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PRELIMINARY RESEARCH OF GAS TORCH IGNITION SYSTEM FOR THE HYBRID ROCKET MOTOR

The work aims to describe the design and development process of an alternative concept, a torch ignition system that uses methane and nitrous oxide as propellant pair. This system architecture aims mainly to allow the performing of multiple ignitions and the re-usage of the main motor oxidizer to do so.

Key words: hybrid rocket motor, Ignition system, Gas torch, Flow simulation, Rocket combustion.

Досліджено процес альтернативної концепції системи запалювання, у якій використовують метан і закис азоту як паливну пару. Показано, що розроблювана архітектура системи запалювання призначена головним чином для здійснення декількох займань палива та повторного використання основного окиснювача для запуску двигуна.

Ключові слова: гібридний двигун ракети, система запалювання, газовий факел, моделювання потоку, згорання ракети.

Исследован процесс альтернативной концепции системы зажигания, в которой используются метан и закись азота в качестве топливной пары. Показано, что разрабатываемая архитектура системы зажигания главным образом предназначена для выполнения нескольких возгораний топлива и повторного использования основного окислителя для запуска двигателя.

Ключевые слова: гибридный двигатель ракеты, система зажигания, газовый факел, моделирование потока, сгорание ракеты.

Introduction. The development of hybrid propulsion technologies has become an area of great interest. The main objective in aerospace propulsion area is to develop new technologies for rockets motors that can provide the possibility of increasing the performance parameters and provide more reliability to the rockets motors. It is also important reducing of manufacturing costs.

Hybrid rocket motors use liquid oxidizer and solid fuel as propellants [6]. This kind of motor is an intermediate between a solid motor and a liquid propellant engine. The fuel is stored as a solid grain in the combustion chamber. The oxidizer is stored as a liquid in a separate tank. These motors have advantages such as safety operation compared with others types of rockets motors, multiple restart capabilities, higher specific impulse than solid rocket motors and low cost. The hybrid rocket motor presents extensive application in many fields of interest such as sounding rockets, missiles, manned rockets and others.

The ignition system is essential to ensure the operation of all types of rocket engines by the reason that it is responsible to providing the initiation of the combustion process in the combustion chamber of the motor. The ignition system must provide enough energy to pyrolysis the solid fuel as well as have enough residual energy to initiate combustion [3].

Ignition technology is a key aspect to be studied in order to ensure and improve the advantages of hybrid rocket motors. Ignition can be considered a critical step in the operation of a rocket engine. The system has to deliver a certain mass flow rate of a certain temperature into a combustion chamber. Dependent on the local mixture ratios in the combustion chamber and the temperature of the hot igniter gases, ignition occurs [8**]**.

Different approaches have been used to ignite rocket motors. These include hypergolic reactants, resistive elements (low voltage), augmented high voltage spark (liquid bi-propellant torch), pyrotechnics, catalyzed monopropellants, gas-dynamics systems, and high power plasma arcs [3, p. 2].

The project of an efficient and reliable ignition system is a challenging task to do for hybrid rocket motors. In many cases, the ignition process may negate much of the hybrid motor's inherent simplicity or safety and may deny the ability to restart the motor [3]. In the literature, can be mentioned the work of Judson Jr., a Direct Electrical Arc Ignition of Hybrid Rocket Motors. The concept uses a spark to directly ignite the main propellants. This ignition concept allows for hybrid motor systems fully realize the safety, simplicity, and restartablility advantages.

Research of the new ignition system is mostly executed by undergraduate students of Chemical Propulsion Laboratory in University of Brasilia (UnB).

Purpose of the work. In the context of hybrid rocket motors, the design of ignition system is a fundamental activity, since the ignition system is one of the systems that can ensure safety and reliability for a rocket, thereby increasing the viability of different types of space missions. By these reasons, it can be stated the importance of research in the field of ignition. Adhering to this context, this paper developed with the objective to present a new concept in ignition system.

This ignition system has how one of its advantages the fact of being simple manufacturing and be capable to ensure the possibility of multiple ignitions. It is showed a description of High Power Hybrid Rocket Ignition system applied to the ignition system proposed in this work. Simulations in the flow passing through this ignition system were made with the purpose of perform data analysis.

Research methods. The initial parameters used for the calculation are shown in tab. 1. They are formed to satisfy the motor operation and design constrains.

Table 1

System parameters

Initial data	
Initial combustion chamber pressure, kPa	1 … 100
Initial temperature, K	213 … 313
Fuel type	Paraffin, HDPE
Oxidizer type	Nitrox oxide
Mass flow of oxidizer, kg/s	1.5 … 3.0
Design criteria	
Minimal number of ignitions:	16 x 3 seconds each
Reliability	High
TRL	5
Simplicity	possibility to manufacture by Brazilian industry
Possibility to recharge	for ground tests
Constrains	
Max. Volume	4 liters
Place of the ignition	Pre-chamber
Electric power	20W

1. Analytical approach. The system is designed to be operational in stoichiometric mixture properties. In order to ensure proper Oxidizer-to-Fuel (O/F) ratio following chemical process summary reaction calculated:

$$8N_2O + 2CH_4 \rightarrow 2CO_2 + 4H_2O + 8N_2,$$

which gives the volumetric flow ratio, proportional to stoichiometric coefficients:

$$\mathrm{v[N_2O] = 0.8,\ v[CH_4] = 0.2},$$

and with respect to equal pressure in feeding lines of propellants it gives the oxidizer to fuel injectors area ratio 4:1.

The combustion chamber geometry calculated by the models of liquid rocket engine design, described in Reference [2]. The following parameters were obtained: injectors geometry, combustion chamber length and diameter, shape of the igniter nozzle, etc. The calculations result in the preliminary mechanical structure, shown in fig. 1.

2. Mechanical structure. The structure of the ignition system presented in the Figure 1. The torch ignition system is modelled as a simple cylindrical combustor with a convergent nozzle. There are two oxidizer injectors and one fuel injector. The injectors for oxidizer and fuel have identical design. With the use of the same design for both injectors, the complexity for assembling the parts will be decreased thereby providing an ignition system of simple manufacturing. The simplicity of the ignition system is an important design criteria because it can reduce the manufacturing costs. The ignition system mechanical structure made in order to simplify the manufacturability by industry or university means.

Nozzle and injector inserts were designed in order to allow easy exchange between the parts, making possible regulate both the injection and nozzle configuration. Connected to the structure, there is a spark plug which is responsible to ignite the fuel/mixture by an electric spark.

For the construction of the ignition system, a suitable material that can be applied is the stainless steel due to its good mechanical and thermal properties.

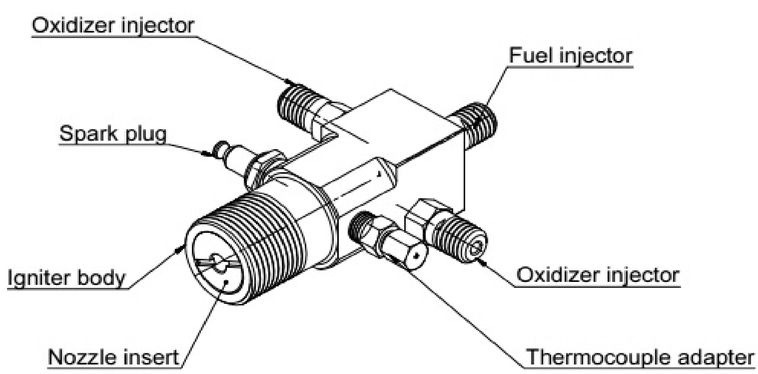


Fig. 1. Structure of the ignition system

The ignition system operation can be described briefly as follows: The methane is injected in a simple axial configuration by the fuel injector. The oxidizer, nitrous oxide, is injected by the oxidizer injector. After being injected, the methane mixes with nitrous oxide and as consequence, the methane receives rotational momentum from the oxidizer flow. This rotational momentum causes swirl in the torch chamber. The swirl method provides self-cooling of the torch chamber. The purpose of the self-cooling provided by the swirl injection method is protect the body material against combustion's heat.

In the end part of the igniter body, the mixture between the fuel and oxidizer should provide the energy required for the combustion.

3. Numerical simulation. Simulation of flow process inside the ignition system can give various advantages compared to the analytical calculations. There are different possibilities to do the simulation and choose the model of processes. In general, the following processes inside the gas-torch ignition system have to be taken into consideration: Flow of sub- and supersonic compressible fluids; Multicomponent one-phase mixtures; Combustion of non-premixed flow; Boundary layer; Real wall-gas interaction.

One of the possible software, which corresponds all these requirements, is ANSYS CFX. Unfortunately, the time limitation of the project execution, and also the cost of the program components did not allow to provide the full model simulation.

The other possibility which was available, is to provide assumptions and use the other software for the simulation of the flow processes. The simplifications of the flow physics are: One-component flow of the combustion products with the average combustion temperature; Non-reacting flow; Non-viscous flow (at high-Reynolds numbers); Constant wall temperature, because of short heat exchange time.

The commercial software used for the simulation is SolidWorks. Allowing the 3D solid modelling and simulation inside the application, decreases the design and calculation time of the product.

The model chosen for the flow simulation described by 3D compressible non-viscous flow equations. The solver of the program uses 2-nd approximation order for time and space derivates.

Boundary conditions of the task are:

- real wall with constant temperature of 400K, as the assumption of the heat transfer between the combustion zone and the wall during the short time (0,1 s);

- inlets of the oxidizer and fuel injectors receiving propellants in gas state, and also the outlet of the ignition system, with parameters described in tab. 2. The outlet boundary conditions are set as «Ambient pressure» option, which allows to correct the outlet pressure at the exit of the igniter.

Initial conditions of the flow are also shown in tab. 2.

Computation goals are stabilized aerodynamic parameters inside the computational domain.

Table 2

Flow parameters

Parameter / Conditions	Fuel inlet	Oxidizer inlet	Outlet
Mass Flow, 10^{-3} kg/s	7.1	63	-
Static temperature, K	3000	3000	-
Static Pressure, MPa	3	3	-
Ambient Pressure, MPa	-	-	0.1
Mixture molar concentrations	$[N_2] = 4/7$; $[CO_2] = 1/7$; $[H_2O] = 2/7$		

The adaptive mesh was chosen for the internal flow problem. Initial mesh resolution is 25x9x18 cells, which was adapted for increasing the simulation accuracy by the program in zones of detailed geometry and large gradients of flow parameters. The resulting internal cells of the mesh in main cross-section layer are shown on the fig. 2. Totally, computational domain consists of 15.000 cells.

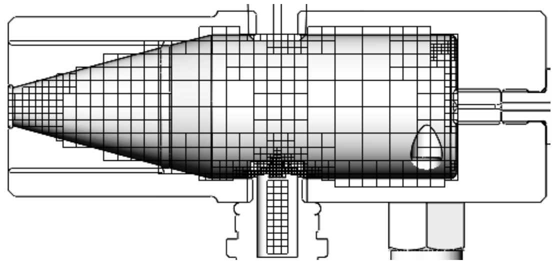


Fig. 2. Computational mesh cross-section (internal flow cells are shown only)

The simulation of the unsteady flow with described initial and boundary condition was made. The simulation goals were reached after 90.000 time steps – steady aerodynamic parameters inside the computational volume. The physical simulation time is 0.1s, which gives the average time step approximately Dt = 1.1×10^{-6} s.

4. Study of electric circuit. The electrical component of the system is a generator of such voltage among the terminals that induces an electrical field in the environment. This electrical field is capable to break the insulation properties of the gas (dielectric) around the electrodes. By other words, it generates an electrical field among the electrodes that is strong enough to transform a dielectric material in a conductor of electricity, because the electric field tends to make the electrons of the gas atoms go far from the nucleus and when it rises to a given value, the pushing force can be bigger and makes the electrons to flow [6]. A dielectric is an electrical insulation (a material or substance with high electrical resistance) such as atmospheric air [7].

In the dielectric materials, the electrons are attached to the nucleus in way that does not allow them to move across the atomic structure of the material. The minimum value of the electric field that makes possible the flow of electrons in a dielectric material (substance) is called dielectric strength [7]. This means that when the dielectric strength of the material is broken, the dielectric becomes a conductor. When it happens, is possible to note the dissipation of the electric energy into radiation (light), thermal energy due to the heating of the gas, and mechanical energy (sound) [7].

In space, the generation of a high quantity of electricity can be difficult, because of the limitations from generators like solar panels and the weight in case of using a great amount of batteries. Due to this, the ideal spark generator for this category of rocket ignition system must be effective with the minimum amount of electric energy possible. This study tries to follow this concept, by using a low power DC battery, aimed to generate the required sparks.

In order to proceed with the control of the ignition system tests, seemed convenient to use programming LabView. The electrical characteristic of this system grant reliability due to the capacity of multiple ignitions. Its behavior on field tests is still uncertain, and should be investigated. The flight model of the system will be composed of a flight computer can be programmed to receive a radio frequency command (uplink), to activate the spark plug and open/close valves, or can be programmed in order to ignite in a given time, and in a sequence of times, in order to perform orbital insertion maneuvers, for instance. The board computer can be either a simple Arduino or other with greater processing power, which the correct one to be chosen, depends of the necessity of the applications. In bench tests an Arduino is quite enough to provide control to the engine ignition, by Lab View programming.

The key component is the transformer, which is going to increase the voltage. The electrical system can be analyzed by the diagram below.

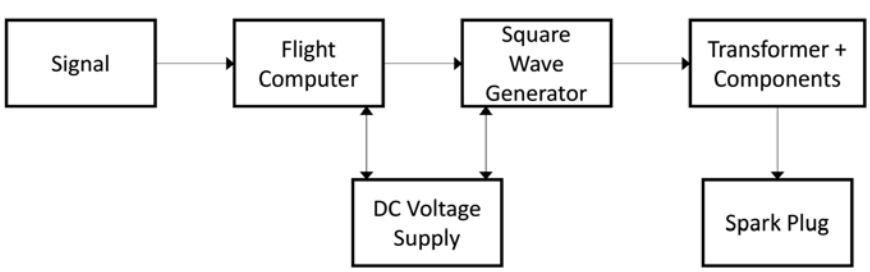


Fig. 3. The electrical system schematics

The flight computer of the system is going to control when the sparks are generated. To do this, he will be placed in the circuit as a switch, and in the same sense that a switch in the house controls when the light is turned on or off, the computer will turn on or off the Square Wave Generator. When this generator is turned on, the square wave signal is generated and then this should excite the high voltage generator.

The transformer only can work with alternate current (AC), but as space flight compact equipment, the system can only have DC power supplies, such as a battery. Because of this the square wave generator is used, as it can transform a DC voltage to pulsed DC (square wave), in a way of trying to approximate the signal to a sinusoidal AC and make the transformer to work, increasing the voltage.

After the transformer and some components, the spark plug discharges the voltage in the gas, when ignition is expected.

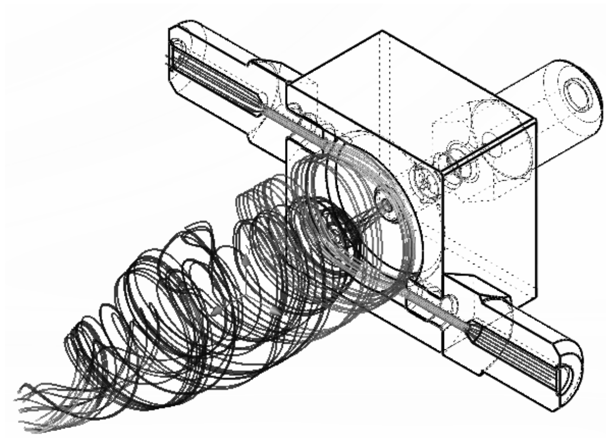


Fig. 4. Path-lines in computational volume, starting from injectors

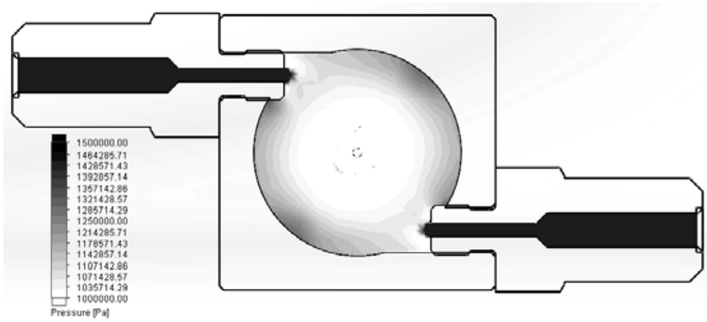
Results. The flow structure presented on fig. 4 shows the path-lines of the gas virtual particles. Presented flow structure has the following characteristics. Oxidizer flow injected in swirl configuration, distributed on the periphery of the igniter body. Fuel flow injected axially, mixes with oxidizer and receiving rotational momentum of the oxidizer flow. Two flows are mixed forming the preferable conditions for the combustion of the mixture. Same time, periphery and axial flows are not mixed completely near the wall and in igniter central axis. It prevents flame to appear on the wall, allowing efficient cooling of the igniter surface. At the nozzle part of the igniter, two flows are mixed enough to support the combustion in entire cross-section. Higher temperature of the flame in the nozzle puts additional requirements to the nozzle insert material. Same time, stoichiometric composition can be reached at the spark plug igniter, which ensures the flame stabilization.

The fig. 4 also shows that spark plug device and thermocouple adapter do not brake the cooling vortex of oxidizer. The distribution of the pressure, presented on fig. 5 shows the pressure load distribution for the further structural design and mass minimization process. Maximum design pressure inside the ignition system during the motor operation initiation is around 11bar. However, the motor chamber nominal pressure in limits of 30…50bar puts additional requirements to the strength of the ignition system. Totally, with means of the safety factor, the ignition chamber wall may be reduced to value, less then 1.5mm. Optimization of the mass of ignitor body puts additional requirements to the manufacturability and machining tools.

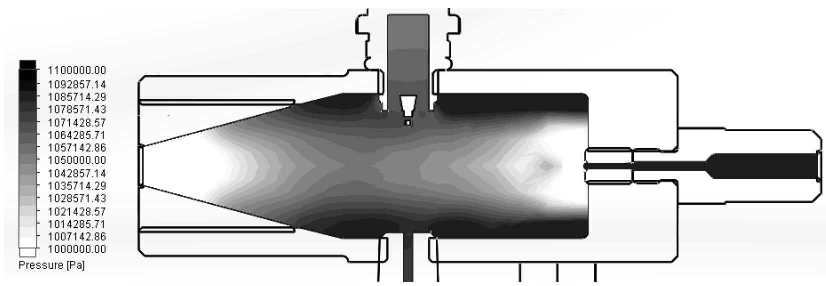
The velocity distribution near the spark plug device (fig. 6) shows the limits of the Mach number around 0.0…0.18. For the cold oxidizer gas and premixed flow with the fuel it results in velocity in average of 35m/s. According to the reference [5], the flame formed near the spark with velocity less then 50m/s is stable and will not separate from the plug. The small recirculation zone is supporting flame stabilization as well.

Circuit Tests. The complete circuit was still not tested but some parts.

The last tests of the Square Wave Generator of the circuit showed good results. The output of this part of the circuit was capable to generate a square wave without many imperfections. To simulate the battery, the input voltage used was 14 V. After the generator, the result as expected was a square wave with the following parameters obtained by using the oscilloscope: VPP = 13.4V, Frequency = 60,86Hz, Prd = 16,43ms.



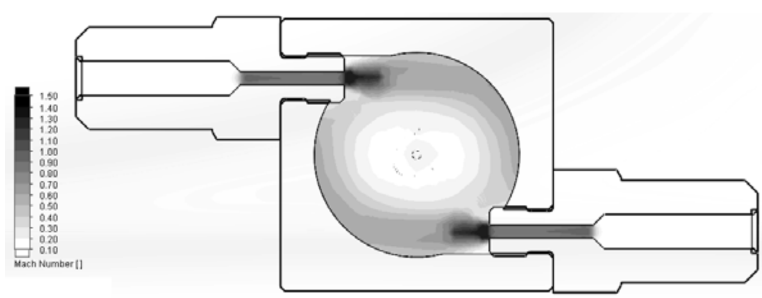
a



b

Fig. 5. Pressure distribution in cross-sections

a – of vortex injectors; *b* – of axial plane



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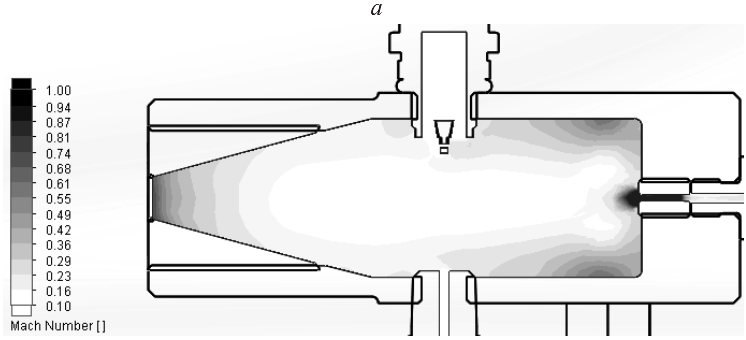

b

Fig. 6. Mach number distribution in cross-sections:

a – of vortex injectors; *b* – of axial plane

The AC usually frequency is 50 – 60 Hz, so the result obtained by the generator is good, 60, 86 Hz. The pulsed signal voltage of 13,4V is the one that the transformer will increase.

To increase the voltage of the transformer, can be associated a Cockcroft Watson Generator, which consists of capacitors and diodes arranged in such geometry that stages can be added. As more stages grater is the output voltage, but bigger is the impedance, so the optimal number of stages should be selected [4].

Conclusion. Provided simulation showed the distribution of the flow parameters inside the model of the ignition system. Future step an be the one-dimensional analysis of the flow with combustion in non-commercial or commercial software. Use of the SolidWorks showed problems of the simulation algorithms, such as extremely long simulation time of the compressible non-viscous flows. It hopefully will stimulate student's research of the non-commercial simulation software with higher performance and possibilities.

Although the study of the ignition system seems show good results, is unknown its behavior on the space environment, then space conditions tests are required.

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Державне підприємство «Конструкторське бюро “Південне” ім. М. К. Янгеля»

ВПЛИВ ВІЛЬНОГО ГАЗУ НА АНТИКАВІТАЦІЙНІ ЯКОСТІ ШНЕКО-ВІДЦЕНТРОВОГО НАСОСА

Наведено результати аналізу отриманих експериментальних даних кавітаційних характеристик насосів, спроектованих в ДП КБ «Південне». Надано рекоменда-