Hybrid Engines. A new approach

A.M. Gubertov, V. V. Mironov, N.N. Volkov, L.I. Volkova, R.G. Gollender, S.M. Tsatsuev, A.A. Zhemejcev, V.A. Popov,
“Keldysh Research Center”, Russia.

Abstract

Some approaches to HRE with minimal relative lengthening development are viewed in this report. Fuel blocks configurations with plane and radial-slot canals are suggested. Ways of combustion intensification and combustion efficiency increasing by flow hydrodynamics and boundary layer control are expounded.

1. Introduction

Hybrid engines are used to be an alternative to LRE and SFRE traditionally, because they grade weaknesses of both types and has high energetic characteristics[1, 2]. They inherited construction simplicity, high fuel density and lower price from SFRE. High thrust specific impulse (close to LRE on oxygen-hydrocarbon fuels), multiple launchings ability and thrust control from LRE. Also attraction of HRE is conditioned by their explosion safety and relative construction simplicity. As a result HRE are considered to be promising engines for deep space flights, space tourism and other commercial applications last years[3,4]. One of primary questions in HRE application is choice of solid fuel blocks configuration providing stable energetic characteristics coupled with high fuel combustion efficiency. HRE combustion chambers have relatively large specific elongation (L/D = 5÷15) (fig. 1a,1b) in most cases to provide high combustion efficiency and necessary combustion surface. Such compositions can provide required thrust-consumption characteristics as has been shown in experiments[5].

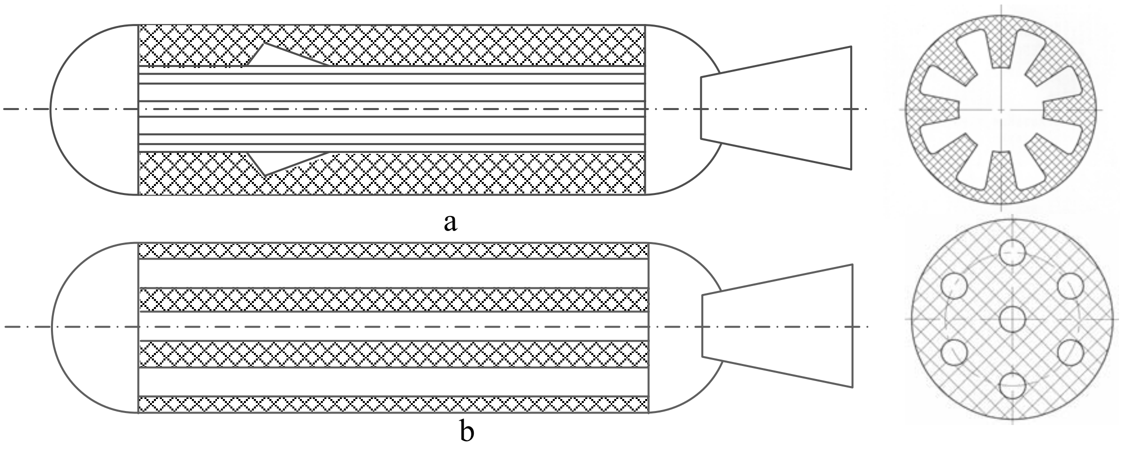


Figure 1: HRD with big elongation examples.

2. Problem analysis and it’s solution

Different fuel blocks configurations analysis show that attempts to provide high enough fuel volume population of combustion chamber cause two problems as a rule. They are:

- pressure (thrust) curve has depressing rate (fig 2). Pressure drops when engine operates long enough (it can be unacceptable, and from the point of view of providing given engine thrust and in the view of combustion stability and combustion efficiency in view of large free volumes in chamber);
- free (not connected to frame) fuel odds can appear in multi canal block configurations (fig 1b). It caused by gasification fronts closure as shown on fig 3.

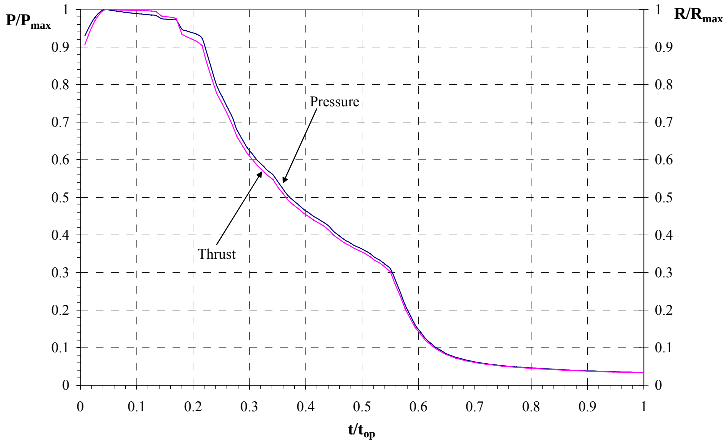


Figure 2: Pressure and thrust curves.

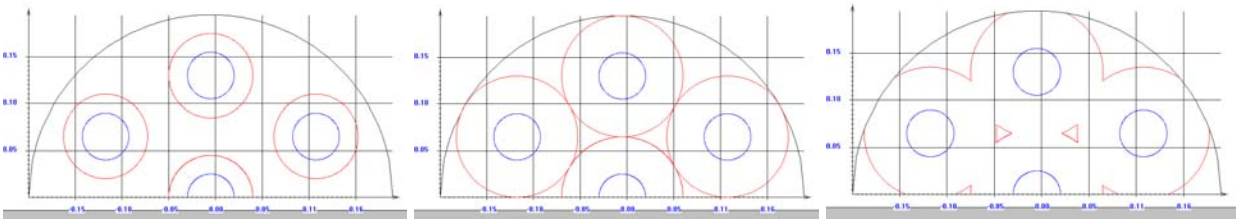
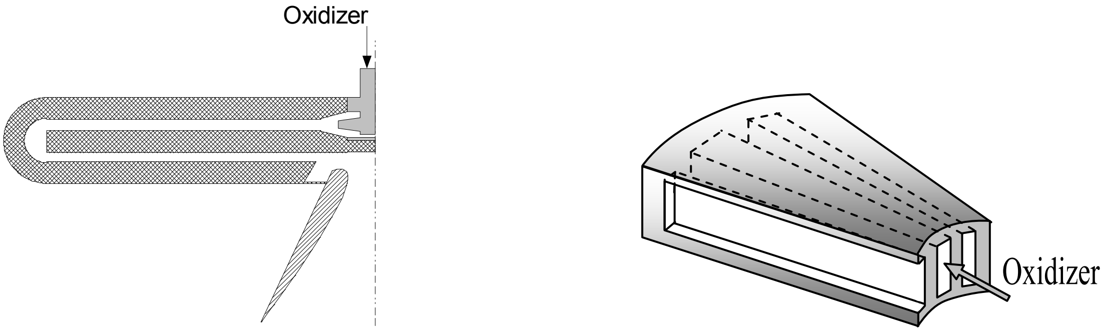


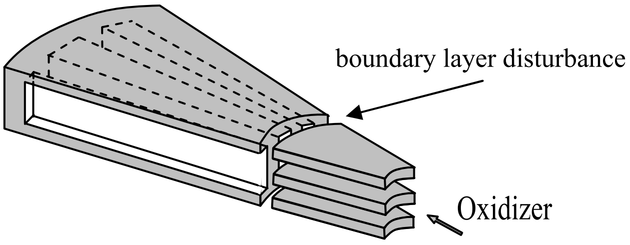
Figure 3: Burn-out fuel block profile and free oozes formation.

Both problems can be solved by special canal profiling, oxidizer consumption control, including of special strengthen elements (grates) etc. However it is needed to have HRE with minimal specific elongation (L/D ≤ 1) with required energetic characteristics conservation and maximal mass perfection in many cases for means of interorbital transportation as example. This problem demands to provide bigger area of fuel combustion surface keeping maximal combustion efficiency. It’s natural to suggest changing fuel blocks with canals parallel to chamber and nozzle on canals perpendicular to them (fig 4a, 4b, 4c).



a) Horizontal slots

b) Vertical slots



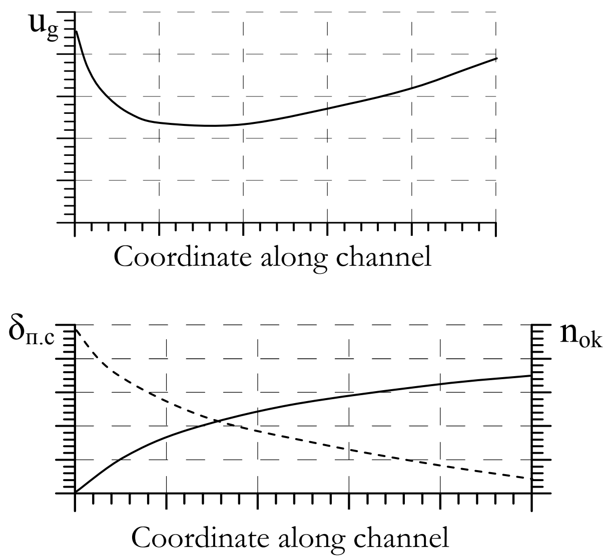
c) Combination of vertical and horizontal slots

Figure 4: Fuel block configuration with nozzle perpendicular canals schemas.

For example charge with flat canals (fig 4a) provides bigger area of fuel combustion surface while minimal specific elongation. Still questions connected to fuel combustion effectiveness and evenness remain as earlier because flow density in canal section is inversely to its radius. And so charge burning near center and on periphery is strongly uneven. This fact demands to pay maximum attention to canal profiling. Radial-slot canal fuel configuration is examined as alternative (fig 1b). Higher flow density and near constant combustion area can be achieved in this case.

Different ways of combustion intensification can be examined to provide combustion effectiveness. Their local applying can provide even charge combustion. Different factors influence on combustion rate differently:

- flow density and pressure increasing increase rate;
- boundary layer thickness increasing and decreasing of oxidizer concentration along canal decrease rate.



Channel form changing

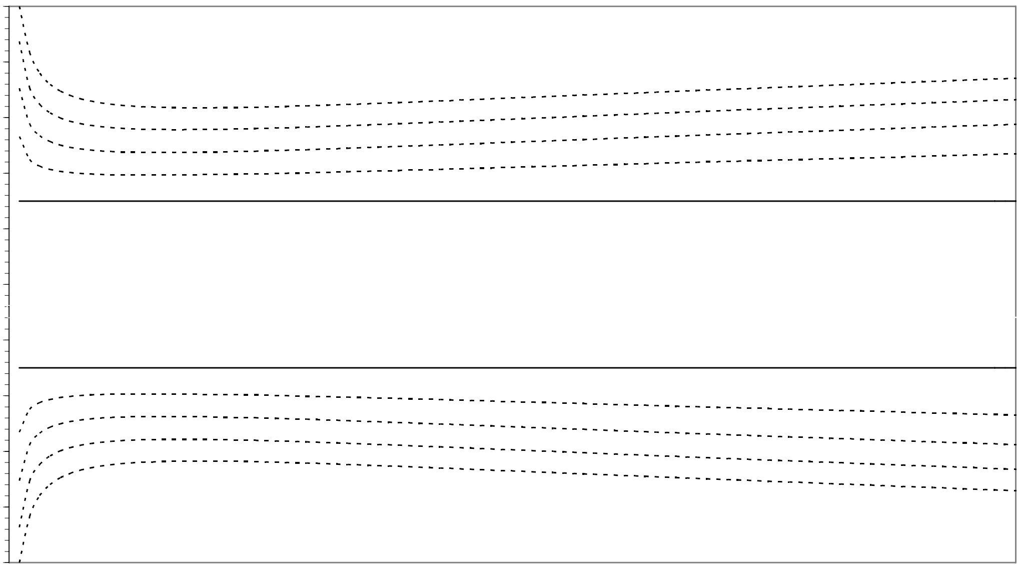


Figure 5: Different factors influence on charge burn out.

Whole of mentioned factors cause unevenness in combustion rate. It is shown on fig 5 schematically. Non-monotony appears and evaluate in time in proportion as canal area increases. It is connected with all determining factors changes in time as well as with such factors as radiation heat flow, boundary layers closure (or its absence), local combustion breakaway zones, oxidizer consumption changing, oxidizer and fuel temperature changing. Charge profiling allows influencing on flow density along canal and around its periphery. Also it's possible to influence on boundary layer development. Local ledges and section profile changes destroying boundary layer can be provisioned for example. Typical example of boundary layer control is shown on fig 6. Fuel block consists of several sections and canals in different sections are displaced in this example. Boundary layer control effect is that of as boundary layer, which thickness reaches $\delta \sim \frac{1}{2}h$ at the end of section, destroys and begin to develop in the next section again when flow pass from one section to another. Thus convective thermal and diffusion flows were intensified. Combustion and gasification rate has been increased proportionally.

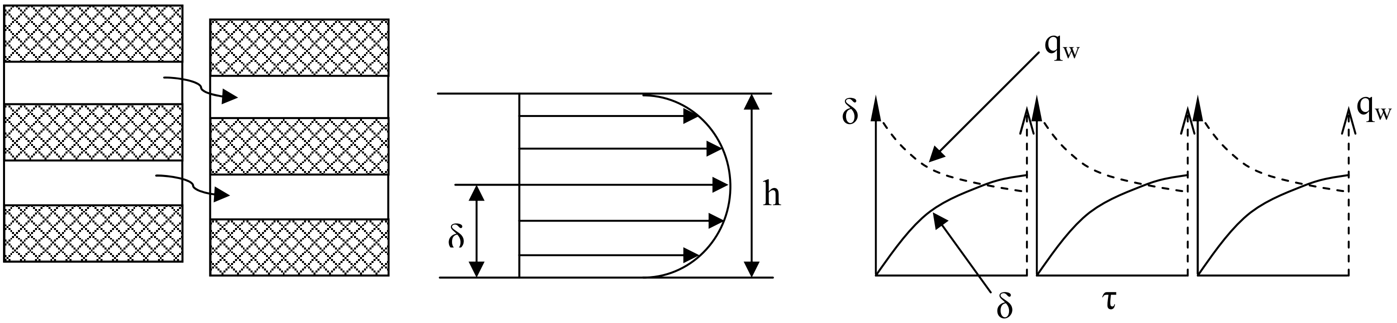


Figure 6: Boundary layer destruction schema.

Combination of axis and radial slots configuration combined with block dividing for boundary layer control allow considering of relatively short HRE chambers. Such configuration's scheme in section is represented on fig 7.

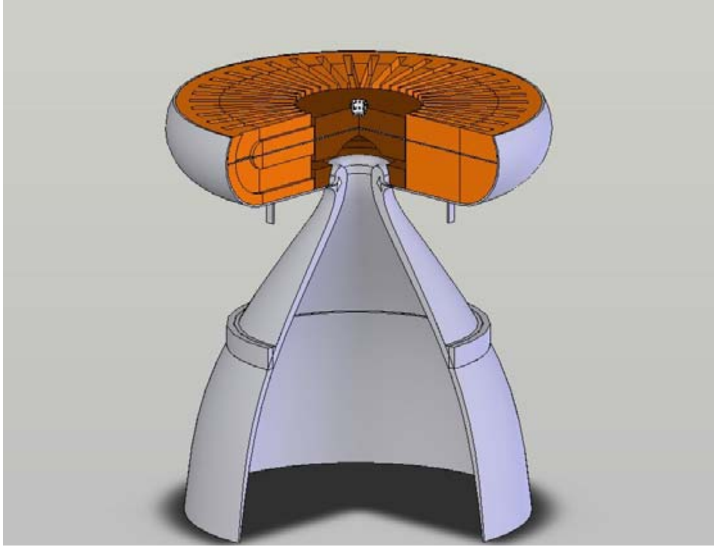


Figure 7: HRE chamber with small elongation schema.

Oxidizer supply is realized by cylindrical head in the top part of chamber in this scheme. Oxidizer flows through inner fuel block radial slots and then through outer block axis slots. Afterwards it moves back through axis slots in bottom part of outer block chamber and to the nozzle through radial slots.

Boundary layer, developing in individual canals, destroys while gas flows from one section to another; heat-mass transfer intensification takes place in such a way. Jets collision takes place forward of nozzle when gas flows in the inner chamber compass. It causes additional turbulization and fuel gasification products after-burning increasing the combustion effectiveness.

The suggested schema has considerable freedom degree in addition to boundary layer control ability. It allows changing of block size, individual slot length and proportions, their form, orientation and number. By this means gasification surface area can be varied providing its considerable increasing in time and compensating combustion speed decreasing due to slot net area increasing and gas flow density decreasing.

It's naturally that fuel block form choice is determined by wide set of rational demands and limits. However, only one condition will be considered in the context of this report. This condition is given pressure on time dependency providing. It will be written by the following way:

$$\frac{dP}{dt} = \text{const} \tag{1}$$

Constant pressure in the chamber is provided when $const = 0$. Regressive curve with finite engine operating time τ_{max} (fig 8) is provided if const < 0.

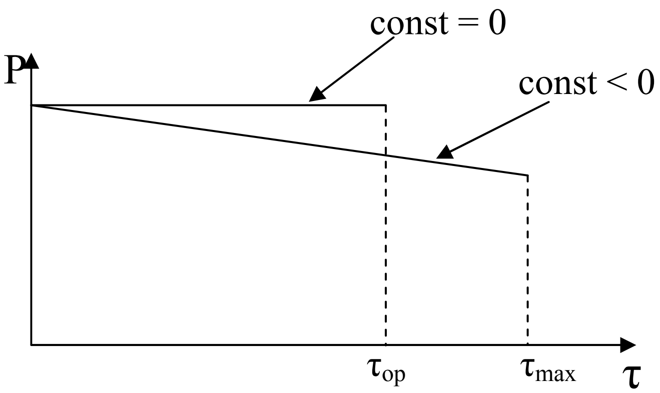


Figure 8.

To find out block sizes meeting condition (1) gasification surface area can be written by the following way:

$$S_g = \sum_i \int_0^{L_{0i}} N_i \left[P_{i0} + 8 \cdot \tau \cdot u_0(x) \right] dx \tag{2}$$

where N_i – slot number in section *i*

P_{i0} – slot *i* initial perimeter

x – coordinate, counted along the slot *i*

L_{0i} – slot *i* initial length

τ – current gasification time

$u_0(x)$ – gasification rate, depending on coordinate and time.

Summation is carried out in all blocks. Fuel of ρ_g density consumption, taking in account (2) can be presented as:

$$G_g = \rho_g \sum_i \int_0^{L_{0i}} N_i \left[P_{i0} + 8 \cdot \tau \cdot u_0(x) \right] u_0(x) dx \tag{3}$$

Condition (1) (if $const = 0$) when nozzle throat is constant is equivalent to

$$\frac{dG}{d\tau} = 0.$$

Local medium gas mixture flow density can be written as:

$$\rho u(l, \tau) = \frac{G_0 + \rho_g \sum_i \int_0^{l} N_i \left[P_{i0} + 8 \cdot \tau \cdot u_0(x) \right] u_0(x) dx}{N_i (h_{i0} + 2 \cdot u_0 \cdot \tau)(d_{i0} + 2 \cdot u_0 \cdot \tau)} \tag{4}$$

where h_{i0}, d_{i0} are initial height and width of an individual slot, if integration takes place not along whole canal length, but till some length $l < L_i$.

It's possible to use one of semi empiric ratios, defining local gasification rate $u_0(l,\tau)$ to formally close the task. The next formula can be considered for polymeric materials thermo destruction conditions for example.

$$\rho_g u_0(l,\tau) = A\cdot\left[\rho u(l,\tau)\right]^n (\mathrm{Re}_l)^{-m}\,\frac{T_e - T_w}{H_w} \tag{5}$$

where $A \approx 0{,}03$ – experimental constant,

$m \approx -0{,}2$ – experimental constant, for turbulent conditions of gas mixture flow,

T_e – combustion temperature,

T_w, H_w – fuel gasification temperature and enthalpy.

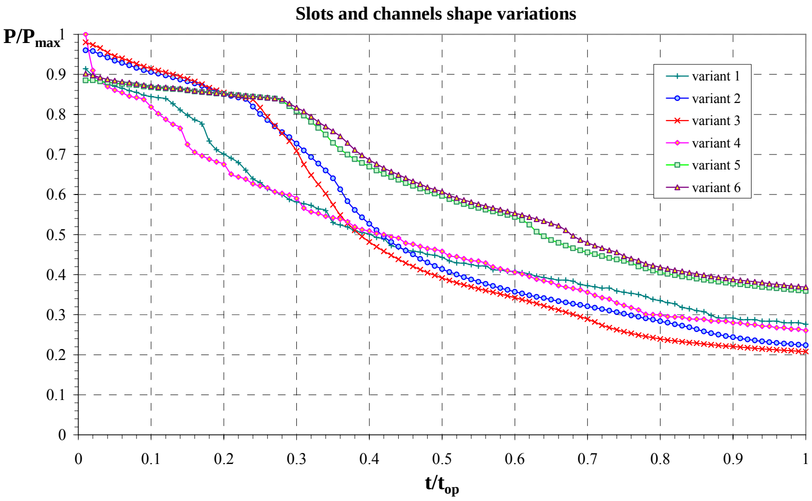


Figure 9: Pressure-time history

It is significant that formula (5) describes characteristic conditions of non-monotone u_0 changes along the canal length, which were shown on fig 5.

2. Results

Equation system (1-5) formalizes the task of choosing the values of d_{i0}, h_{i0}, L_{0i} and slots number N_i in blocks, providing condition (1) fulfillment.

Assigned task salvation example applying to block form shown on fig 7 represented on fig 9. Parametric calculation results show that required gasified fuel consumption can be provided by corresponding geometric parameters choice. Thus given dependency $P(\tau)$ will be observed.

References

[1] Гибридные ракетные двигатели: преимущества и перспективы. Губертов А.М., Голлендер Р.Г., Миронов В.В., Волков Н.Н., Давыденко Н.А. Aerospace Science and Technology, 2005.
[2] Гибридные ракетные топлива: возможности применения и преимущества. Авторы: Губертов А.М., Миронов В.В., Голлендер Р.Г., Жемейцев А.А., доклад на 5-й международной конференции «Авиация и космонавтика-2006», Москва.
[3] NRO contracts fuel hybrid propulsion development. Warwick Graham. Flight Int., 2000. 160, №4741, p.25.
[4] Hot rod to space. Wall Robert. Aviat. Week and Space Technol. 2003. 159, №12, pp. 48-50,53.
[5] Экспериментальные исследования характеристик демонстрационного образца гибридного ракетного двигателя (ДГРД). Волков Н.Н., Голлендер Р.Г., Давыденко Н.А. и др., Авиакосмическая техника и технология №3 2001

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