NON-SELFMAINTAINED DISCHARGE INFLUENCING LEAN PROPANE-AIR MIXTURES

N. V. Ardelyan, *V. L. Bychkov, *D. V. Bychkov, *S. V. Denisiuk, K. V. Kosmachevskii, and M.N. Sablin

Lomonosov Moscow State University, Moscow, Russia
**Moscow Radiotechnical Institute RAS, Moscow, Russia*

I. Introduction

This paper is devoted to continuation of investigations [1-3] on application of the non-selfmaintained discharge with the application of the electron beam (Eb) accelerator for irradiation of the propane-air mixture. In [1-3] we have created the experimental chamber, controlling devices and the diagnostic complex for Eb experiments. First experiments on inflammation of the flammable mixture in the chamber at the application of the ignition system, of the external electric field and of the ignition system and a combination of the Eb and the electric field in air and flammable mixture have been fulfilled. In the experiments we used the industrial electron accelerator EOL -400M have. The combination of the external electric field and the electron-beam plasma create a non-selfmaintained discharge. The Plasma of the non-selfmaintained discharge has been realized in the conditions without the ignition of the propane-air flow and with it. Experiments on the inflammation of the flammable mixture [1-2] in the chamber and at the injection of the beam into air and flammable mixture have been fulfilled. Experiments have shown sharp increase in the temperature at application of the non-selfmaintained discharge. Gas temperature and ion currents to electrodes in the mixture have been measured at the action of the non-selfmaintained discharge under the combustion conditions and without them.

This work is devoted to continuation of these investigations. In this paper we analyze a role of a new electron beam system which can be used in the experiments. We also model electron beam plus electric field impact on lean propane - air mixtures.

II. About a new type of experiment devices

Works on application of electron beams and non-selfmaintained discharges shows their high efficiency for solution of plasma combustion problems [1-3]. However, one of an the main obstacles of these devices application is their large sizes and difficulties of maintenance. These difficulties could be overcome at applications of MW power sources [4]. Such devices have been already developed and manufactured [5]. The principles of designing of small size electron sealed off guns generating and transmitting broad electron beams having electron energy of 200 keV into atmosphere or other gases have been considered in [5]. The electron beam of the gun is brought out through a thin titanium foil across a rather large area without using any beam sweeping devices. Vacuum-tight, reliable electron output windows have been made. Electron optical systems generating broad beams based on the application of round ribbon and multitip cathodes have been developed. The electron sealed off guns are used without any vacuum pumps, they are reliable and convenient in operation. In Their parameters are represented in Table1 [5].

Table: Parameters of the installation

Electron energy (controlled)	100÷200 keV
Max. pulse power of extracted beam	300 kW
Irradiation area	200×100 mm
Max. dose rate of electron beam	10 kGy/s
Max. pulse dose rate of electron beam	5×10^4 kGy/s
Max. radiation dose outside the case	0.2 mGy/hour
Max. power consumed	2 kW
Overall dimensions (w/o computer)	2×0.7×0.7 m
Overall weight	700 kg

Comparison of their parameters show that they are similar to those of [1-3] which we use for our investigations. So all results obtained by us earlier can be obtained with a help of these installations. From another point of view we can continue our investigations with a help of EOL 400 M knowing that application of their results can be put into practice with a help of SOG.

III. Modeling

We consider propane air mixture (with participation of water vapor) ignition under impact of the igniter with its smallest electric field strength of E=3 kV/cm. At this stage we are interested in the plasma chemical and thermal processes in the mixture, since they show a dynamics of the mixture composition and the temperature change in time. This information is necessary for further development of experiments on the plasma combustion and the theoretical analysis.

As in [2-3] as the basic we have chosen a simplified system of chemical reactions with added reverse reactions (at first stage we considered stoichiometric mixture) 74 reactions: Hydrogen-Oxygen chain, Hydroperoxyl and Hydrogen Peroxide reactions , Propane reactions, I-Propyl, N-Propyl and Propene reactions, Ethylene, Ethyl, Vinyl, Vinoxy and Ketene reactions , Methyl, Methoxy, Formaldehyde, Formyl reactions), standard energy equation with computed enthalpies on the basis of [6,7] . Air chemistry and rate constants for air plasmas were taken from our detailed code for air plasmas [8] and [9]. This model includes 20 components (neutrals, positive and negative ions) and 120 plasma chemical reactions. It was complete with reactions with participation of CO_2.

Electron energy equation in air mixture with accounting of water molecules we present in the following form based on works [8,9]:

$$\partial T_e/\partial t = eE\,w + W\cdot\eta\ \{1\} + \Sigma K_i\,[M_i^+]T_e/2\ \{2\} + \Sigma K_j\,(2/3\,I_j+3T_e)\,[M_j^+][e]\ \{3\} + I_{aff}\,k_{det}\,[O_2^-]\,[O_2+N_2+H_2O]\ \{4\} - K_{at1}\,[O_2]^2\,T_e^2\,d\,K_{at1}(T_e)/d\,T_e\ \{5\} - K_{at2}\,[O_2]\,[H_2O]\,T_e^2\,d\,K_{at2}(T_e)/d\,T_{at2}\ \{6\} - K_{el1}\,[O_2+N_2](T_e-T)\ \{7\} - K_{el2}\,[H_2O](T_e-T)\ \{8\} \qquad (1)$$

where a term of the electron heating in the external electric field is *eEw* (*E* is the electric field strength, w - electron drift velocity, **e** - electron charge), {1} - heating due to injection of fast electrons into energy region below the vibrational excitation threshold; {2}, {3} - heating due to processes of electron-ion recombination, {4} -heating due to electron detachment; {5}, {6} - Cooling due to attachment processes to O_2 molecules, {7}, {8} - Cooling due to elastic and inelastic collisions of slow electrons with O_2, N_2 and H_2O molecules.

At the modeling we used reactions with participation of the following reagents: positive ions O^+, O_2^+, O_4^+, H^+, H_2^+, OH^+, HO_2^+, H_2O^+, $O_2^+(H_2O)$, H_3O^+, $H_3O^+(H_2O)$, $H_3O^+(OH)$, $H_3O^+(H_2O)_2$ negative ions O^-, O_2^-, O_3^-, H^-, OH^-, atoms O and H, molecules H_2, O_2, H_2O, O_3, free radicals OH, HO_2, H_2O_2, excited states $O(^1D_1)$, $O(^1S_0)$, $O_2(^1\Delta_g)$ electrons and molecular species including nitrogen from the system of reactions developed by us for dry air, the estimate number of all reactions (including those of dry air) is 280-300. Besides reactions with these components we considered reactions of ion - recombination of each positive ion with each negative ion, and the rate constants for these reactions were estimated, since these reactions are not investigated yet for all ion combinations. These rate constants were determined according to the Flannery method with respect to the mixture temperature and pressure. At that their rates are to be normalized by the typical mobility value of these ions 2.5 cm^2/(V·s). In the model we accounted the plasma electron cooling due to the elastic collisions with water, oxygen and nitrogen molecules, and excitation of their vibrational and rotational levels of freedom. At that we supposed that de-excitation of vibrational and rotational levels takes place mainly during the collisions with molecules. The corresponding heating and cooling terms for the electron energy equations were interpolated with respect to the electron temperature T_e. The model includes also reactions of the three-body attachment to the molecule O_2 at presence of H_2O as the third body, and the charge – exchange.

In case of the electron beam impact the power put into the gas by the electron beam W (we usually use it in eV/(cm^3 s) units) and the velocity of the molecule excitation Q are connected by the equation $Q=W/(U_i)$, where U_i is the ionization cost, in air it is U_i = 31.6 eV per electron-ion pair. One can show that the excitation velocity W in air is connected with parameters of the relativistic electron beam (with the beam electron's energy E_b = 200-500 keV) by the relation $W = 10^{22} J_b \cdot P$, where the current density J is expressed in A/cm^2, and pressure in atm, and in case of the non-relativistic electron beam (at E_b <150 keV) $W = 4 \cdot 10^{22} J_b \cdot P$. For conditions of our experiments estimates give the values in the range W=10^{17}-10^{18} eV/(cm^3·s) (at the corresponding electron beam current density 10^{-5} -10^{-3} A/cm^2).

In Fig. 3- 10 we present results of the calculations of concentrations of charged particles, electrons, neutral and excited particles by the electron beam and electric field in the humid propane-air mixture with 2 % of propane and 0.5% water vapor at the room temperature and the atmospheric pressure. In Fig. 11 a)-c) we present results of calculations of the gas and the electron temperatures at C_3H_8 of 1, 2 and 4% and percentage of water vapor 0, 0.1, 0.5, and 1%.

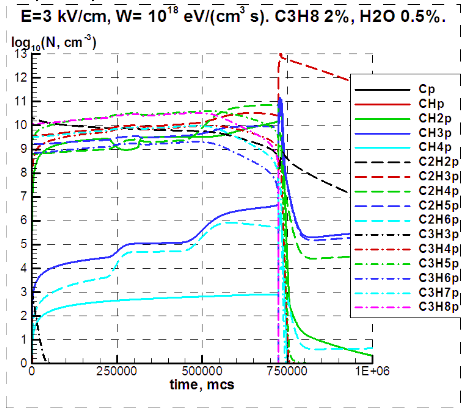

Fig.3.Ions..

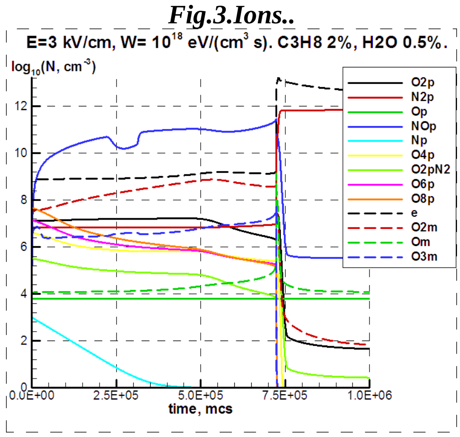

Fig.4. Ions (continuation).

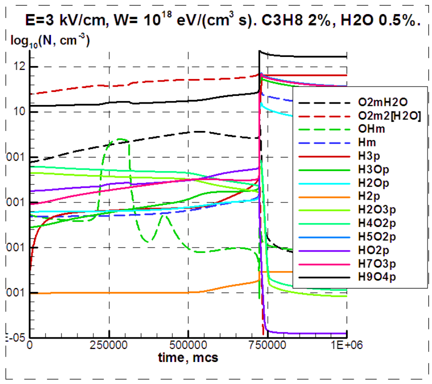

Fig.5. Ions (continuation).

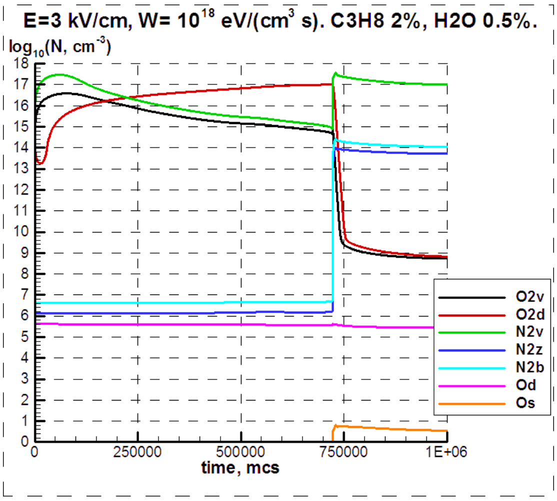

Fig.6. Excited states of molecules.

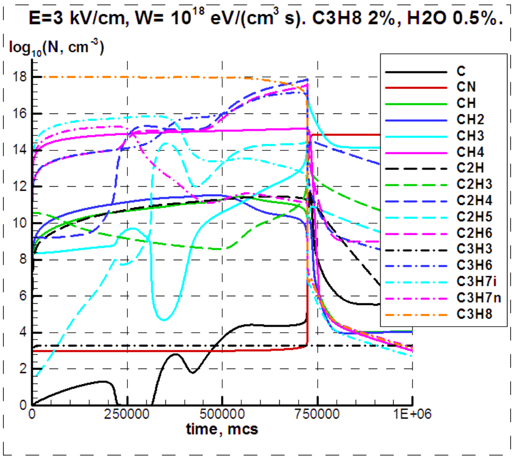

Fig.7. Neutrals.

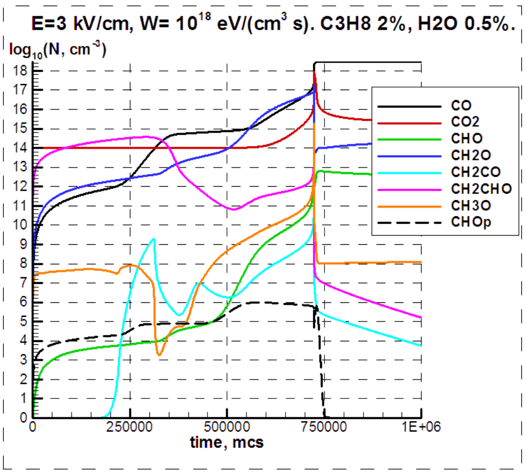

Fig.8. Neutrals (continuation).

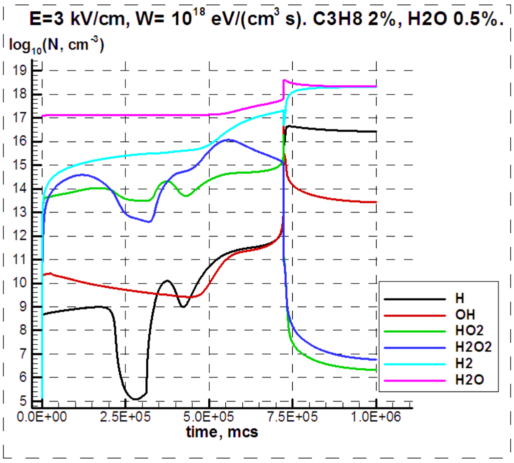

Fig.9. Neutrals (continuation).

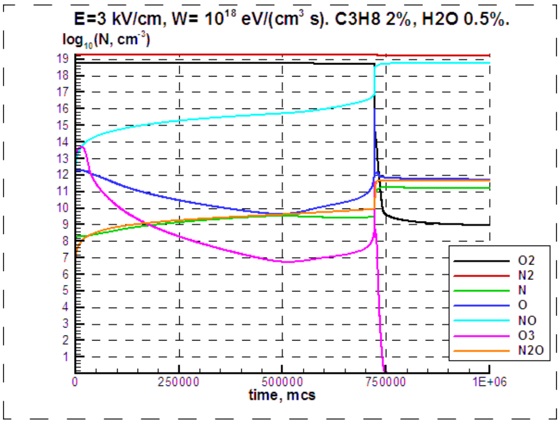

Fig.10. Neutrals (continuation).

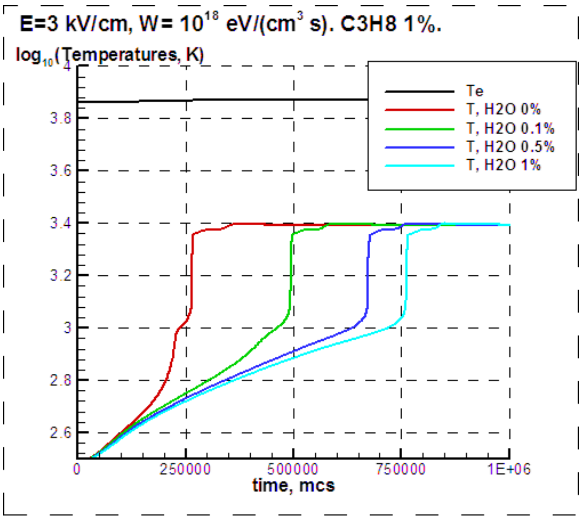

Fig.11. a)

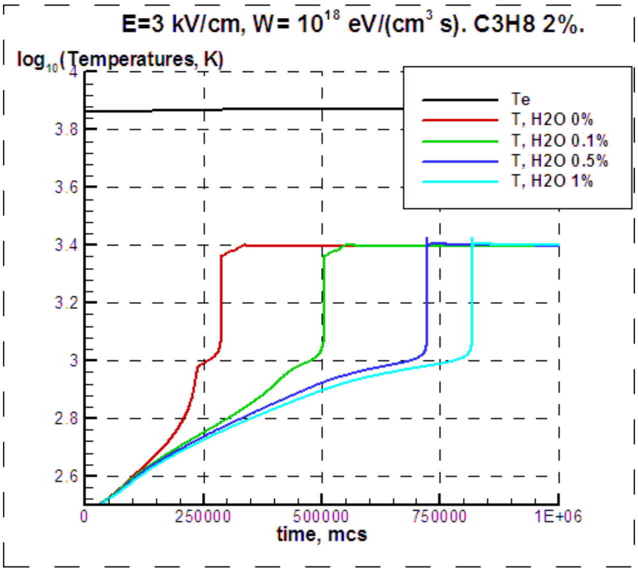

Fig.11 b)

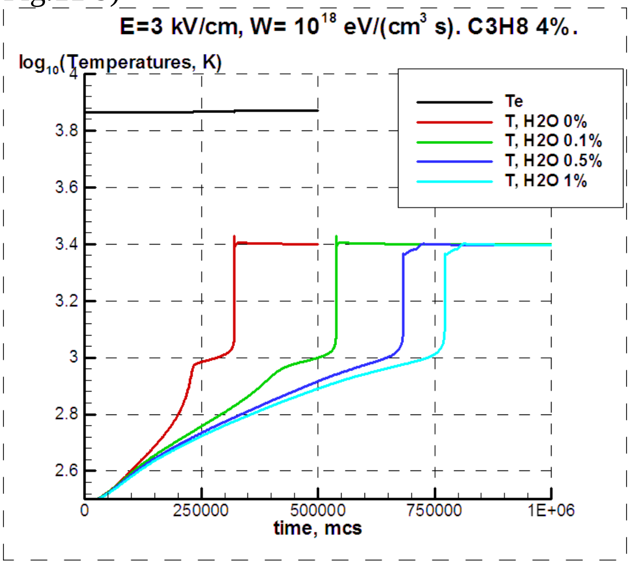

Fig.11 c)

Fig.11. Electron, Te, and gas, T , temperatures at different percentage of propane in the mixture and different percentage of water vapor.

Our calculations show that during the electron-beam combined with electric field pulse many types of molecules and molecular ions appear in the result of the electric field impact on the gaseous mixture. The pike electron and ion concentrations reach values in the range of 10^{11} -10^{13} cm^{-3}. The sharp decrease of the oxygen O_2 concentration and rise of the NO concentration takes place during the voltage pulse.

The concentration of H_2O in the plasma is not large, but water vapor plays an efficient role during the excitation pulse. The temperature rises up to 2600 K during the time 0.25-0.75 s. As one can see in Fig.11 the ignition delay time decreases with decrease of water vapor concentration, best results are obtained at water vapor concentrations 0.1-0.5 %.

So for efficient ignition of propane-air mixture in experiments is necessary to dry a mixture during an action of the external sources of the excitation.

III. Conclusions

Works on non-selfmaintained discharge system with a help electron beam installation for impact on propane-air mixture have been considered. New type of compact sealed off electron beam installation has been discussed. This device can change in practice large size devices EOL type and can be applied at plasma combustion problems solution

Works on modeling of electron-molecule processes in lean propane-air mixture under impact of the E-beam and external electric field have been made. They

Theoretical and computation works on modeling of the electron-molecule processes in the propane-air mixture in the external electric field under the impact of the electron for C_3H_8 of 1, 2 and 4% in the air propane mixture and the percentage of water vapor 0, 0.1, 0.5, and 1% have shown that the ignition delay time decreases with decrease of water vapor concentration, best results are obtained at water vapor concentrations 0.1-0.5 %. So for efficient ignition of propane-air mixture in experiments is necessary to dry a mixture during an action of the external sources of the excitation.

Acknowledgement

The work is performed with the partial financial support of EOARD (Project ISTC #3775p).

References

1. Ardelyan N.V., Bychkov D.V., Bychkov V.L., Gudovich V.A., Denisiuk S.V., Kochetov I.V., Kosmachevskii K., V. Non-Selfmaintained Gas Discharge for Plasma Impact on Gas Flammable Mixtures. AIAA -2010-0269. 48-th AIAA Aerospace Science Meeting, Orlando World Center Marriott, 4-7 January, 2010, Orlando, Florida.
2. Bychkov V., Bychkov D., Denisjuk S., Gudovich AIAA-2011-1215 Non-self-maintained gas discharge for impact on flammable gases. (Experiment). 49-th AIAA Aerospace Science Meeting, Orlando World Center Marriott, 4-7 January, 2011, Orlando, Florida.
3. Ardelyan N.V., Bychkov V.L., Bychkov D.V., Denisiuk S.V., Kochetov I.V., Kosmachevskii K.V. An Ignition System of Non-Selfmaintained Gas Discharge Installation for Impact on Flammable Gas Mixtures. AIAA-2012-0827. 50th AIAA Aerospace Sciences Meeting . 9-12 January. Nashville, TN. 2012.
4. Bychkov V.L., Vasiliev M.N., Koroteev A.S. Electron - Beam Plasma. Generation, Properties, Application. Moscow. MGOU (Moscow State Open University) Publishers. A/O "Rosvuznauka". 1993. 168 P.
5. Korolev A.K., Simonov K.P. New class of compact electron sealed guns with wide electron beam. Elektronnya Tekhnika. Ser. MW – techique. 2. (482). 2003. P. 9-16.
6. Varatharajan B., Williams F.A. Reduced Chemistry Descriptions for Ignition and Detonation of Higher Hydrocarbons. 40-th AIAA Aerospace Sciences Meeting and Exhibit. 14-17 January, 2002, Reno, NV.
7. Westbrook C.K., Chase L.L. Chemical Kinetics and Thermochemical Data for Combustion Applications. Lawrence Livermore Laboratory UCID-17833. Rev.1, April, 1981.
8. Ardelyan N., Bychkov V., Kosmachevskii K., Chuvashev S., Malmuth N. Modeling of Plasmas in Electron Beams and Plasma Jets . AIAA 2001-3101 Proc. 32-nd AIAA Plasmadynamics and Lasers Conference and 4 th Weakly Ionized gases Workshop 11-14 June 2001, Anaheim, CA.
9. Ardelyan N.V., Bychkov V.L., Kosmachevskii K.V. and Kochetov I.V. Non-Selfmaintained Discharge plasma in Propane- Air Mixture. IEEE Transactions on Plasma science. 2011 V. 39, N. 12.