Journal of Engineering Science and Technology Review 11 (1) (2018) 146 - 150

JOURNAL OF
Engineering Science and Technology Review

www.jestr.org

Note

Hybrid Rocket Engine Control by the Electrostatic Field

Reshetnikov S.M.[1], Zyryanov I.A.[1], Budin A.G.[1] and Reshetnikov I.S[2]

[1]Vyatka State University, Kirov, 610000, Russia
[2]OGSS Research Center, Moscow, 117630, Russia

Received 3 September 2017; Accepted 15 January 2018

Abstract

Design of the effective hybrid rocket engines requires development of adequate control methods for the condensed phase regression rates. There are two traditional approaches: prescription with catalytic additives and geometrical with oxidizer flux involution or burning channel profiling. Other methods are significantly less investigated, including using various fields for the combustion process control. The paper presents some experimental results on the influence of electrostatic field on the combustion rate for the PMMA - gaseous oxygen hybrid fuel engine. It was shown that it is possible to control engine thrust with parameters of the control field. Some analysis and model explanations are performed.

Keywords: Hybrid rocket engine, Electrostatic field, Combustion rate, Engine thrust

1. Introduction

A Hybrid Rocket Engine (HRE) is a kind of the chemical rocket engines where one component is solid while second one is either gas or liquid [1,2]. Hybrid rocket engines are positioned between liquid propellant engines and solid propellant engines. Main advantages of HRE are their simplicity, cost efficiency and safety. Usage of natural and organic components such as paraffin and polyethylene as solid phase propellant and oxygen (hydrogen peroxide and others) as second component allows creation of ecology-friendly engines.

However HREs have a significant shortcoming - low component combustion rate for solid phase which leads to insufficient combustion efficiency and low propulsion power. Known methods for increasing combustion rate are chiefly based on injection of catalysts, optimization of channel geometry and using turbulent oxidizer streams [1-3]. These methods however do not allow controlling rate of burn of fuel during engine operation without changing of either oxidant usage rate or injection method of oxidizing agent.

It is possible to influence combustion process by applying an electric field. A possibility to control combustion of liquid hydrocarbons and polymers with static electric field was demonstrated in [4-6]: flame temperature dependence on presence of electrostatic fields [5], change in phase transition parameters [6], deformation of flame edge [4, 5]. Application of electrostatic fields to control combustion rate appears particularly promising because maintenance of electrostatic fields does not require additional energy consumption while field's shape, direction and intensity can be easily controlled.

The paper investigate influence of electrostatic field on a combustion rate of a solid fuel component for hybrid rocket engine based on polymethylmethacrylate (PMMA) – oxygen propellant pair. Impact of the field on propulsion power is also studied.

2. The laboratory HRE model

Investigation of electrostatic field effect on combustion processes in HRE have been conducted using specially designed laboratory HRE. The overview of the installation is shown in Fig. 1. The engine uses PMMA block as the solid fuel component and the gas oxygen as the oxidizer. Engine consists of (Fig. 2):

- oxidizing agent injection chamber
- ignition system
- electrode system
- combustion chamber made from the replaceable PMMA cylinder block
- afterburning chamber
- nozzle.

Oxygen is supplied via regulator with mass flow rate up to 80 kg/m^{2}s. Ignition is provided by the nichrome spiral located at the base of PMMA block. Dimensions of fuel block are 200 mm length and 50 mm height/width. A cylindrical channel of 20 mm in diameter is running along the central axis of the fuel block. Exhaust is directed to subsonic nozzle with critical dimension of 13.6 mm. Propulsion power is measured by strain gauge with accuracy of 1g.

Main feature of this engine setup is a possibility to apply an electric field to the combustion area using various configuration of electrodes. This paper presents data on the case of "coaxial capacitor" where positive electrode (2 mm in diameter) was located in the center along the channel in the PMMA block and metal grid located on the outer side of the block was used as negative electrode (50 mm in diameter). To avoid electric contact with the flame the

*E-mail address: cynepcoyc@rambler.ru

doi:10.25103/jestr.111.17

positive electrode was placed inside the 5 mm diameter quartz tube. In order to preserve quartz isolation properties from destruction at high temperatures the tube was constantly cooled by nitrogen flow supplied at 0.01 kg/m^2s rate. Voltage difference across electrodes in range of 35V-35kV was maintained using high voltage source HCP35-35000. Because leakage current between electrodes was measured to be below 0.1uA electric field within the chamber is static.

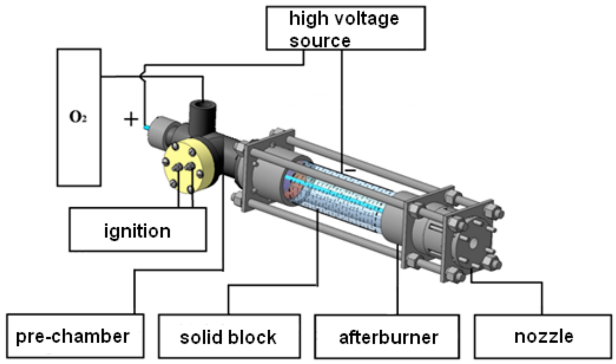

Fig. 1. The laboratory HRE installation

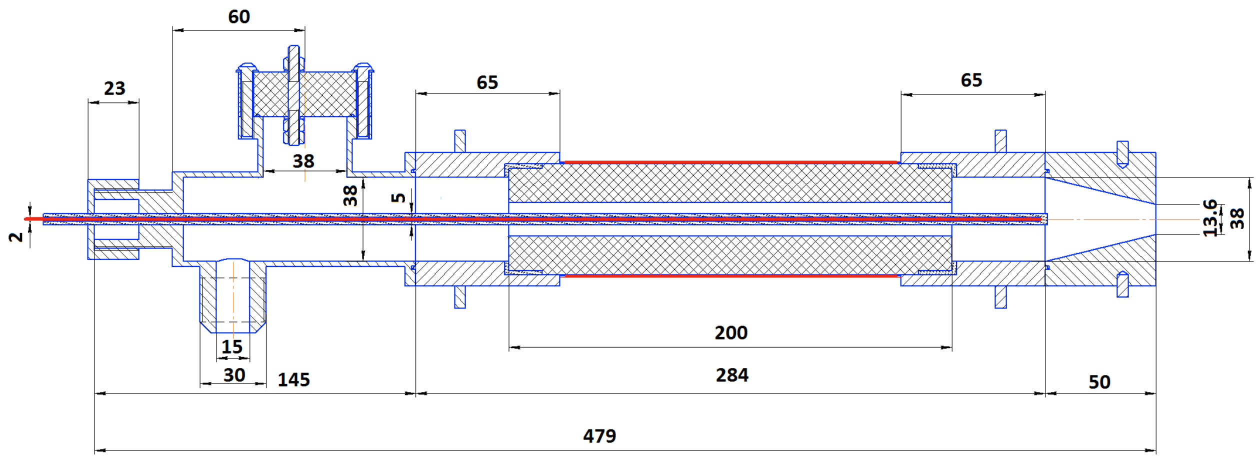

Fig. 2. HRE scheme

Measurement of the linear combustion rate was done using two methods. The first approach was based on the transparency of the PMMA block which allowed video recording of the burning process. Linear combustion rate was derived by checking markings along the fuel block. Average linear rate is obtained after averaging over the block's length. In the second approach the average linear combustion rate is derived from difference in weight of fuel block before and after the experiment and duration of the burning of the fuel [7].

3. Experimental results

Experimental investigations have been conducted at the oxygen flow rates ranging between 15 and 80 kg/m^2s. Results for the time averaged combustion rates u, mm/s vs. linear channel coordinate l, mm are shown in Fig. 3, where subfigure a) corresponds to the absence of the external field and b) corresponds to the applied external field 160 kV/m on the phase boundary. Oxygen flow rate was equal to 23 kg/m^2s. Horizontal lines show the average combustion rates for the first (solid line) and second (dashed line) methods.

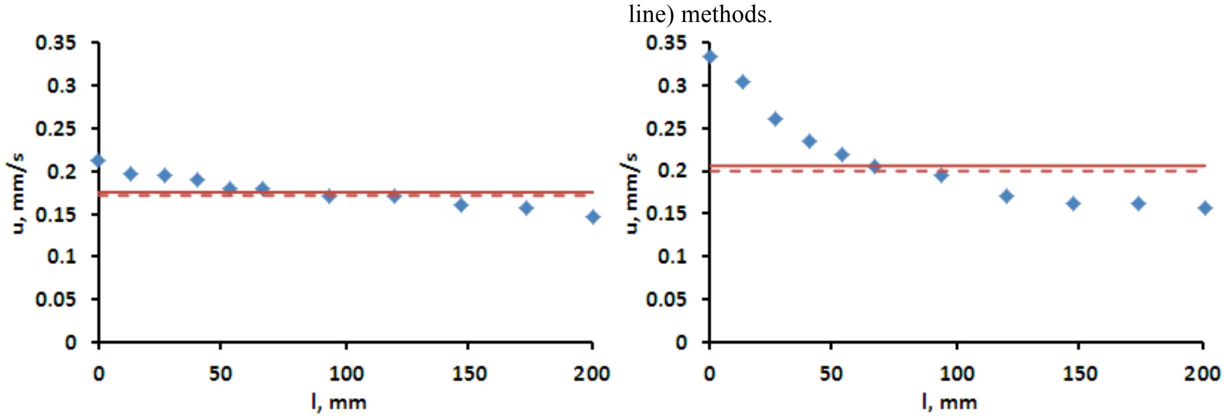

Fig 3. Average combustion rates vs. length of burnt channel of fuel block (explanation in the text)

Fig. 4 presents results on the dependence of the engine thrust P, N vs. the time for various oxygen flows in the absence (blue marks) and presence (red marks) of the electric field. It can be seen that for all conditions application of the field leads to the increment of the pulling force up to 30%.

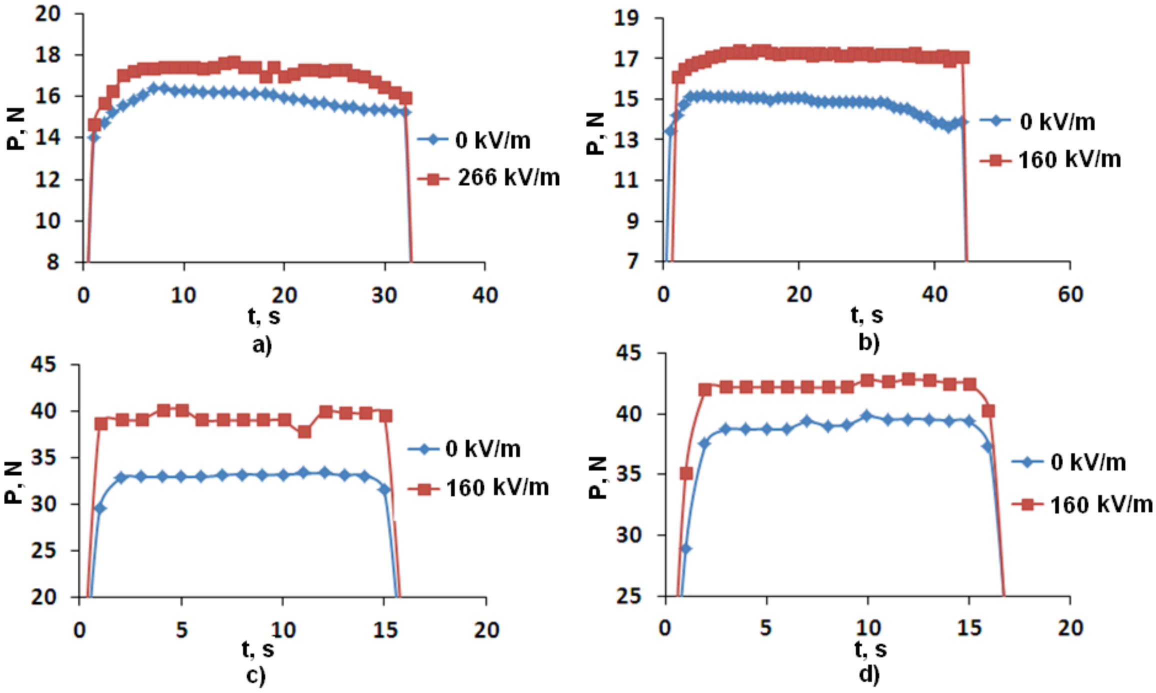

Fig. 4. Propulsion power vs time for various oxidizer flows: a) 20 kg/m^{2}s b) 23 kg/m^{2}s c) 47 kg/m^{2}s d) 51 kg/m^{2}s

Numerical results are summarized in Tab. 1, where E - intensity on the phase boundary, kV/m, $\rho\upsilon$ - oxidizer mass flow rate, kg/m^{2}s, α - coefficient of oxidizer excess, Re - Reynolds number on the entrance of the PMMA block, M - mass of burned PMMA, g, t - engine activity time, s.

Table 1. Experimental results

No	E, kV/m	$\rho\upsilon$, kg/m^{2}s	α	Re	M, g	t, s	u, mm/s	P, N
1	0	15	1.97	17900	101	42	0.142	8.1
2		23	2.45	26600	121	42	0.171	15.1
3		31	2.61	35000	146	41	0.211	23.0
4		39	2.98	44900	144	36	0.237	30.1
5		47	3.27	53300	121	28	0.256	34.0
6		51	3.18	58900	123	25	0.291	39.8
7		61	3.66	69800	76	15	0.300	52.0
8	160	15	1.82	17900	117	45	0.154	9.5
9		23	1.90	26600	160	43	0.200	17.5
10		39	2.58	44900	120	26	0.273	31.5
11		47	2.84	53300	164	33	0.294	40.0
12		51	2.93	58900	112	21	0.315	43.3
13	266	20	1.78	23000	111	32	0.205	17.5
14		31	2.13	35000	96	22	0.258	28.1
15		47	2.60	53300	125	23	0.322	43.2
16		61	2.78	69800	193	29	0.394	60.0

On the base of the measured data it can be concluded that application of the electrostatic field with intensity of 160 and 266 kV/m on the boundary between solid and gas components (phase boundary) leads to increase in linear combustion rates for the PMMA block of 14 and 31% respectively. For HRE the correlation between the linear combustion rate and the mass oxidizer flow is defined by the combustion law [1,2]

$$u = A(\rho\upsilon)^{v} \tag{1}$$

where A and v are constant parameters.

In examined cases combustion laws were u = $0.029(\rho\upsilon)^{0.57}$ at E=0 kV/m, u = $0.029(\rho\upsilon)^{0.57}$ at E=166 kV/m, u = $0.038(\rho\upsilon)^{0.56}$ at 266 kV/m. In other words, increase in the rate of combustion is reflected in the increase of the coefficient “A” before the ($\rho\upsilon$) in formula (1), while the constancy of exponent value v shows that the combustion regime remains “mixed” and does not change for the duration of experiment.

The increase of combustion rate in the presence of electrostatic field increases engine thrust as well. Fig. 5 shows dependence of the averaged thrust vs. flow rate of oxidizer and demonstrate expected increase due to influence of electrostatic field. Error in measurement of engine thrust is less than 5%.

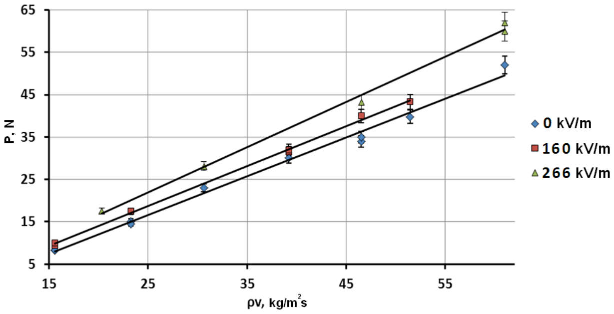

Fig. 5. Thrust vs oxidizer mass flow rate

To summarize, in presence of electrostatic field engine thrust was increased on average by 12% when field's intensity on the phase boundary was 160 kV/m and by 21% when exposed to the field with intensity of 266 kV/m.

4. Discussion

Main mechanism of the electric field influence on the flame is effect of mass forces, which may be similar to the "ionic wind", i.e. formation of charged particles flowing in the direction to oppositely charged electrode which in turn pulls neutral particles into the flow [8-10]. It is also known that the PMMA flame contains a surplus of positive particles [4]. The configuration of electrodes used in this work is such that charged particles must move closer to the combustion surface thus increasing the heat flux to the condensed phase and, as a consequence, combustion rate. Previously it has been shown [5] that the electric field in the flame zone increases heat flux up to 30%. But at the same time rising of the combustion rate leads to the change of flow from the surface of products of pyrolysis reaction. This flow is usually taken into account via the blow-in parameter *B* [11]. Calculation based on the standard method [11] predicts that the flame front will depart from the surface. This, in turn, decreases the heat flux to the surface. Thus increase of the heat flux due to mass forces effect is compensated by the change in blow-n parameter. Mass forces mechanism cannot be used solely to explain observed effects.

It was shown [12] that electric field impacts both kinetics and mechanism of thermal degradation of polymers. Visual examination of the reaction layer of PMAA surface during combustion showed that the surface is covered with the cylindrical cavities 30-50 um deep and 10-15 um in diameter. The total amount, allocation and distribution of these cavities remain constant during the experiment. The presence of the electric field initiates process of cavity formation due to the decrease in amount of work required for its formation [13]. It was observed experimentally: the field with the intensity *E* = 160 kV/m results in the increase of cavity concentration to 11%, with *E* = 266 kV/m to 32%. Because cavity formation is the result of the bulk nature of the PMMA pyrolysis, the electric field intensifies this process.

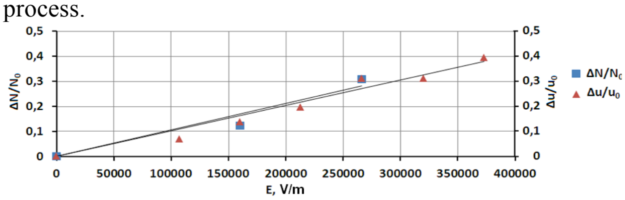

Fig. 6. Normalized dependence of cavities concentration and combustion rate vs field tense

There is a direct relationship between the concentration of cavities N, m^{-2} and the linear combustion rate (Fig. 6). It can be seen from the figure, the dependence in first approximation can be considered as linear and can be described as 1st order equations:

$$\Delta N / N_0 = \alpha E \tag{2}$$

$$\Delta u / u_0 = \beta E \tag{3}$$

where correlation parameters are α = 1,02·10-6 m/V and β = 0,99·10-6 m/V. Taking into account experimental error (5%) these parameters can be considered to be equal. Thus increase of the linear combustion rate is determined by the cavity concentration in the surface layer, which, in turn, increases proportionally to the intensity of the applied electrostatic field.

5. Conclusion

This paper shows that an external electric field applied between electrodes can be used to control combustion rate and propulsion power of HREs. Our experiments demonstrated an increase of propulsion power of up to 30% using *E* = 266 kV/m field. The electrostatic field mainly intensifies thermal degradation of condensed component of PMMA – oxygen fuel system in HRE.

References

1. L.G. Golovkov, *Hybrid Rocket Engines*, Voenizdat, Moscow, 168 p, (1976).
2. M.J. Chiaverini, "Fundamentals of Hybrid Rocket Combustion and Propulsion", *Progress in astronautics and aeronautics*, *American Institute of Aeronautics and Astronautics*, **218**, 648p, (2007).
3 R. Wilkinson, K. Hart, R. Day and I. Coxhill, "Proof-of-concept testing of a sustained vortex-flow configuration for hybrid rocket motors", *Proceedings of the 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, pp 1-10, (2010).
4 S.M. Reshetnikov, I.A. Zyryanov, A.P. Pozolotin and A.G. Budin, "The distribution of excess charges in the diffusion flame of hydrocarbons," *Journal of Physics: Conference Series,* **669**, 1, p. 012040, (2016).
5 S.M. Reshetnikov, A.S. Bobrov and I.A. Zyryanov, "Electric field effect on the diffusion flame structure at different oxidizer excess coefficients," *Russian Aeronautics*, **53**, 2, pp. 206-211, (2010).
6 A.F. Panteleev, G.A. Popkov and Yu.N. Shebeko, "Effect of an electric field on the vaporization and burning of combustible liquids," *Combustion, Explosion and Shock Waves*, **28**, 3, pp. 242–244, (1992).
7 M.K. Hudson, A.M. Wright, C. Luchini, P.C. Wynne and S. Rooke, "Guanidinium azo-tetrazolate (GAT) as a high performance hybrid rocket fuel additive", *J. Pyrotechnics*, **19**, pp. 37-42, (2004).

8 Y. Gan, M. Wang, Y. Luo, X. Chen, J. Xu, "Effects of Direct-current Electric Fields on Flame Shape and Combustion Characteristics of Ethanol in Small Scale", *Advances in Mechanical Engineering*, **8**, 1, 14 p, (2016).
9 I. Barmina, A. Kolmickovs, R. Valdmanis, M. Zake, "Control of Combustion Dynamics by an Electric Field", *Chemical Engineering Transactions*, **43**, 6 p, (2015).
10 M. Belhi, P. Domingo, P. Vervisch, "Effect of Electric Field on Flame Stability", *European Combustion Meeting*, 6 p, (2009).
11 G. Marxman, and M. Gilbert, "Turbulent boundary layer combustion in the hybrid rocket", *Symposium (International) on Combustion*, **9**, 1, pp. 371-383, (1963).
12 M. Zake, I. Barmina, A. Kolmickovs, and R. Valdmanis, "Electric Field Impact on the Biomass Gasification and Combustion Dynamics", *World Academy of Science, Engineering and Technology International Journal of Chemical, Molecular, Nuclear, Materials and Metallurgical Engineering*, **9**, 7, pp. 810-816, (2015).
13 V.S. Vorobev, and S.P. Malyshenko, "Thermodynamics of phase transitions in liquids in external fields", *High Temperature*, **48**, 6, pp 957-982, (2010).