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DEVELOPMENT OF THE 3D PRINTED FUEL GRAIN FOR A SOLID-FUEL RAMJET ENGINE

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Abstract. *Solid-fuel ramjet (SFRJ) is a perspective propulsion system invented for tactile missiles, currently under investigation by many research groups. This motor has a simple structure and provides reliable propulsion characteristics. The Chemical Propulsion Laboratory of the University of Brasilia has built the test SFRJ working on paraffin and polyethylene fuels. A solid-fuel ramjet's primary design challenge is to organize optimal combustion of the solid fuel in incoming high-velocity airflow. High-regression rate fuels like paraffin allow creating a compact combustion chamber and optimize the motor's size. However, such a solution requires an additional investigation on the motor performance addressed to control the oxidizer-to-fuel ratio. 3D printing of the fuel charge is one of the methods currently used to overcome the disadvantages of simple one-port cylindrical grains in the hybrid of air-breathing propulsion: non-uniformity of the regression rate and variation of SFRJ performance in time. The research aims to create a composite paraffin-ABS fuel grain to ensure a constant fuel mass flow rate during the motor operation. The other current work goals are analyzing the motor operating conditions, reviewing the 3D-printed grain geometries, their advantages and disadvantages, and building a composite grain design methodology. The object of study is widely presented in the literature. The reference publications provide analytical and empirical models about the fuel grain design. Current development is based on the Laboratory's previous experimental work, allowing a more accurate fuel regression calculation. The compressible flow model with chemical reactions allowed obtaining the motor's flow properties in the combustion chamber. The fuel regression in time was calculated numerically, integrating the regression law with the flow equations. The 3-D printed fuel grain casing is ready to be tested on the test bench at the Laboratory. Due to the quarantine restrictions in 2020 - 2021, an extensive study on motor performance was provided using analytical calculation and numerical simulation, including the protection layer regression rate, paraffin regression rate, and grain degradation. The theoretical analysis results correspond with other research groups' studies and complement solid-fuel ramjet knowledge with new data.*

Keywords: *solid-fuel ramjet, additive manufacturing, composite fuel grain, regression Rate, numerical methods*

1. INTRODUCTION

The development of the power unit plays a central role in the designing of any aerospace system. Usually, the motor envelope defines the profile of the whole system, especially when flying in supersonic conditions that require high thrust.

The current study originates from the missile development for tactical purposes Alves (2018) or civil meteorological applications presented in Figure 1. Such a missile would operate in two regimes to perform its mission. First, a solid rocket booster accelerates the vehicle to supersonic velocity. Second, the ramjet motor thrust pushes the rocket to fulfill the mission: reach a certain flight altitude and distance in a specific time.

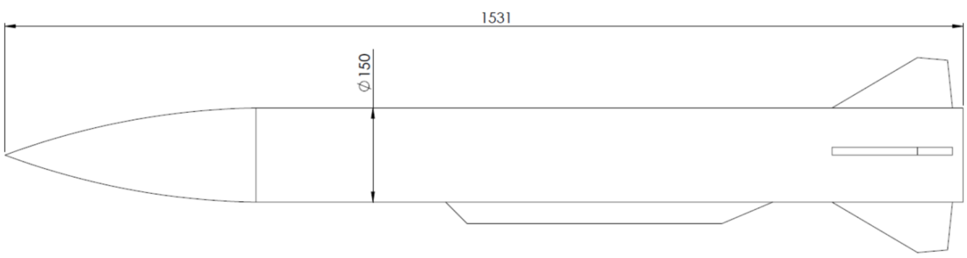

Figure 1. Preliminary design of the air-to-air missile, Alves (2018)

The ramjet engine has three main parts: a diffuser, a combustion chamber, and an exhaust nozzle El-Sayed (2016). As the ramjet engine only operates at sonic and supersonic speeds, the air arrives at the diffuser with a supersonic velocity. Upon entry into the diffuser, the air compresses through the engine walls. Then, with the reduced speed, the air is injected into the combustion chamber, and after the complete combustion of the oxidant with the propellant, the mixture flows out from the nozzle at a very high speed. According to Ou *et al.* (2017), by physical principles, there is a reaction of this combustion, where it is a thrust is generated, which is responsible for the movement of the flight vehicle that uses the ramjet engine.

Among other types, the solid-fuel ramjet (SFRJ) motor has several advantages: safety of storage, absence of moving parts, and simplicity of operation. However, it also has several disadvantages that complicate its implementation in the aerospace field, such as organizing efficient combustion in a high-velocity airflow and variation of the fuel mass flow rate due to the grain regression.

Several techniques help us solve these problems. For example, to achieve efficient combustion, splitting the flow to reduce its velocity in the combustion zone, applying the flame holder to intensify the turbulence in the combustion chamber, uses the flow separators and diaphragms to create recirculation zones.

The change of the fuel mass flow rate along the flight originates from the following physical process. First, the air entering the combustion chamber interacts with the fuel grain and burns its surface, Sutton and Biblarz (2016). As a result, the crossectional flow area grows. Consequently, the flow velocity in the combustion chamber decreases, reducing the amount of oxygen that reaches the combustion zone near the fuel grain surface. Because of that, the mass flow rate of the fuel in the combustion chamber of SFRJ slows down with time. In such a regime, the motor operation becomes inefficient, resulting in high fuel consumption (reduced time of motor operation) or smaller thrust (reduced flight velocity). Such a problem happens not only in SFRJs but also in hybrid rocket motors.

There are several techniques to overcome the variable mass flow rate problem, keeping the constant burning and flow areas, for example, combining different fuel materials and protecting some fuel surfaces from unwanted burning.

The current project, Alves (2018) developed in the Chemical Propulsion Laboratory of the University of Brasilia, focuses on the test SFRJ of 300 N working on paraffin as a solid fuel (Fig. 2). The development passed the preliminary design and construction phases Alves (2018); Azevedo (2019), experimental characterization of the motor performance Azevedo *et al.* (2018, 2019); Shynkarenko *et al.* (2019a), development of the heater for the diffuser bench simulation Shynkarenko and Simone (2020); Shynkarenko *et al.* (2019b); Souza and Shynkarenko (2017); Shynkarenko *et al.* (2015); Silva and Shynkarenko (2018), grain structural integrity Andrianov *et al.* (2019), chamber cooling effect Filho *et al.* (2018), experimental investigation of hydrocarbon-based fuels in SFRJ Shynkarenko *et al.* (2019a); Azevedo *et al.* (2019), experimental and analytical study of cold flow within a ramjet bench motor Freitas and Shynkarenko (2020), combustion instability for motors with a diaphragm Lee *et al.* (2019), investigation of a dual-fuel hybrid rocket engine for missile and rocket applications Gontijo and Shynkarenko (2020), development of a thrust control system for ramjet applications simulating different flight regimes Shynkarenko and Contijo (2020). Table 1 shows main motor characteristics according to Alves (2018).

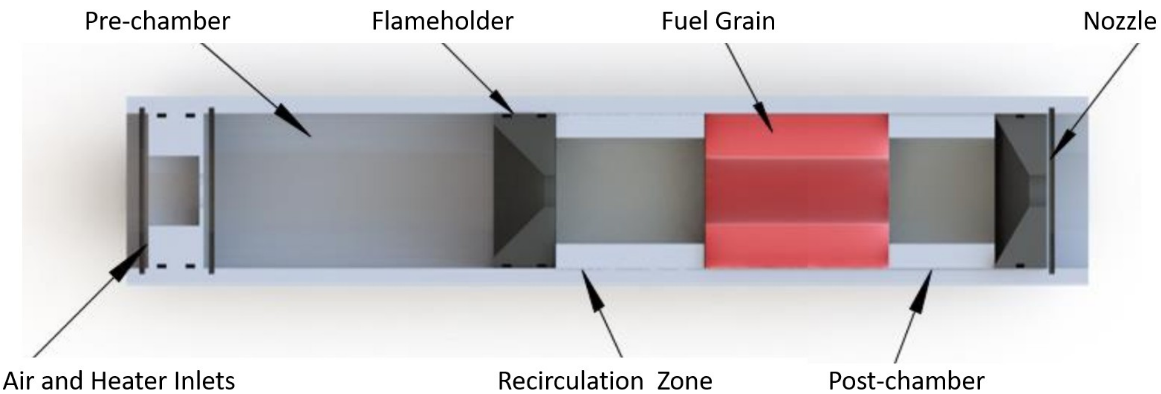

Figure 2. 3D model of the solid-fuel ramjet test motor developed in the Laboratory

According to the flight program, current work will focus on developing the analytical model of the paraffin-plastic composite 3D printed grain that ensures continuous fuel delivery in the combustion chamber of SFRJ. The design criteria are simplicity for manufacturing the fuel grain, dimensions compatiblility with the previously developed motor for further experimental testing and validation of the grain design.

The subject of additive manufacturing in solid-fuel ramjets or hybrid rocket motors is widely studied due to its simple applicability to improve the propulsion system performance. These advances became achievable due to three following factors. First, it is growing interest, especially among universities, in hybrid and solid-fuel ramjet technology. Second, it is related to the wide spreading of accessible 3D-printing technologies affordable for small research groups. Moreover,

Table 1. Parameters of the solid-fuel ramjet motor according to Alves (2018).

Parameter	**Value**
Specific impulse (average), s	1050
Operation time, s	15
Stagnation pressure, bar	3.07
Maximum motor diameter, mm	150
Initial fuel grain diameter, mm	76
Fuel total mass, kg	0.5
Air mass flow rate, kg/s	0.49
Fuel mass flow rate, kg/s	0.03

finally, third is the ubiquity of numerical methods allowing rapid calculation of efficient propulsion systems. Let us give some recent examples of these works that motivated current development. For example, Oztan and Coverstone (2021) studied the utilization of additive manufacturing in hybrid rocket technology. Chandru *et al.* (2018) researched additive manufacturing of solid rocket propellant grains. Fuller *et al.* (2011) investigated the advantages of rapid prototyping for fuel grain for the hybrid rocket motor. Bauer and Metsker (2016) showed the application of additive manufacturing in solid and hybrid rocket grain design. Piscitelli *et al.* (2018) provided the characterization and manufacturing of paraffin wax as fuel for hybrid rockets.

Figure 3 shows the motor assembled on the test bench at the Chemical Propulsion Laboratory of the University of Brasilia. Four air hoses circumferentially supply the motor with air. The methane-oxygen heater stays on the central axis of the motor. There are pressure and temperature sensors to measure flow properties at the combustion chamber inlet.

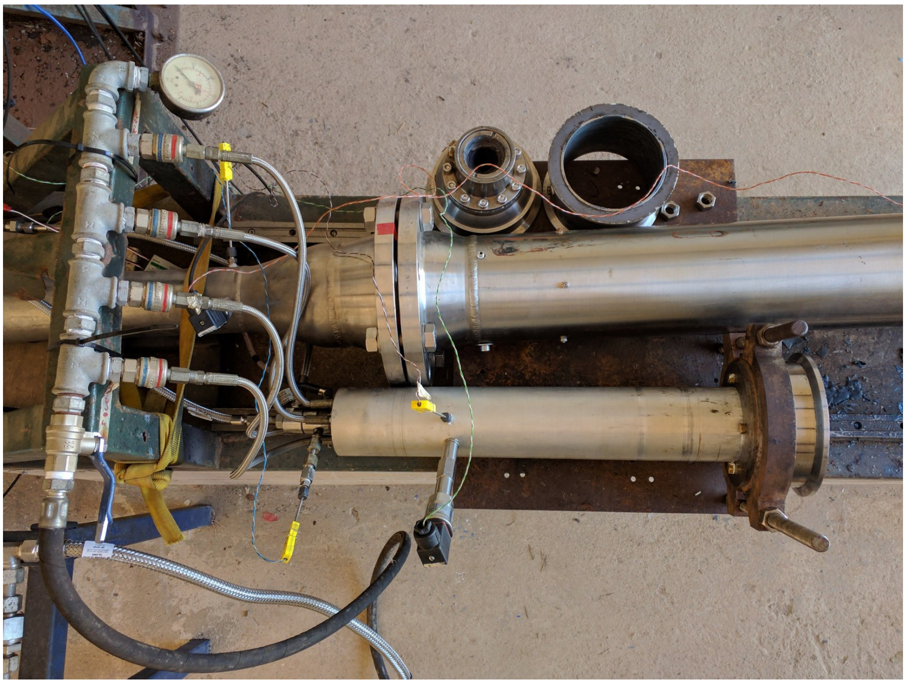

Figure 3. Motor assembled on the test bench.

The research aims to create a composite paraffin-ABS fuel grain, where it is expected to analyze the engine operating conditions and ensure a constant fuel mass flow rate. An extensive study on engine performance was provided using analytical calculation and numerical simulation, including the protective layer regression rate, paraffin regression rate, and grain degradation. The theoretical analysis results correspond to the studies of other research groups, complementing the knowledge regarding the solid fuel ramjet engine. Another goal of the current research is to review the geometry of 3D printed grains by bringing out their advantages and disadvantages, which make part of a composite grain design methodology. It grounds on the previous research, where reference publications provide analytical and empirical models on fuel grain design.

2. METHODOLOGY

The solid fuel grain is the object of the current study. The regression model of the grain helps to obtain the motor characteristics, such as the propellants' mass flow rate, heat loads in the combustion chamber, chemical composition of the combustion products, specific impulse, and thrust, among others. In this work, the grain consists of a 3D-printed shell from ABS plastic as a protective layer filled with paraffin as the primary fuel.

Paraffin is a petroleum derivative. Its properties include purity, excellent gloss, reduced odor. It is also a stable, high-regressive, ecologically green fuel. According to Speight (2015) it has the hydrocarbon chemical formula C_nH_{2n+2}. ABS (Acrylonitrile Butadiene Styrene) plastic is a thermoplastic resin derived from petroleum. The composition of ABS plastic comes from butadiene, styrene, and acrylonitrile. Jr (2006) showed one of its features. ABS can melt relatively quickly when subjected to specific high-temperature conditions. Such a property makes ABS an excellent material for 3D printing.

Among its advantages are variety, flexibility, chemical resistance, and its reduced value Akcelrud (2006). Another parameter to be considered when choosing this plastic is the glass transition temperature T_g. It is directly related to the mobility of polymer chains. Thus, as the temperature decreases, the energy supply restricts molecular movements. With the increase in temperature, the energy supply to the material becomes sufficient for the chains of the amorphous phase to acquire mobility. Materials that are above their T_g present a rubbery behavior of its amorphous phase. That is, this fraction will have a flexible and malleable behavior. This fact is important because the grain manufacturing process requires filling the ABS shell with liquid paraffin. Therefore, the glass transition temperature must be above the paraffin melting temperature, which is 60°C. Another essential parameter is the melting temperature range of the ABS plastic, which is relevant, as it increases the possibility of the grain structure resisting until the end of the combustion tests Askeland and Phulé (2003).

Figure 4 shows the composite solid fuel grain structure used in current research. It has a protective layer of plastic (light-gray colour on Fig. 4) with a thickness proportional to the time of the exposed fire. In such a way, a plastic surface is "programmed" to sustain a certain amount of time at each specific point, opening the high-regressive paraffin (dark-gray colour on Fig. 4) surface to the fire at a particular time moment.

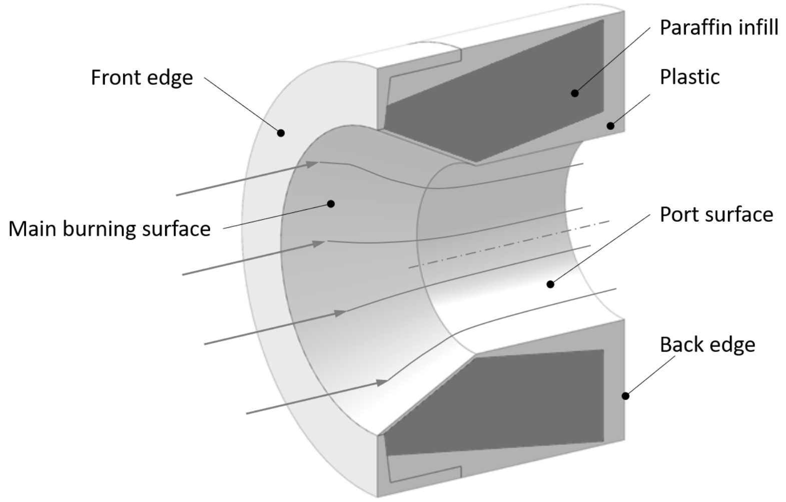

Figure 4. Fuel grain cross-sectional view

The thinnest layer of plastic occupies the conical port inlet surface. It burns during the grain ignition process, which lasts about 2 to 3 seconds. Thus, the "Main burning surface" of paraffin opens to the fire. During the motor operation, the port surface covered with plastic burns slowly, keeping the flow area almost constant, where the paraffin regression is rapid. With a slow growth of the port, the paraffin area also increases, keeping constant a relative mass flow rate in such a way, ensuring operation of the motor in optimal conditions. Figure 5 represents the grain schematics for mathematical modeling. Here, lines according to the edges and burning materials represent the surface cross-section. The principal geometric points to build the regression model are: (1), $(2A)$, $(3A)$, (4), and (5) correspond to a plastic surface, and $(2P)$ and $(3P)$ correspond to a paraffin's "main burning surface".

The formula 1 empirically describes the regression rate according to Sutton and Biblarz (2016). It has several assumptions and allows calculating the fuel melting and combustion in a highly simplified way.

$$\dot{r} = aG_{ox}^n \tag{1}$$

Here, G_{ox} is the relative oxidizer mass flow rate, a and n are the experimental constants. G_{ox} is calculated using the

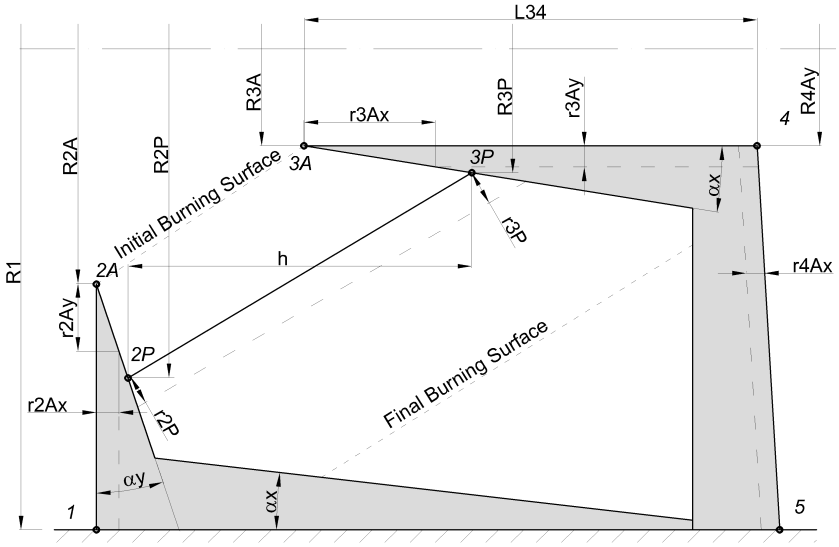

Figure 5. Grain schematics for the mathematical modelling

equation 2.

$$G_{ox} = \frac{\dot{m}_{ox}}{A_f} \tag{2}$$

Here, $\dot{m}_{ox}$ is the oxidizer (air) mass flow rate and A_f is the flow-through area.

The coefficients a and n in equation 1 are known for each propellant pair. $a = 0.1267, n = 0.3728$ for ABS plastic and $a = 0.611, n = 0.34$ for paraffin, according to Oztan *et al.* (2020). The engine operation mode, heat transfer at the burning surface, grain configuration, chamber pressure, and oxidizer injection method influence the regression rate of solid fuel.

$$\dot{m}_i = \rho_i A_{si} \dot{r}_i \tag{3}$$

Here, ρ is the material density, equal to 900 kg/m^3 for paraffin and 1040 kg/m^3 for ABS plastic, A_s is the burn surface area, and $\dot{r}$ is the regression rate of the material. The following grain firing surfaces were studied according to defined points (1-2A, 2P-3P, 3A-4, 4-5). Summating the flows from all the grain surfaces, the total fuel mass flow rate will be equal to:

$$\dot{m} = \sum_{i=1}^{4} \dot{m}_i = \sum_{i=1}^{4} \rho_i A_{si} \dot{r}_i \tag{4}$$

According to the geometrical definitions in Fig. 5, the surface areas A_s are equal to:

$$A_{s1-2A} = \pi[R_1^2 - (R_{2A} + \int_0^t \dot{r}\, dt)^2] \tag{5}$$

$$A_{s2P-3P} = \pi[(R_{2P} + R_{3P} + \int_0^t \dot{r}\, dt)\sqrt{(R_{2P} - R_{3P})^2 + h^2} \tag{6}$$

$$A_{s3A-4} = 2\pi L_{3-4}(R_0 + \int_0^t \dot{r}\, dt) \tag{7}$$

$$A_{s4-5} = \pi[R_1^2 - (R_4 + \int_0^t \dot{r}\, dt)^2] \tag{8}$$

The following relations represent the flow areas with respect to the calculation points:

$$A_{f1} = A_{f2A} = A_{f4Ax} = A_{f5A} = \pi(R_1 + \int_0^t \dot{r}\, dt)^2 \tag{9}$$

$$A_{f2P} = \pi(R_{2P} + \int_0^t \dot{r}\, dt)^2 \tag{10}$$

$$A_{f3P} = \pi(R_{3P} + \int_0^t \dot{r}\, dt)^2 \tag{11}$$

$$A_{f3A} = A_{f4Ay} = \pi(R_{3A} + \int_0^t \dot{r}\, dt)^2 \tag{12}$$

Equations 1 - 12 form a system allowing to calculate the burning surfaces during the motor operation. As the fuel regression happens perpendicularly to the surface, integration of the regression equation by time gives trajectories of points 1-5. In such a way, the authors calculate the grain regression as a function of time.

Obtaining the equation system described above and calculating the propellants' mass flow rates, one can proceed to the combustion analysis and determining the propulsion characteristics of SFRJ in terms of operation time. The motor performance and space-averaged flow properties will be numerically estimated using the computer program for the Calculation of Complex Chemical Equilibrium Compositions and Applications (CEA) developed by NASA, Gordon and McBride (1996).

3. RESULTS

The numerical calculation of the grain regression bases on prior experimental work Shynkarenko *et al.* (2019a). Table 2 shows the airflow grain geometrical parameters (Fig. 5) according to the previously obtained research data.

Table 2. Initial parameters for the solid grain calculation.

Parameter	**Value**
Chamber pressure, bar	2.9
Operation time, s	10
Air mass flow rate, g/s	29.76
Motor throat diameter, mm	14
Grain external diameter (R_1), mm	73
Grain port diameter (R_{3A}), mm	32
Grain length, mm	50
Cylindrical port length (L_{34}), mm	30
Protection angle (α_x), °	9
Protection angle (α_y), °	10

As seen from Table 2, the grain geometry is compact and similar to the previously tested configurations Azevedo *et al.* (2019). Defining the geometry of the grain and flow conditions, the authors calculated the evolution of the grain geometry, fuel regression, and composition of the combustion products. Exclusively for the proof of the concept, the authors selected the motor operation time of 10 s.

Fig. 6 presents the results of the grain regression in graphical form, and Fig. 7 shows the variation of the burning area in time. As seen from the figure and according to the model, the plastic protection burns slowly, and according to the regression rate equation (1), opens the paraffin surface to the hot reacting flow. Same time, the protection layer of plastic resists the thermal loads protecting the wall from overheating. The regression rate of protective material was estimated from 0.25 to 0.49 mm/s and paraffin from 1.14 to 1.38 mm/s.

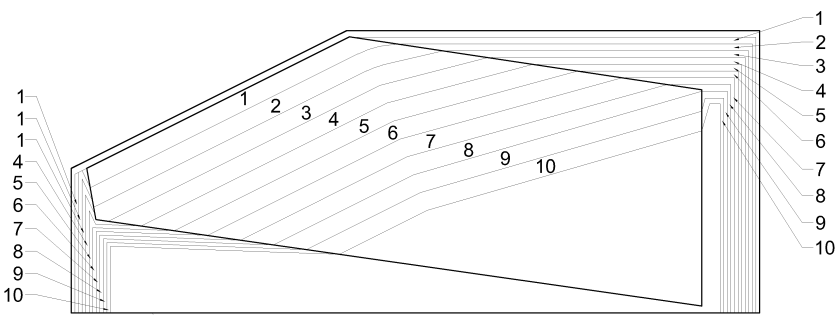

Figure 6. Grain regression in time (s)

In Fig. 6 the numbers correspond to each second of combustion, starting from the ignition. At the initial moment of the motor ignition, the grain is covered with a thin protective layer of plastic (not numbered external area) which burns during the ignition sequence, according to experiments Shynkarenko *et al.* (2019a). The protective layer assures a "smooth" ignition process due to the low regression of protective material. It also helps store the fuel grains in cleaner conditions and keep the grain integrity during the storage.

The regression analysis shows the following.

- The lower surface thickness of the plastic can be reduced because it burns slower than the back edge of the grain;
- The burning surface of paraffin is inclined to the axis. It is possible to achieve longer grain combustion, increasing its length and protection layer thickness in the port and the back edge surfaces proportionally to operation time.

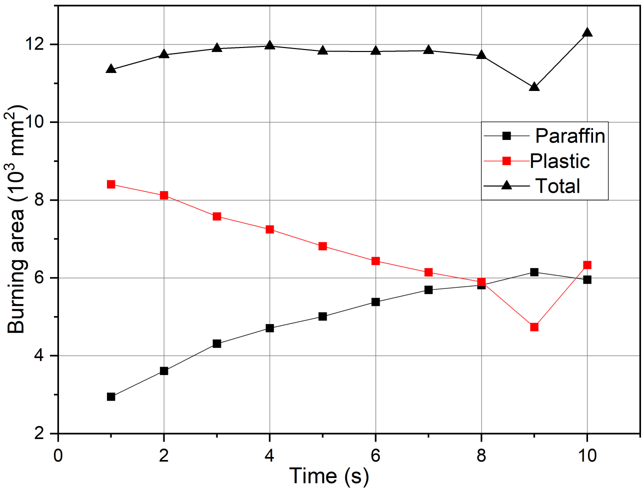

Figure 7. Burning area of the grain

Fig. 6 also shows high regression of paraffin to the plastic protective layer. The calculation showed that the front surface of plastic would burn similarly to the back cover because the mathematical model uses the same reference combustion area according to equation 9. In the real experiment, this is not exactly true. The variation of the combustion temperature along with the motor and the local direction of the flow influence the fuel regression. However, modern hybrid propulsion theory does not employ these processes in the regression rate law.

The most significant regression of the protective layer happens in the port of the grain, where the crossectional area is minimal and flow velocity maximal. Such behavior was also observed previously by the authors Azevedo *et al.* (2019).

As seen from Fig. 7, the protective area decreases in time, whereas the paraffin area grows, keeping the total practically constant and close to $12 \cdot 10^3$ mm^2. The regression rates, and consequently the mass flow rates of plastic and paraffin, were calculated by previously presented equations 3 - 12. Fig. 8 shows the mass flow rates of paraffin, plastic, and their total.

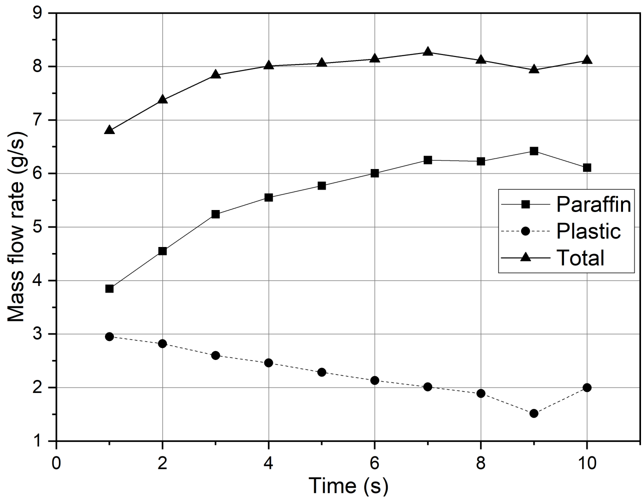

Figure 8. Mass flow rate of fuel components

The calculation results demonstrate that during the combustion process, the paraffin mass flow rate increases from approximately 4 g/s to 6 g/s, and the plastic mass flow rate drops from 3 g/s to 1.5 g/s. The total mass flow rate stabilizes after about 3 s from the motor start and stays almost constant during its operation, at near 8 g/s. Thus, according to the numerical calculations, the fuel flow remains nearly constant during the motor propulsion phase, satisfying the primary purpose of the current study.

In such a way, we have a complete set of boundary conditions to estimate the combustion process in the chamber of the solid-fuel ramjet engine: operating pressure (Table 2), oxidizer and fuel chemical composition and properties, propellants mass flow rates, the geometry of the combustion chamber, and the nozzle. As an assumption, the authors supposed that the liquid particles and droplets of fuel completely evaporated and chemically transformed in the combustion chamber due to its considerable volume (Fig. 2) and recirculation effect after the fuel grain.

The results of numerical calculation with CEA show the following. Due to the reduced O/F ratio (OF=3.72) to stoichiometric (OF_{stoich}=14.77), the temperature (Fig. 9) in the combustion chamber changes from 1100 K to 1060 K, ensuring a possibility of long (tenths of seconds) motor operations in the future. The reduced O/F ratio also prevents oxidation of the combustion chamber and burn-out of the nozzle. As a disadvantage of such a solution, the missile should carry an additional mass of fuel. However, extra fuel in a total vehicle weight balance is a relatively small price to mitigate combustion chamber burn-out.

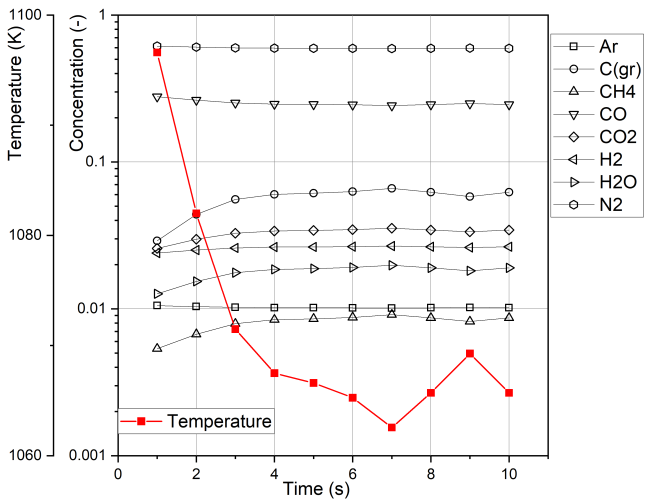

Figure 9. Temperature and species concentrations in the combustion chamber

Figure 9 also presents the distribution of the chemical species with considerable concentrations at the exit of the combustion chamber. As expected, the unburned nitrogen has a maximum mass concentration in the mixture $[N_2] \approx 59\%$. Due to the fuel-rich combustion, the second component is carbon monoxide $[CO] \approx 25\%$. The concentrations of other species are negligible, at most 6.2%. However, as known, they play an essential role in the chain reactions of hydrocarbon fuels.

4. CONCLUSIONS

This study allowed us to obtain in-depth knowledge regarding the paraffin-ABS 3D-printed grain regression in a solid-fuel ramjet engine. The initial simplified grain model allowed preliminary analytical calculation to get an optimized grain geometry. Next, implementing modeling of the grain regression led to studies related to increasing combustion efficiency and enable further investigation of more complex geometries in propulsion systems.

The authors have made the following conclusions.

1. According to the theoretical studies, 3D printing technology allows the fabrication of the fuel grains for a solid-fuel ramjet, pre-programmed for a specific regression, and mass flow rates profiles. Combining low-regression (ABS) and high-regression fuels (paraffin), it is possible to design a compact, short, single-port fuel grain with desired functional properties. A 3D printed, paraffin-filled fuel grain may have a thin external plastic protective layer that improves its storability and transportation properties.

2. The authors described and tested the methodology of composite fuel grain design. The numerical calculation showed satisfying uniformity of the fuel mass flow rate for 10 seconds combustion process, which further could be extended by increasing the fuel grain length. The regression rate of protective material was estimated from 0.25 to 0.49 mm/s and paraffin from 1.14 to 1.38 mm/s. The mass flow rate stabilizes during the first 3 seconds from the motor propulsion start and stays nearly constant during operation. Low O/F ratio of the mixture to stoichiometric reduces the combustion chamber temperature to 1100 K and prevents motor overheating and erosion.

3. The detailed analysis of the combustion products plays an essential role in profiling the efficient motor nozzle.

The authors propose to continue the current study making CFD simulations and experimental testing of the fuel regression to prove the concept proposed in current work. Future grain designs can focus on the search of different thrust profiles using 3D printed technology. The study on the combustion efficiency improvement, implementing 3D-printed recirculation zones (diaphragms and flame holders) in the combustion chamber may also improve overall motor performance.

5. ACKNOWLEDGEMENTS

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