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Deeply subcritical MW discharge in the submerged stream of propane-air mixture

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Results of experiments on ignition of propane-air mixture flow with a help of deeply subcritical MW discharge are described. The discharge was initiated by a linear electromagnetic vibrator, which axis was parallel to a vector of a flow velocity. The discharge realized by a field of linearly polarized electromagnetic beam was burning in a stern area of the initiator. The flammable mixture flow was formed in a working chamber in a form of a submerged stream, and it had a velocity about tens of meters per second. Integral photo detection of the discharge appearance and combustion area of the mixture was made in experiments. Gas temperature in the discharge trail and in flammable mixture area has been measured. Experiments have shown that MW discharge ignites propane-air mixture and spatially stabilizes combustion area. Ignition of rich and essentially lean mixtures has been realized. Dependence of gas temperature drop on decrease of propane content in the mixture in the trail of the combustion area has been determined. Influence of propane share in the mixture on geometric parameters of the combustion area has been investigated.

I. Introduction

This paper represents an initial stage of continuing investigations on an ignition of propane-air flammable mixture with a help of deeply subcritical microwave (MW) discharge in a high-speed flow.

This discharge in general case is realized in a given area of a quasi-optical electromagnetic (EM) beam in range of wavelengths, $\lambda = (2 \div 10)$ cm (see Fig.1)[1]

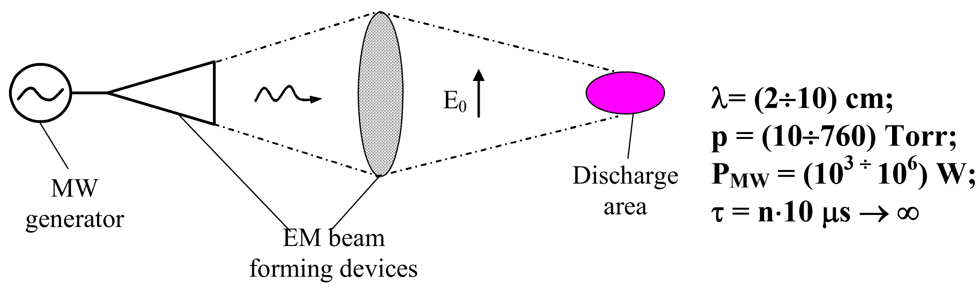

Figure 1. MW discharge realization in quasi-optical EM beam

The discharge was investigated in a wide range of pressure, for example, in air at p = (10÷760) Torr. It is realized in EM beam at power $P_{MW} = (10^3 \div 10^6)$W, at that at large $\mathbf{P_{MW}}$ in pulses with a duration $\boldsymbol{\tau_{MW}}$ of about

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some tens of microseconds, and at low $\mathbf{P_{MW}}$ **-** up to EM radiation continuous mode. Typical appearances of this discharge in different $\mathbf{E_0 - p}$ areas are represented in **Fig.2**, where $\mathbf{E_0}$ is amplitude of initial electric component of EM-field in the discharge area. In present investigations we have applied the discharge corresponding to the region **V** of the picture. It is, so called, deeply subcritical MW discharge in a high pressure gas with undeveloped streamer structure attached to the initiator.

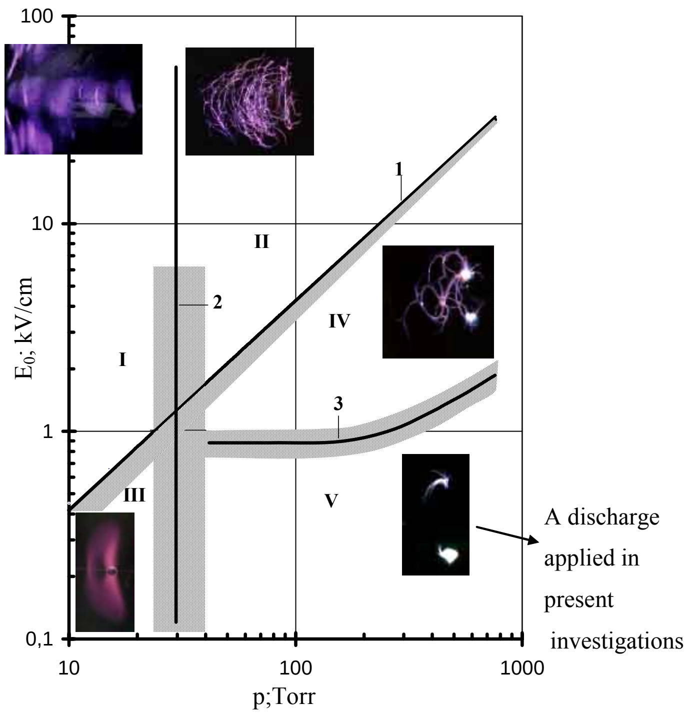

Figure 2. Existence areas of MW discharge various types in quasi-optical wave beam, experimental observations at λ=8.9cm

The quasi-optical beam in present experiments was formed by radiating EM horn. Microwave beam had a structure of linearly polarized TEM-wave. Linear cylindrical EM vibrator was placed in this wave over conducting screen, which plane was perpendicular to Pointing's vector **Π** of EM radiation. Vibrator axis was parallel to the vector $\mathbf{E_0}$. The vibrator was blown on by the gas flow, which velocity vector $\mathbf{v_{fl}}$ was parallel to EM vibrator's axis. It initiated at required sizes an electrical breakdown at $\mathbf{E_0}$ of about 100 V/cm and $\mathbf{v_f}$ of about (10÷500) m/s. Maximal pressure **p** in air was about of hundreds of Torr. The discharge in this experimental formulation was realized in attached form in a stern part of an initiator. Realization scheme of this discharge and its typical appearance are represented in **Fig.3.**

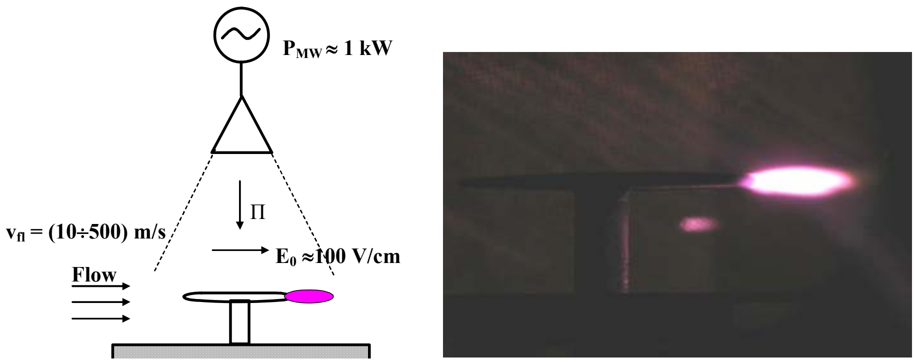

Figure 3. A scheme of initiated deeply subcritical MW discharge realization in a high-speed gas flow and discharge appearance

During the first stage of present investigations the initiator was blown on by air and poor propane was injected into discharge plasma through a hole in a stern outlet of EM vibrator as it shown in **Fig.4.** The discharge in this formulation ignited the resulting flammable mixture at various flow velocities including their high-speed values. However, the energy released during combustion was not controlled[2].

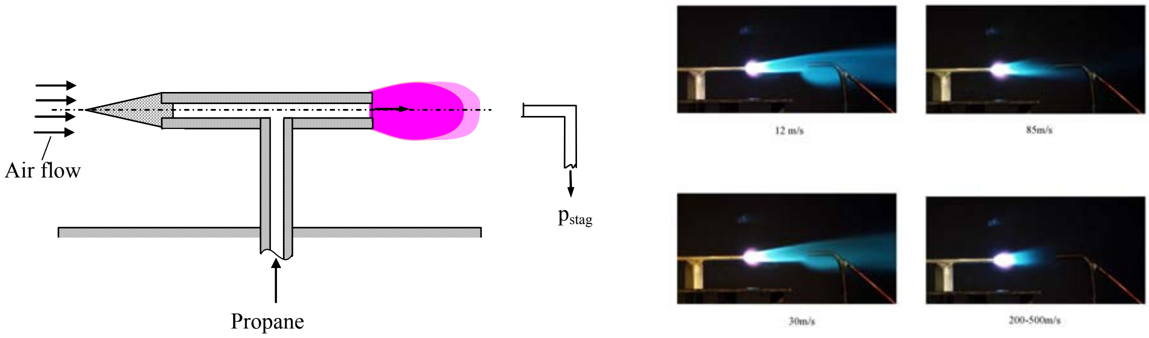

Figure 4. Propane injection directly to the discharge plasma region

Experiments were carried out also with the stream of the clean air at the second stage of these investigations, as it is represented in **Fig.5.** Initiators had complicated geometries at this stage. Propane was delivered into its internal area through initiator's fixing post and air - directly from the flow through vibrator inlet. A mixture formed in required proportion was delivered to a discharge area; here its ignition and combustion was realized. Analysis of measurements of the flow stagnation temperature $\mathbf{T_{stag}}$ in discharge trail and in combustion area of propane-air mixture has shown a high efficiency of mixture combustion. Such a scheme allows effective control of combustion energy in wide ranges with respect to composition of the mixture[3].

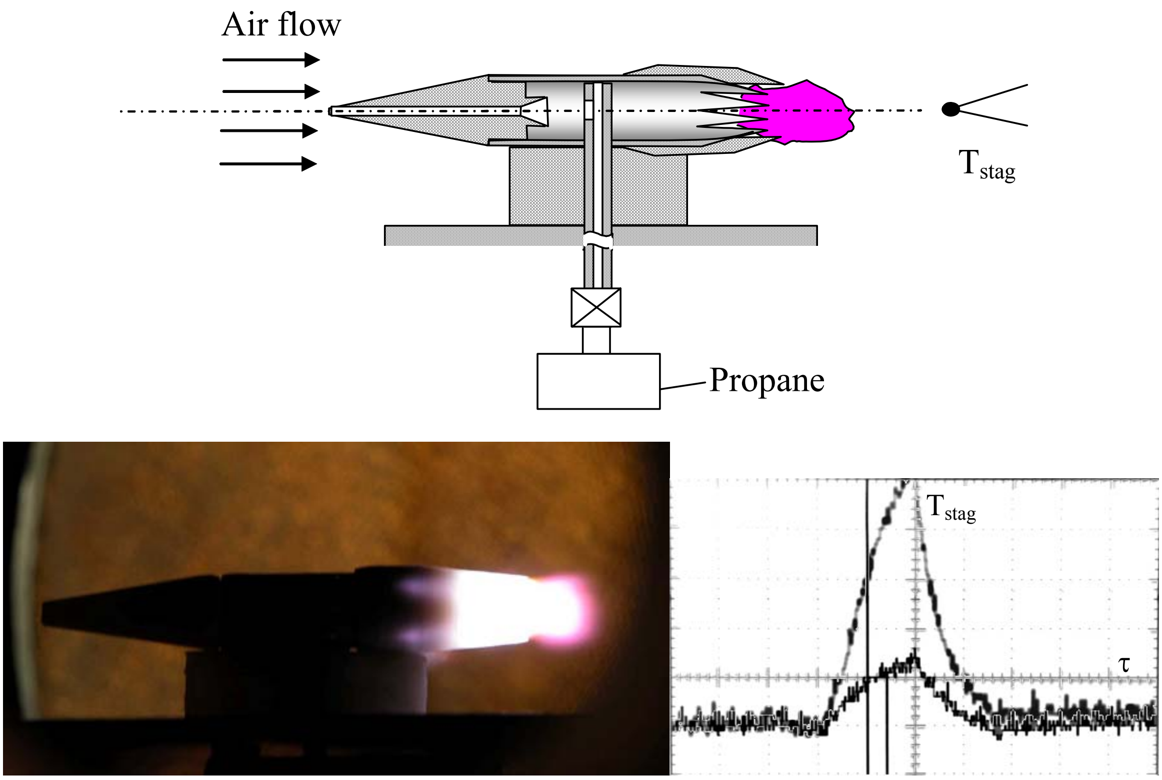

Figure 5. Propane-air mixing in internal area of MW discharge initiator

In **Fig.6** we illustrate experiments on propane-air mixture flowing through area of the subcritical MW discharge which has a spatially developed streamer structure. It corresponds to the region **IV** in **Fig.2**. Experiments showed that flammable mixture velocity of combustion $\mathbf{v_{fr}}$ has a uniquely high value in vicinity to discharge streamer channels. All these experiments stimulated present investigations[4].

In undertaken experiments we applied deeply subcritical (attached) MW discharge, which streamer channels were attached to a pole of EM-vibrator initiating the discharge, i.e. the discharge corresponding to the region **V** in **Fig.2**. In difference to initial stages initiators in present investigations were placed into preliminary prepared stream of propane-air mixture. First stage of these investigations at comparably low velocity $\mathbf{v_{fl}}$ is reflected in this report.

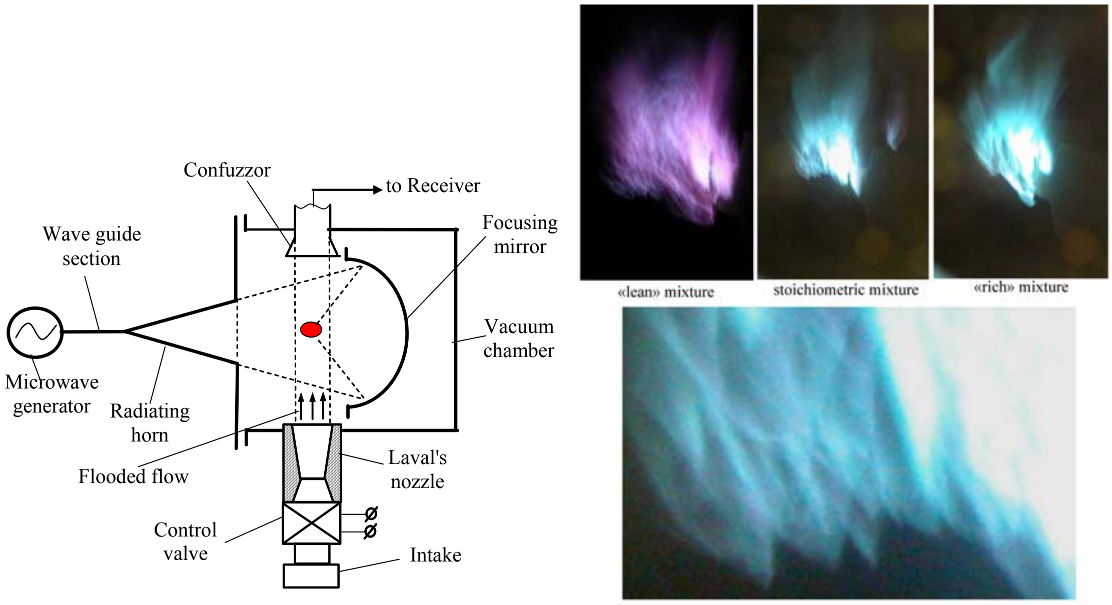

Figure 6. High-speed propane-air mixture flow ignition by subcritical MW discharge with spatially-developed streamer structure

II. Experimental scheme

Experiments have been carried out with a help of the modernized setup described in Ref.[3]. Its scheme is represented in **Fig.7** and a photo of the working area in **Fig.8**.

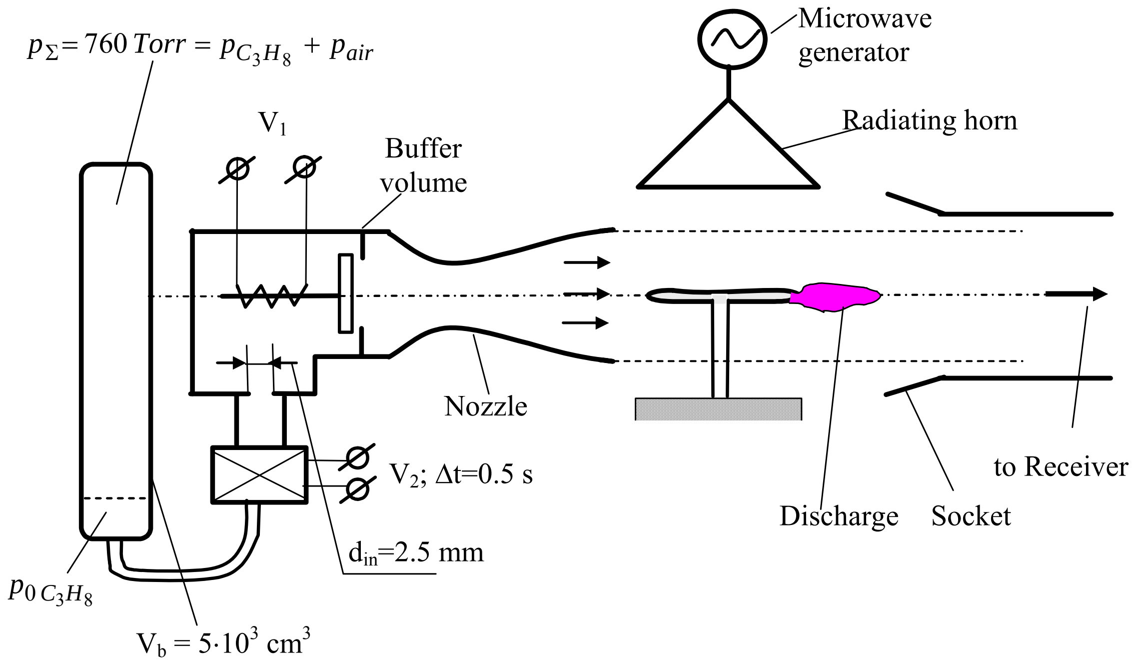

Figure 7. The scheme of experiment

Microwave radiation with λ = 12.3 cm came to the working «EM-echoless» chamber of the setup through a horn "**1**" with a radiating outlet size 9×9 cm. The horn is above in the photo. Radiation beam power was a P_{MW} = 1 kW at radiation duration of τ_{MW} = 0.2 s. The vibrator "**2**" with a diameter 2a = 4 mm and length 2L = 50 mm was located in MW beam over a metallic plate. The vibrator was located into the submerged stream of either clean air or its mixture with propane. The stream was formed by a nozzle "**3**" with outlet aperture of a diameter d_{out}=30 mm. In **Fig.8** the nozzle is to the left of the EM vibrator**.** Air pressure in the hermetic working chamber was p_c =114 Torr and stayed practically constant. Thermocouple measurer of a stagnation temperature $\mathbf{T_{stag}}$ was placed down the flow coaxially with vibrator "**4**". In the photo it is to the right. A distance from its sensitive element to the stern end of the vibrator was 3cm. A signal from the measurer came to the inlet of an oscilloscope. A sensitivity of the thermocouple measurer was S_T = 24.5°K/mV.

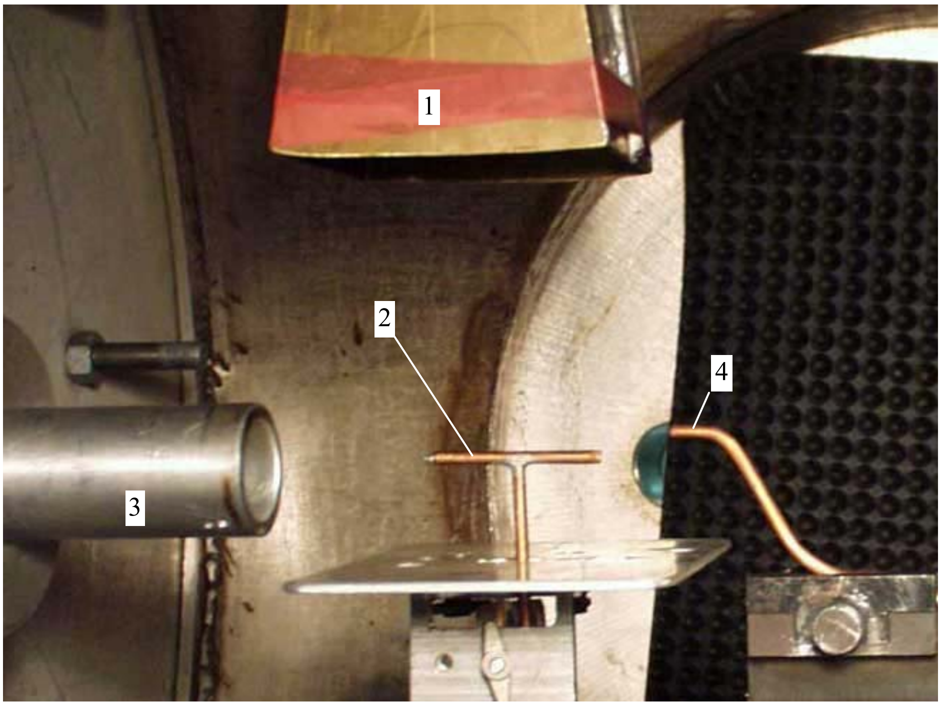

Figure 8. Photo of a working part of setup

In the experiments we used equipment that earlier formed a submerged high-speed air stream. It included a nozzle and electrically controlled valve $\mathbf{V_1}$ with a conditional through diameter equaled to 63 mm. A hermetic shutter with a hole of a diameter d_{in} = 2.5 mm was placed on its inlet in present experiments. A hermetic balloon was connected with this hole through the electrically controlled valve $\mathbf{V_2}$ by a corresponding duct of a larger diameter. Its volume was $V_b = 5.2 \cdot 10^3$ cm^3. The balloon in experiments was preliminarily pumped out to the pressure $p < 1$ Torr, then it was filled by propane up to given pressure p_{0C3H8}, and then it was additionally filled in by the atmospheric air up to p_Σ = 1 atm ≈ 750 Torr. The valve $\mathbf{V_2}$ was opened for a time Δt = 0.5 s. Propane air mixture flowing from the balloon during this time formed a submerged stream with static pressure $p_{fl} = p_c$, which blew along the MW vibrator.

Experiments have shown that pressure in the balloon drops by a value Δp_b = 75 Torr during the time period $\mathbf{\Delta t}$. This pressure $\mathbf{\Delta p_b}$ is substantially smaller than $\mathbf{p_\Sigma}$ and one can consider that the stream parameters were practically constant during $\mathbf{\Delta t}$. Flow velocity in the stream $\mathbf{v_{fl}}$ was estimated by a value $\mathbf{v_{fl}}$ = 11 m/s at given values $\mathbf{d_{in}}$, $\mathbf{d_{out}}$, $\mathbf{p_\Sigma}$ and $\mathbf{p_{fl}}$. This value also arises from the measured $\mathbf{\Delta p_b}$.

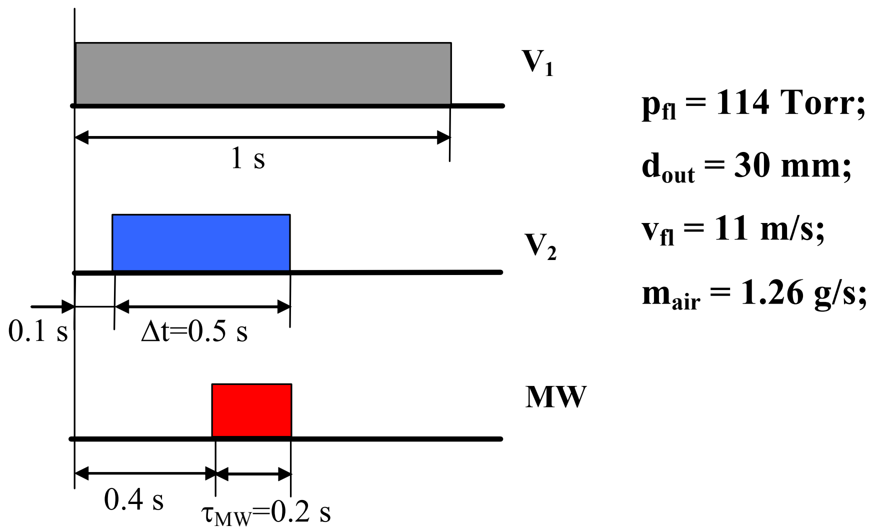

Figure 9. Operation time sequence of the setup devices

Microwave generator was switched on in limits of time period **Δt** for a time duranceτ_{MW} = 0.2 s.

A temporary dependence of setup devices work and values of main characteristics in its working area are shown in **Fig.9.** By a symbol $\mathbf{m_{air}}$ is designated a mass rate of air flowing from the balloon. Its value is m_{air} = 1.26 g/s.

After a first cycle of gas flowing out of the balloon, the former was refilled by air again up to p_Σ = 1 atm. At that a weight ratio of propane and air is $\alpha = M_{C3H8}/M_{air,}$ where MC3H8 - propane mass in the balloon, and M_{air} - mass of air in it was naturally decreased. After another cycle of gas flowing out of the balloon, the former was refilled by air again up to p_Σ = 1 atm, etc.

It is known that a value of **α** is approximately equal to 1/16 in a stoichiometric mixture. Equivalence ratio for fuel defines coefficient α(Φ) = Φ/16. At that a value Φ = 1 corresponds to the stoichiometric mixture, Φ < 1 – to lean mixture, and Φ > 1 – to rich one. In case of described experimental scheme values of Φ can be calculated with a help of a formulae

$$\Phi = 16 \cdot \frac{\rho_{0\,\mathbf{C_3H_8}}}{\rho_{0\,\mathbf{air}}} \cdot \frac{1}{\dfrac{\mathbf{p}_\Sigma}{\mathbf{p}_{0\,\mathbf{C_3H_8}}} \cdot \left(1 - \dfrac{\Delta \mathbf{p_b}}{\mathbf{p}_\Sigma}\right)^{\mathbf{n}} - 1};$$

here p_{0C3H4} =2.2·10^{-3} g/cm^3, p_{0air} = 1.23·10^{-3} g/cm^3 - are respectively propane and air densities at normal conditions, and n = 0, 1, 2….. – is a number of the next in turn flammable mixture injection cycle.

There is a possibility to vary p_{0C3H4} during experiments. Experimental data represented below correspond to definite value of this pressure p_{0C3H4} = 38 Torr.

III. Experimental results and their discussion

Main experimental results are represented in **Fig.10**. In **Fig.10** one can see a set of integral photos of MW discharge realization region and of flammable mixture combustion with an exposure time $t_{exp} > \tau_{MW}$. The flow in the photos is directed from the left to the right.

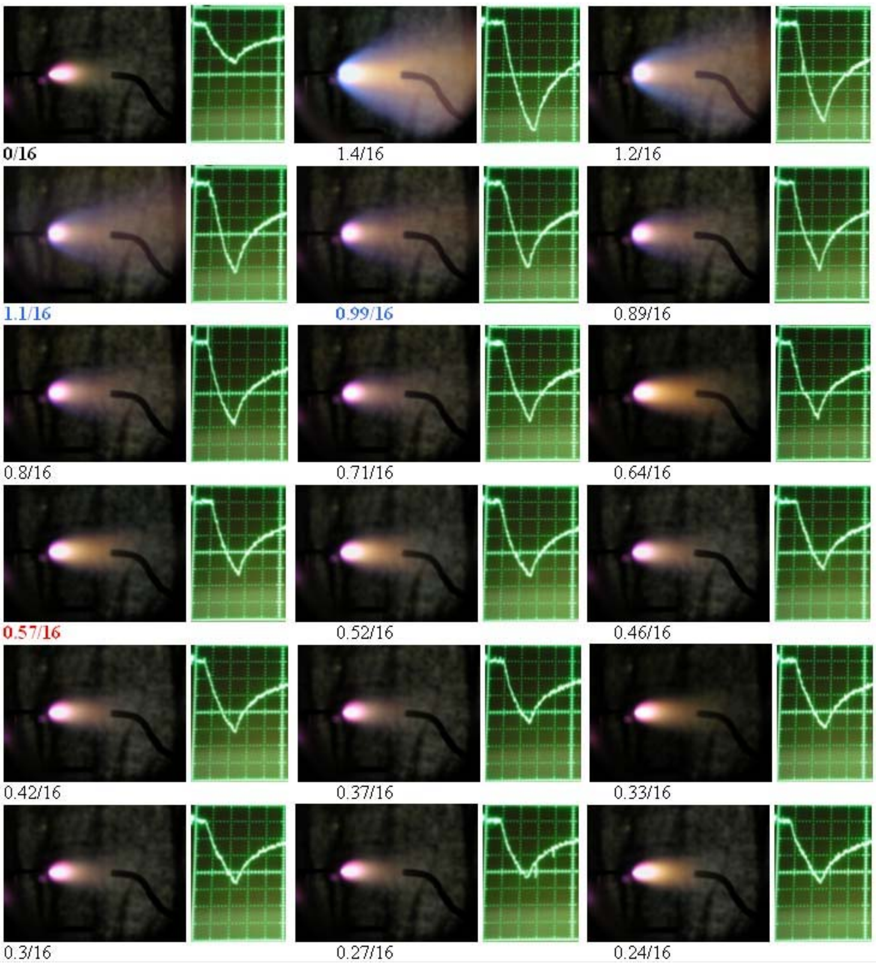

Figure 10. Appearance of propane-air mixture combustion area at different content of propane in it and waveforms from the measurer of the gas temperature

The discharge was realized in the stern area of the EM vibrator – initiator of MW discharge. A working end of flow stagnation temperature thermocouple measurer was placed in the vibrator's trail along its axis. A distance between the stern end of the EM-vibrator and a fore edge of the measurer was X = 30 mm; and a diameter of a tube, into which the thermocouple was placed, was 3.8 mm. Both this size can be used as scales of images. A waveform of a voltage **U** variation at the outlet from the thermocouple sensor is places each corresponding photo. Their initial horizontal sections correspond to absence of the discharge realization. The waveforms are inverted in the vertical direction.

With respect to the cycle **n** photos are placed in rows from the left to the right in each row and up –down in lines. The first left photo in the upper row corresponds to MW discharge realization in clean air. The corresponding value of α in the form $\Phi/16$ is indicated below near each photo. With a help of them one can see that experiments were started with the rich mixture with the value $\Phi = 1.4$ and were finished with the lean mixture with $\Phi = 0.24$.

In **Fig.11** one can see a set of illustrating diagrams. Colored areas in them correspond to a range of propane – air mixture ignition known from literature. The lower limit of the ignition region for the weight ratio of components in the mixture corresponds to $\alpha = 3.6$ %, and the upper to $\alpha = 16$ %. For a concentration ratio of propane and air in a mixture $\beta = n_{C3H8}/n_{C3H8}$, where concentrations **n** have dimensions of molecule numbers in the unit of a volume, this is respectively, $\beta = 2\%$ and $\beta = 9$ %. The value $\Phi = 0.58$ corresponds to the lower limit of the ignition region in the diagram for α in the form $\Phi/16$ and $\Phi = 2.6$ - to the upper one. Experimental values of α corresponding to the consequent cycle's **n** are marked in the special diagram. One can see that experiments were started with rich mixture lying in the area of its ignition and were finished with substantially lean mixture lying below a boundary value of this region. Finally, partial propane pressures p_{C3H8} in the balloon of flowing out corresponding to typical values of Φ are indicated in the below diagram. Values of α close to the stoichiometric ratio are marked by blue color in **Fig.10** and values corresponding to below boundary of mixture ignition area are marked by red color.

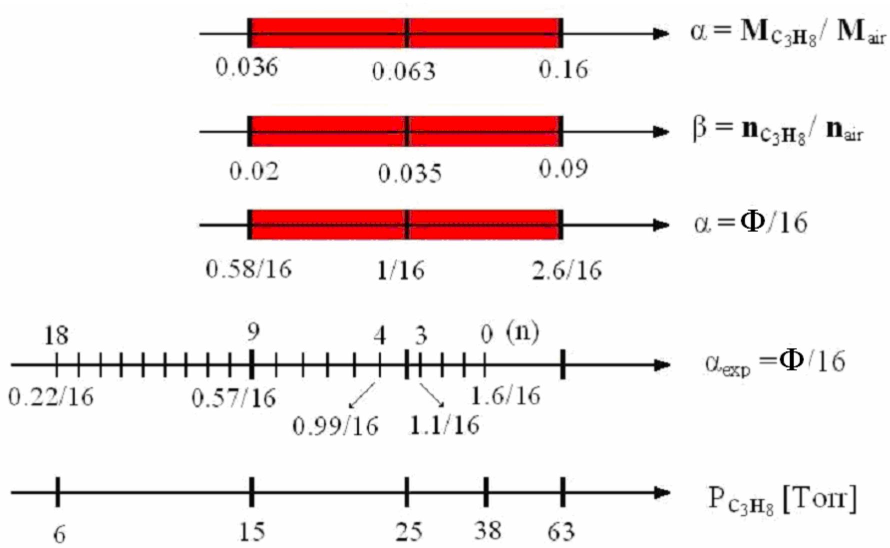

Figure 11. Experimental values of propane content in propane-air mixture with respect to boundaries of its inflammation range

For better clearness in large scale we presented in **Fig.12** corresponding illustrations for typical concentrations of the mixture: 0/16 – MW-discharge in clean air flow; 1.4/16 is the combustion area of the rich mixture flow; 1.1/16 – is the combustion area of the mixture with approximately stoichiometric composition; and 0.24/16 - is the combustion area of the lean mixture. It is known that a flame of the rich mixture combustion with the composition close to the stoichiometric has blue color. In photos in Fig.**12** it is revealed on side boundaries of the combustion area. It is known that yellow-brown color corresponds to combustion of the lean mixture. In photos it is revealed in below with respect to the flow regions of the mixture combustion.

Analysis of photos in Fig.12 shows that a mixture with initial $\alpha = 1.4/16$ and 1.1/16 combusts in the whole cross section of the flammable mixture flow with a diameter of about 30 mm. A flame front propagation velocity in the transversal direction with respect to the stream is very high at the fore front of the combustion area and it gradually decreases. But the lean mixture combusts only directly in the trail of MW discharge. The flame in this case does not propagate over the mixture in the transversal to the flow direction as it should be.

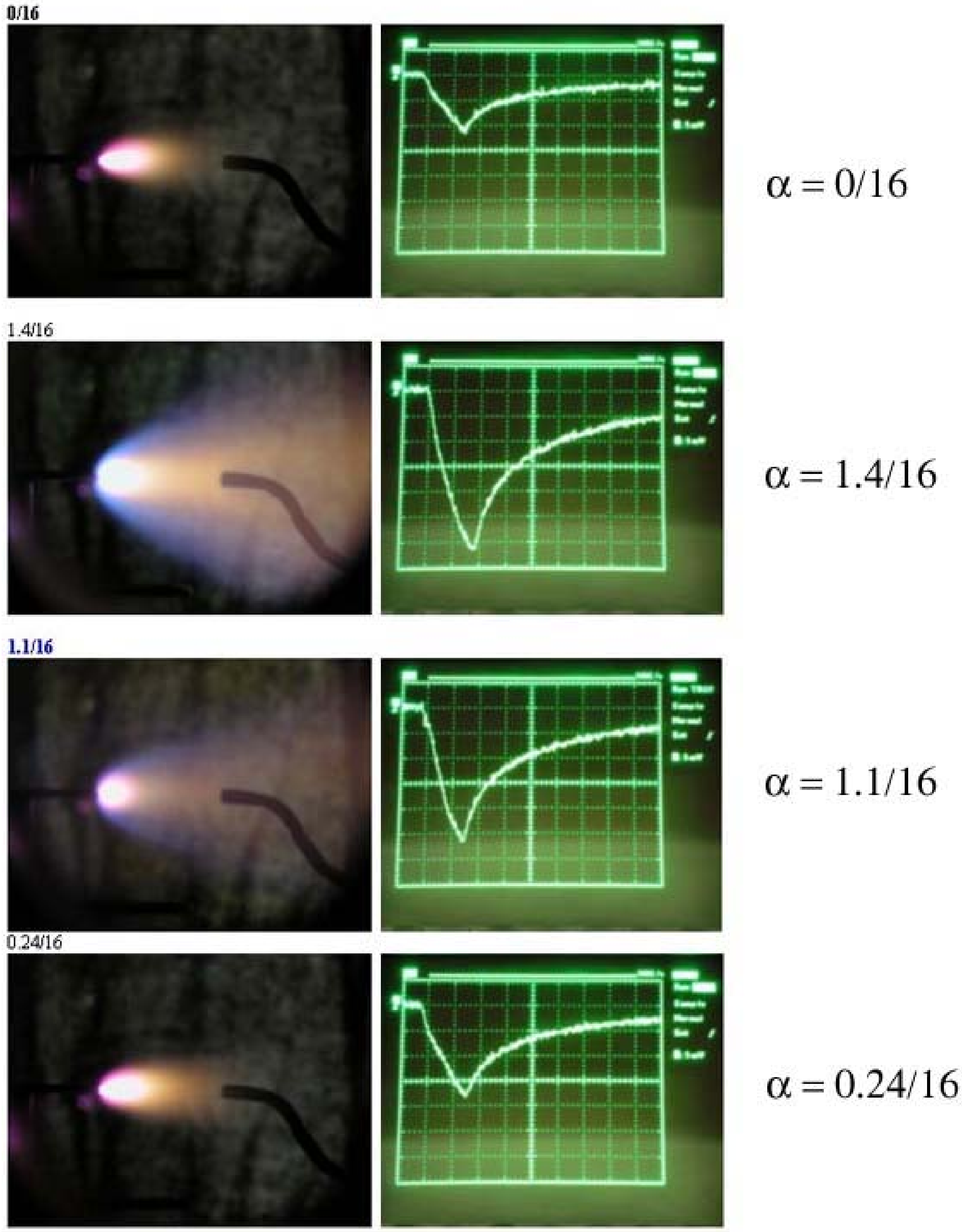

Figure 12. MW discharge luminescence in clean air and ignition of rich, stoichiometric and lean mixtures by it

In **Fig.13** one can see the same photos but proceeded by a computer by the conditional level of relative brightness. In them one can more clearly conduct relative comparison of combustion areas transversal sizes. One can see in these illustrations that the combustion area below with respect to the flow has a turbulence character.

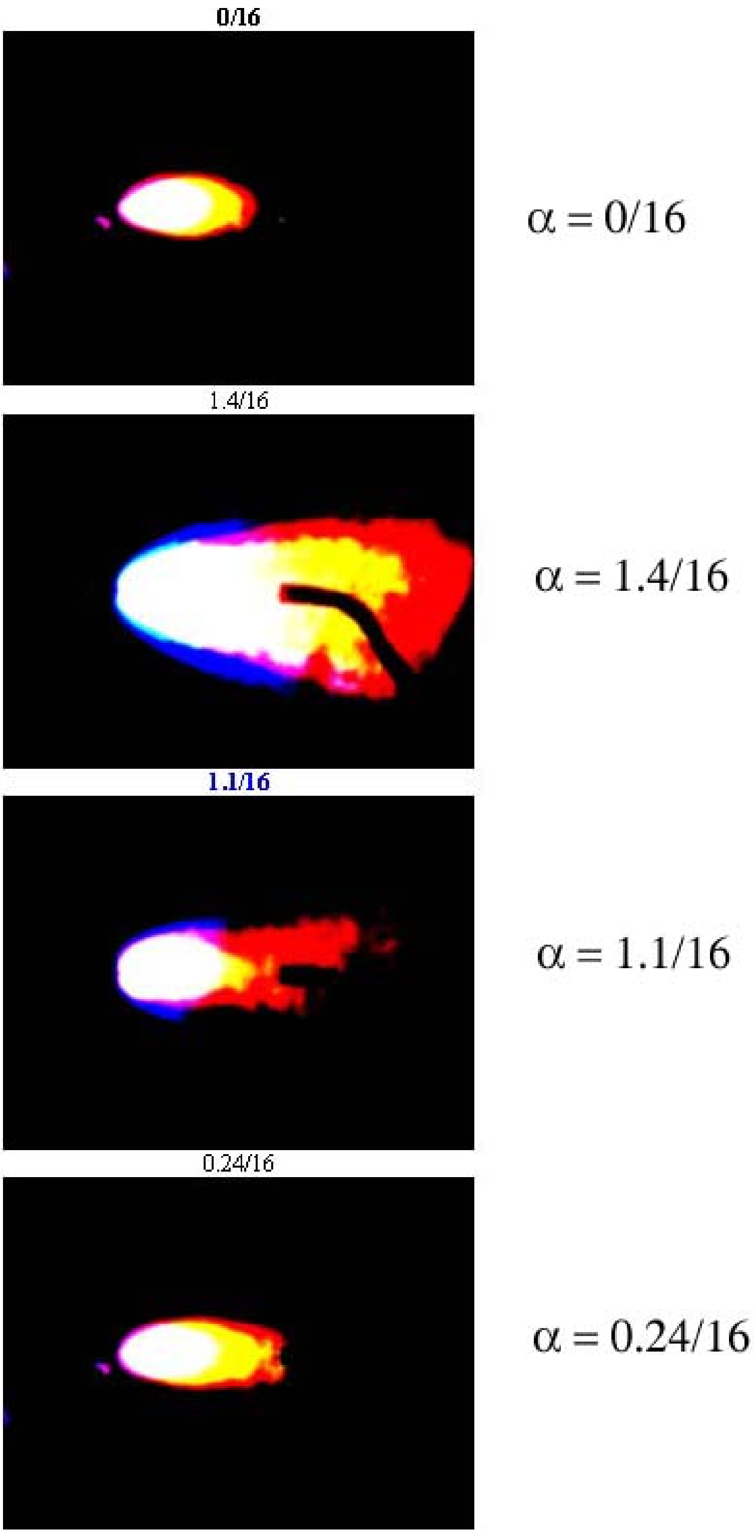

Figure 13. Photos of MW discharge luminescence treated with respect to conditional level of relative brightness in clean air and in rich, stoichiometric and lean propane-air mixture

In **Fig.14** one can see a graph of maximum transversal size of the combustion area $\mathbf{2Y_m}$ with respect to Φ made with a help of complete set of analyzed photos. Below the graph a zone of propane-air mixture ignition is indicated. It follows from the picture that an area of rich mixture combustion spreads to all the transversal cross section of its flow $2Y_m = 30$ mm. The size $\mathbf{2Y_m}$ smoothly decreases with a decrease of **Φ.** It is probably connected with air admixture to the stream from the surrounding space. This leads to decrease of propane concentration in boundary areas of the stream. The size $\mathbf{2Y_m}$ is equal to the maximum "size across" of the combustion area of MW – discharge in clean air at values of Φ smaller than the lower boundary of inflammation area of propane-air mixture, as it should be expected.

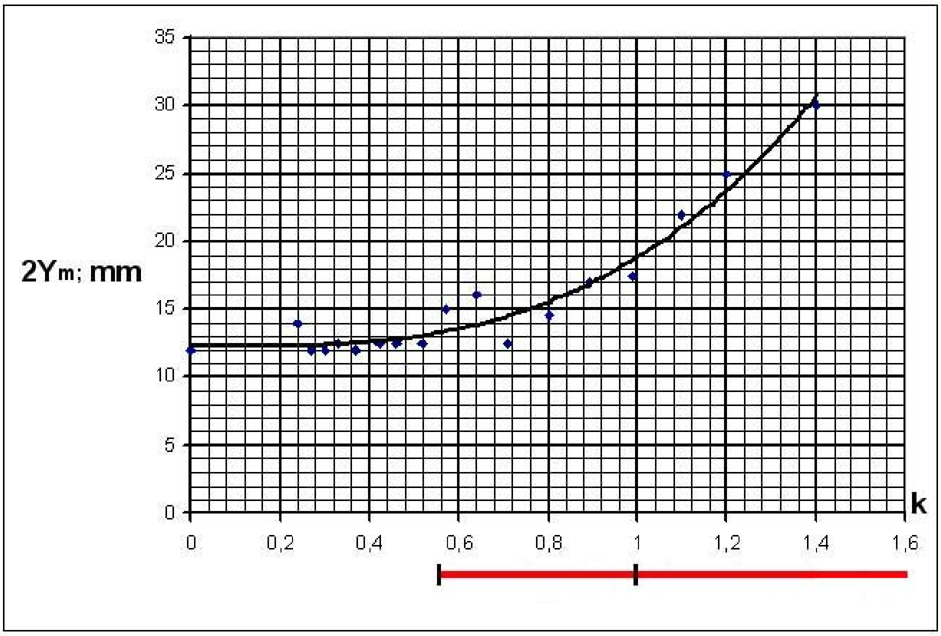

Figure 14. Propane-air mixture flow transversal conditional maximum size of combustion area with respect to propane content in it

In **Fig.15** one can see a graph of combustion area $\mathbf{X_m}$ maximal length along the flow with respect to **k.** In the figure also as in Fig.14 the area of propane-air mixture inflammation is shown below the graph. The graph was made using values $\mathbf{X_m}$, obtained with a help of computer-proceeded photos. So $\mathbf{X_m}$ sizes are conditional. In realty they are much larger. The graph shows relative decrease of the combustion area length with decrease of initial propane amount in the mixture. It follows from it that the size $\mathbf{X_m}$ for lean mixtures is still larger than the maximum length of MW discharge plasma area in clean air at Φ values smaller than the boundary value of the inflammation area.

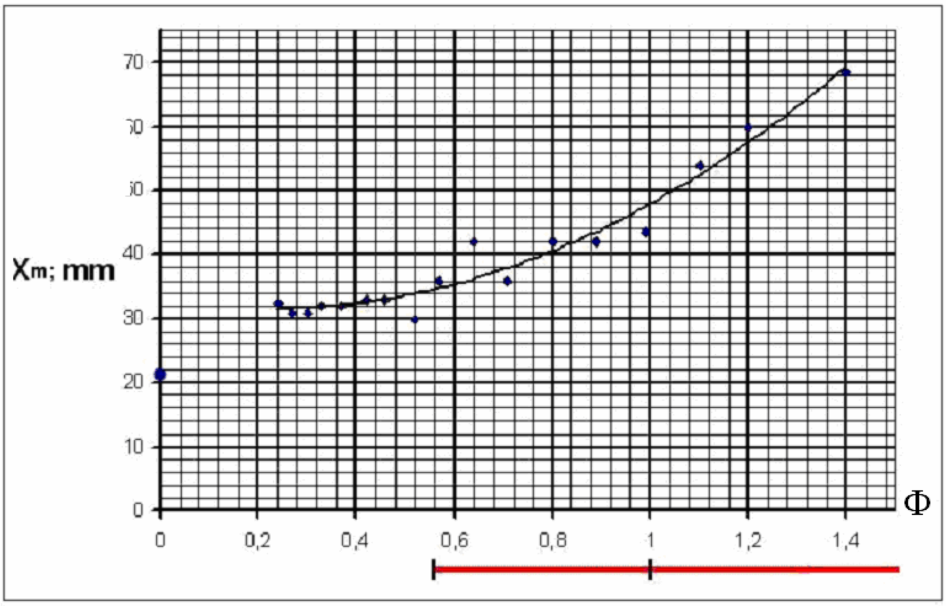

Figure 15. Propane-air mixture flow longitudinal conditional maximum size of combustion area with respect to propane content in it

It follows from the waveforms from the thermocouple measurer presented in Fig.10 and Fig.12 that the signal's amplitude $\mathbf{U_m}$ decreases (the waveforms are inverted) with decrease of α in initial mixture**.** A vertical sensitivity in the waveforms is $S_u = 5$ mV/div and a horizontal scale is $S_t = 0.1$ s/div. The thermocouple measurer used in experiments is inertial. It can be seen from the waveforms that a voltage **U** at the measurer starts to rise in time from the moment of MW-discharge realization, and it drops after the discharge realization. The time of the signal grow up is τ_{dis} = (0.16÷0.18) s. It is somehow smaller than τ_{MW} =0.2 s. This can be explained by inertial feature of MW generator feeding commutation elements. Let us approximate **U (t)** growth dependence by a formulae $U = U_0[1-\exp(-t/\tau)]$. It follows from a set of experimental waveforms that the given temperature measurer is characterized by a time constant $\tau \approx 0.21$ s at this approximation. Accounting this τ value and setting $t = \tau_{dis} = 0.17$ s one can calculate a value $\mathbf{U_0}$ using the waveforms: $U_0 = 1.8 \cdot U_m$. Namely this value characterizes a real flow stagnation temperature $T_{stag} = T_0 + U_0 \cdot S_T$. Here $T_0 \approx 300$ °K is initial gas temperature in the balloon of outflow, and $\Delta T = U_0 \cdot S_T$ – is the temperature obtained by a gas in a result of the discharge realization and propane burning.

In **Fig.16** one can see a graph of **ΔT (Φ)** dependence made with a help of waveforms placed in **Fig.10.** It can be seen that air is heated for $\Delta T_{dis} \approx 510$ °K in the discharge trail. The temperature growth at combustion in the stream of propane ignited in the MW discharge takes place approximately linearly with respect to Φ at presence of propane ignited by MW discharge in the stream.

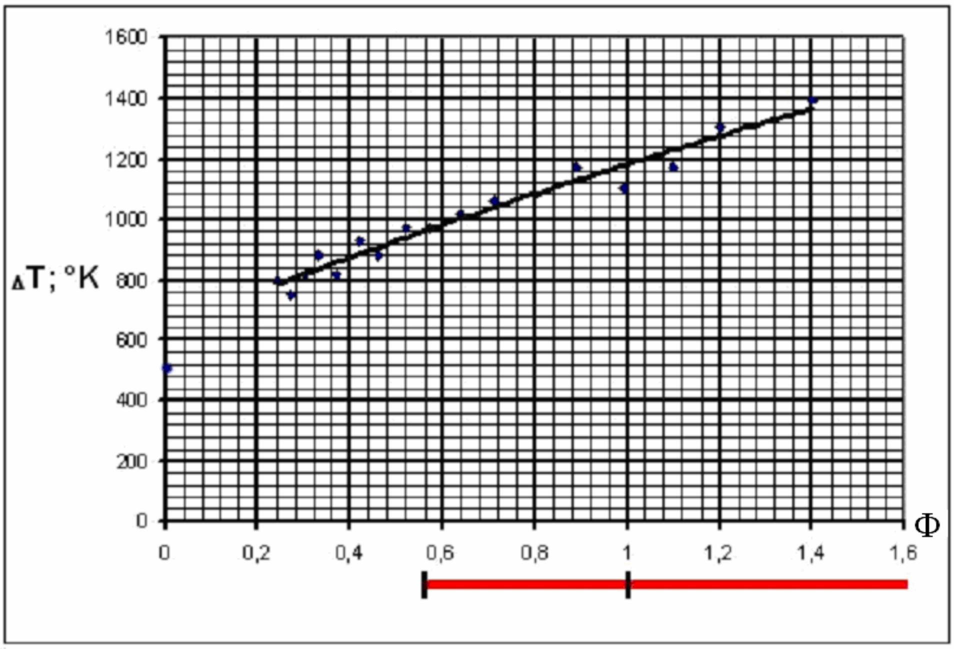

Fig.16. Temperature rise of the gas in the stream with respect to propane content in it

In **Fig.17** we present estimates of energy made with a help of experimental data.

In experiments we used EM radiation with λ = 12.3 cm at MW beam power P_{MW} = 1 kW. A transversal size of MW-beam in the region of EM vibrator has an area of (12x12) cm^2 accounting the size (9x9) cm^2 of an aperture of the horn forming the beam and its opening angle. This gives an estimate of initial field $E_0 \approx 70$ V/cm in this area EM-energy density flux $\Pi \approx 7$ W/cm^2.

A submerged stream at the outlet from the nozzle has a velocity of the gas v_{fl} = 11 m/s at a diameter d_{out} = 3 cm and pressure $p_{fl} \approx p_c$ = 114 Torr and room temperature $T_0 \approx 300$ °K. As a result the rate of air intake to the working chamber is m_{air} = 1.26 g/s during the time of the stream flow out Δt = 0.5 s Propane injection rate is $m_{C3H8} = m_{air}/16 = 7.8 \cdot 10^{-2}$g/sin the case of flammable propane-air mixture. Accounting an energy of propane combustion $Q_{com} = 4.64 \cdot 10^4$ J/g, this value of m_{C3H8} gives complete combustion power P_{com} = 3.6 kW.

Let measured increase of air temperature in the MW discharge trail $\Delta T_{dis} \approx 500$ °K is uniform in a transversal cross section of plasma-discharge area $2Y_{dis}$ = 1.2 cm then air heating power in the discharge is P_{dis} = 80 W. This value gives an effective area $S_{ef\,dis}$ = 12 cm^2 of energy interaction of EM field with the discharge plasma. It is much greater than maximum area of longitudinal discharge cross section $S_{dis} \approx 2.5$ cm^2 obtained by the photo.

Gas temperature in experiments is measured at a distance of X = 3 cm from the stern end of EM-vibrator. This size is larger than the length $X_{dis} \approx 2.6$ cm of the MW discharge plasma area along the flow. But the size of X is much smaller than the length of propane combustion area $\mathbf{X_{com}}$, especially at a composition of the mixture close to the stoichiometric one. It is impossible to determine an absolute value of $\mathbf{X_{com}}$ in experiments.

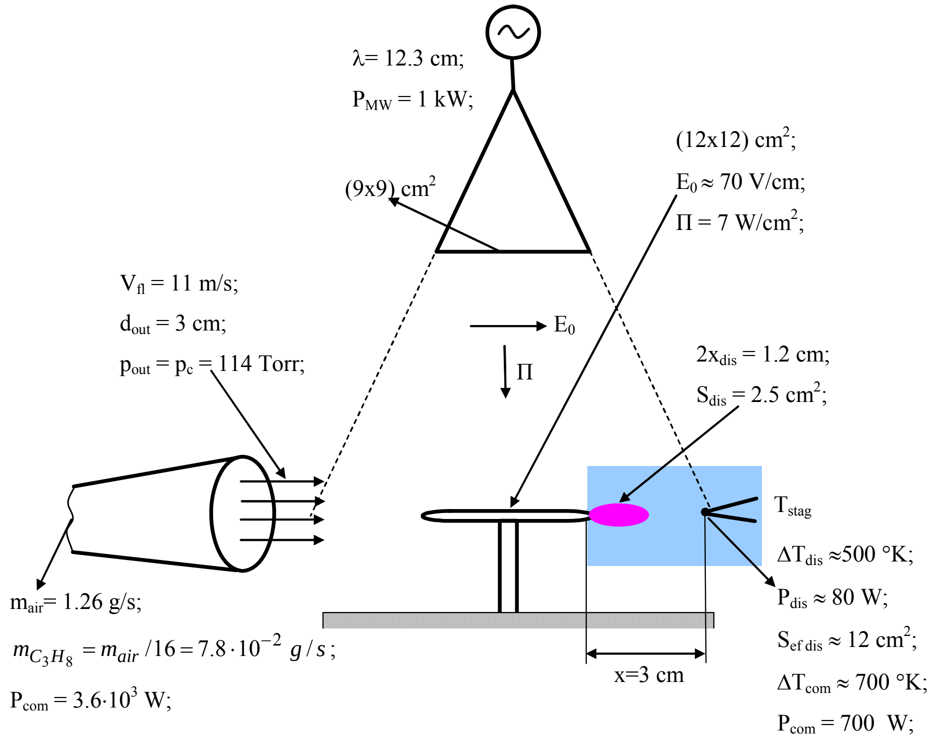

Figure 17. Energy relations

A temperature increase at combustion of initial stoichiometric mixture in the experiment at X = 3 cm was $\Delta T_{com} \approx 700$ °K. If we conditionally accept that this value is constant over a stream's transversal cross section then we obtain an estimation of a combustion power $P_{com} = 700$ W.

IV. Conclusions

The deeply undercritical initiated MW discharge was determined to ignite propane-air mixtures in these experiments, and stabilizes the combustion area in a flow with velocity about 10 m/s. At this condition, the power released in the discharge can be for an order of magnitude smaller than that released as a result of the propane-air mixture combustion. The MW discharge in these experiments resulted in a mixture combustion at propane weight content two times smaller than the typical minimum for the ignition threshold of such a mixture. Gas temperature drops down approximately linearly in the combustion wake with a decrease of propane content in the mixture. Emanating from the MW discharge plasma, the flame front propagates over the entire mixture flow when the propane content in the mixture is greater the minimum threshold of its inflammation. At this condition the velocity of flame propagation is substantially greater than the velocity of gas flow in the region near the discharge and especially near the forward end of the mixture combustion area. The mixture combusts only in the area of the discharge plasma at the propane content is lower than its normal combustion threshold.

Acknowledgments

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