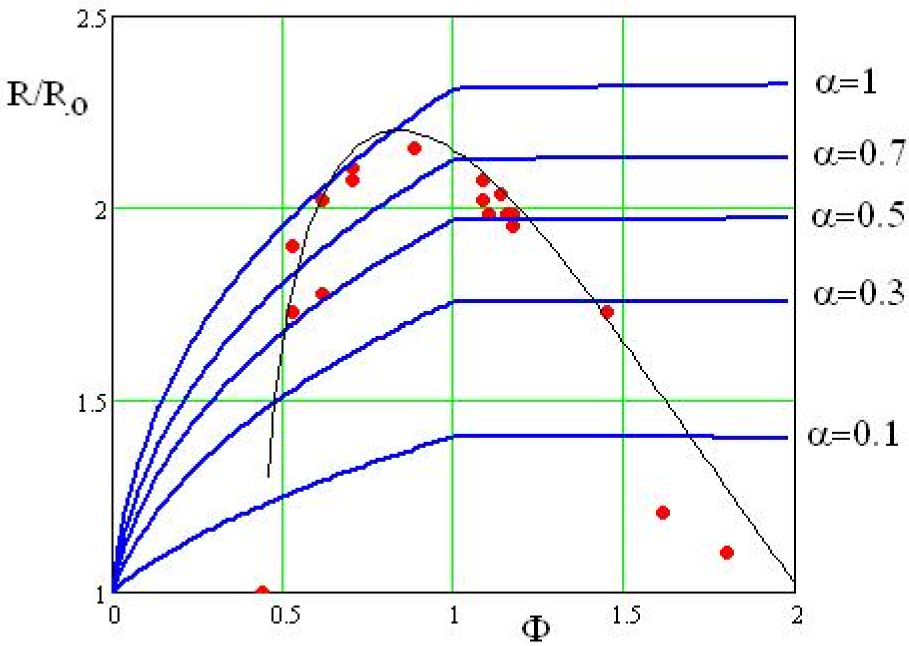


Figure 9. Ratio of finish and initial sizes of ball in dependence on equivalence ratio for fuel Φ and completeness burning α.. Solid lines – theory, dots - experiment

Initial on integrated photos initial and final stages of a ball have allowed to carry out comparison of the measured ratios of initial and final linear the sizes of a ball with the values calculated for known Φ and completeness of combustion α. Results of comparison are given in **Fig.9.**

From **Fig.9** it is visible, that the measured limits of ignition lies inside interval $0.45 < \Phi < 2$, that a little differ from the values given in the literature[11]. Stoichiometric mix burns down practically completely.

At interpretation of time-lapse high-speed shooting data there is a question on dynamics of the ball envelope movement. In case of burning addition of energy in a ball occurs slowly so the ball is inflated, quasi-stationary supporting inside itself the pressure close to external pressure (atmospheric in conditions of experiment). However in case of a detonation process occurs much faster. Dynamics of expansion of envelop not so is simple. We shall consider this process with the help of the simplified model.

The envelop mass (the part of a ball participating in expansion) equals to M = 3 g. It is in some times more than all mass of a gas mixture in a ball (~1.3g). Hence, it is necessary to take into account inertia of an envelope. The detonation wave, having achieved a massive envelope, will undergo reflection and during reverberation will fade. Having assumed, that after passing of reaction the pressure in the ball will equal to average value $\mathbf{p_0}$, defined by combustion energy, it is possible to work out the equation of movement for a massive envelope in view of internal pressure and opposite pressure of external air. Supposing, that during expansion speed of an envelope can achieve supersonic values, it is necessary to determine the opposite pressure as pressure in front of the piston moving in motionless gas. Using known ratios for shock wave, we shall receive expression for pressure in front of the piston depending on speed of its movement

$$p(v) = 1 + \frac{v^2}{4}(\gamma+1) + \left(\left(\frac{v^2}{4}(\gamma+1)\right)^2 + v^2\cdot\gamma\right)^{\frac{1}{2}}$$

In a dimensionless view the equation of movement of the ball envelope appear as

$$\frac{dv}{dt} = \left(p_0 \cdot r^{-3\gamma} - p(v\cdot m)\right)\cdot r^2,$$

$$\frac{dr}{dt} = v.$$

As unites are used

$$v_1 \equiv \sqrt{\frac{p_1}{\rho_1}\cdot m},\ r_1 \equiv R_0,\ t_1 \equiv \frac{r_1}{v_1},$$

$$m \equiv \frac{4\pi \cdot R_0^{\,3}\cdot \rho_1}{M}.$$

In **Fig.10** the result of calculation of the above mentioned equations is shown. It is visible, that movement of envelope begins not at once, with some delay. The radiation connected to passage of reactions, stops, as soon as the detonation wave achieves the envelope. After that moment the envelope moves during 10-20μs insignificantly, as is registered by the high-speed chamber (see **Fig.3**).

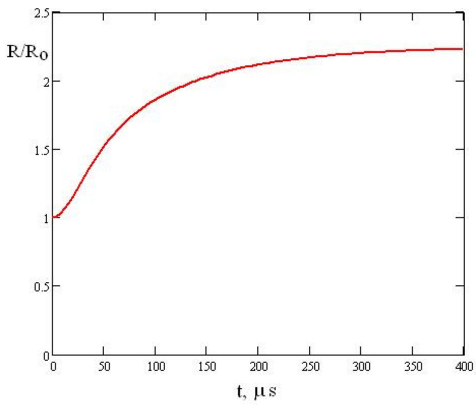


Figure 10. The ball envelop trajectory after detonation. Φ = 1, α= 1

IV. Comparison to results numerical 3D modeling

For comparison to results of observations it was carried out numerical 3D modeling of an opportunity of initiation of a detonation in stoichiometric mixes of propane with air at atmospheric pressure in two variants. In both variants initiation it was carried out by thermodynamic equilibrium heating of a mix in sphere with radius 0.1 cm at total energy addition 1J. In the first variant energy 1J was put during 2μs, and in the second – during 40μs. The second variant corresponds to conditions of experiments with the attached discharge. Modeling was made with the help of program ANSYS CFX 10.0. For calculation of burning the two-level circuit of reactions with participation of C_3H_8, O_2, N_2, CO_2, H_2O and CO, conterminous with recommended in work Ref.[11] was used.

In **Fig.11** results of modeling with conditions of the first variant at the moment of time 20μs are given. For this time the wave of a detonation has run a distance about 3cm, which corresponds to speed 1.5km/s, peculiar for a researched mix. Illustrations show propagation of spherical front indignant by development of instabilities, characteristic for development of detonation.

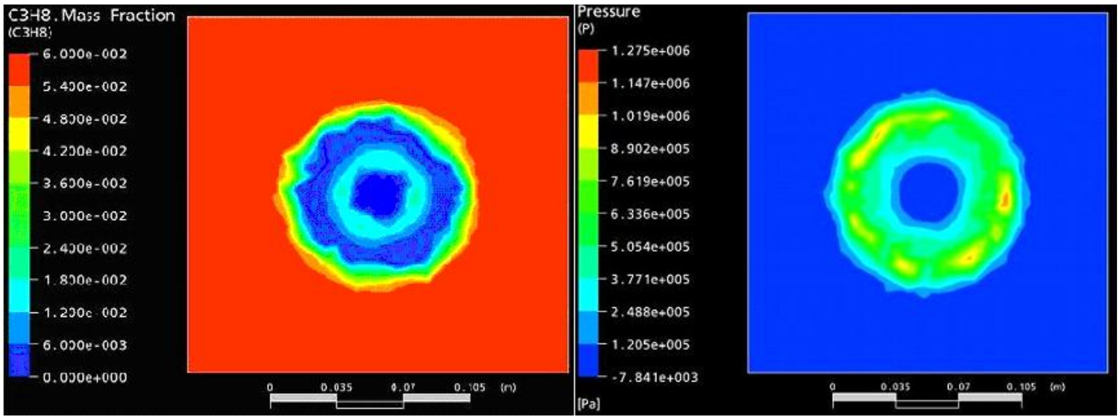


Figure 11. Space distribution of share contents of propane – (a) and total static pressure – (b), t = 20μs

Modeling with conditions of the second variant, appropriate to natural experiment, has shown initiation absence not only detonations, but also burning. It testifies that influence of MW discharge is not reduced to thermodynamic equilibrium heating, but is accompanied by the additional factors promoting initiation of burning and detonation.

V. Conclusion

Experimental and theoretical researches have specified an opportunity of initiation with the help of pulse MW discharges of various types not only of burning, but also a detonation at the reduced requirements to energy addition and duration of a pulse. The circumstances, determining initiation of detonations or burning, have remained obscure else.

The importance of use of MW discharges used in experiment in various applications essentially raises that circumstance, that their feed can occur without contacts and remotely by a beam of the MW radiation.

The carried out researches have specified also on non trivial processes occurring under influence of MW discharges. These researches, having pioneer character, certainly, will be continued because discover many assisting phenomena and details, which can not be explained in frames of traditional physical models and undoubtedly must be investigated in detail.

Acknowledgments

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