PROPULSION PHYSICS: THE KEY PROBLEMS IN THE FIELD OF ENGINES OF LAUNCH VEHICLES AND SPACECRAFT

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The basic approaches to the solution of the key problems originating at creation of propulsion systems of launches and space vehicles of a new generation are observed. The main attention is given to liquid-propellant rocket engines (LRE) of launch vehicles and accelerating stages, and also to electrical rocket engines (ERE) with the closed electron drift for space vehicles.

1. Introduction

Key tendencies of modernization and development of new types of rocket engines (liquid, solid, hybrid) are provision of their high reliability, decreasing of manufacturing and experimental validation costs, while keeping optimal energy and weight-dimension characteristics. In particular, for reaching of engines reliability for the oxidizer staged combustion cycles various ways of guard for the fluid-flow and gas oxidizer channel are used: prohibiting of burn initiators, usage of special alloys and covers, and the fine control by operational modes which is not admitting excess of "threshold" parameters. Creation of an emergency protection system (health monitoring system) in aggregate with a reserved propulsion system is observed as the factor of safety raise of the rocket system, but not the absolute warranty engine operation.

Usage of new low-cost and ecologically pure propellants is observed as one of paths of perfecting a liquid rocket engine (LRE). Methane application as rocket fuel will allow to use the staged combustion cycles LRE both with oxidizer-rich, and fuel-rich gas generation. Experimental study of sootformation at methane fuel gasgeneration, cokeformation and chilling properties of methane allows obtaining real data for usage in designs of perspective engines. Usage of new ecologically pure and safe highly energetic liquid, solid and hybrid propellants instead of toxic ones, will allow securing human activity as on board, and at land maintenance, to reduce level of pollution in a near space. Wide application of advanced metals (aluminum-lithium alloys, intermetallic compounds) and non-metal composite materials (for combustion chambers, nozzles, high altitude nozzle orifices with altering geometry, fuel tanks and high pressure cylinders, gas leads, load-bearing elements of bracing, girders and transfer modules) is also of great actuality.

Hall-effect thrusters (HET) nowadays are among most demanded plasma thrusters. Thrusters of this type are successfully applied on Russian spacecrafts (SC) since 1982. Normal application of Russian SPT-100 thrusters on serial western satellites started in 2004.

Further improvement of HETs is in close connection with tendencies of modern SC development. These tendencies define necessity of new generation HETs development with higher specific impulse value (up to 2000…3000 s) and ability of long-term operation in wide power range.

Key problems occurring during the new HET development are considered in the frame of this work, without pretending to solution of all HET problems. The considered problems are optimization of magnetic field configuration and provision of long fire lifetime, including search for the new materials and development of reliable methodic for life test duration decrease.

Main approaches to solutions of the mentioned problems are illustrated in the report. Most of these approaches are reported in detail in monographs issued by authors teams of Keldysh Center specialists in recent years /1, 2, 3, 4/.

2. Liquid-propellant rocket engines

Ignition resistance of structural materials in a hot oxidizer passage

The created engines RD-171/180/191 have the highest parameters of perfection for engines of the given type. The prospect of utilize of these engines like reusable is tempting idea, as there is a positive experience of multiple operation of engine RD-170 on the test-bench (17 resources). One of the questions of support of resource and safety is the problem of materials ignition in the oxidizer gas passages.

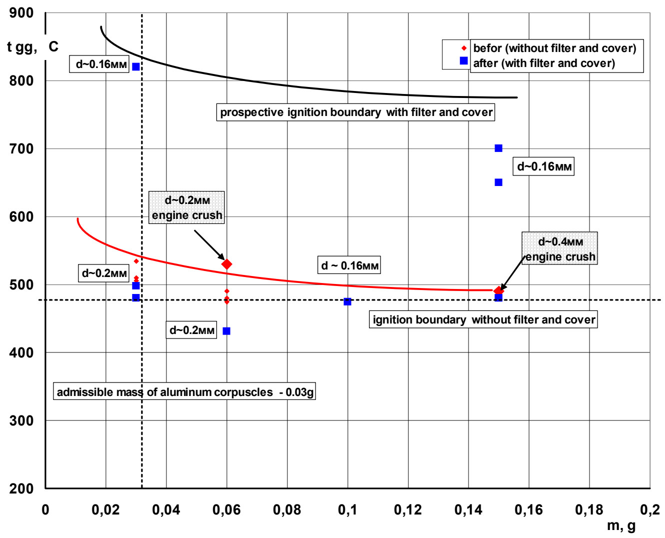


Fig.1. Boundaries of ignition in an oxidizer

The researches conducted in Keldysh Center and NPO Energomash, have confirmed efficiency of the complex of ignition protective measures for used materials at effect of aluminum alloy corpuscles up to the temperatures of a generator gas limited by high-temperature strength of structural materials (marginal) 750÷800°C (at regular temperature of oxidizer gas at level 550÷600°C). Such measures are installation of special filters on an engine entry on the fuel and oxidizer pipelines, special cleaning of propellant tanks, usage of nickel alloys and covers of the turbine rotor blade, application of covers in the gas passage. Ignitions of the gas path of a regular construction do not occur till 1997.

The attained levels on temperature of a generator gas depending on total quantity of the injected corpuscles of aluminum are resulted on fig. 1. Originally ignition occurred at temperature 490÷590°C in the area restricted by the lower curve. After implementationof of measures the prospective boundary line has attained level 800°C and even specially injected corpuscles did not ignite a surface of channels (the size of corpuscles is indicated in squares).

Designed ways can be applied to all engines, taking into account their dimensions that will allow to refuse redundant measures and to spare the cost of the engine without lowering of its reserve and reliability.

For the reusable engine, it is necessary to supply stability of performances at a specified quantity of usages, i.e. in conditions of lowcyclical loads. LRE units are exposed to the mechanical and thermal loads linked with processes of start, activity on a regime and cutoffs (from cryogenic temperatures at chilldown to temperatures of working process in the gas generator and the combustion chamber). At cyclic loadings the processes typical for the material fatigue take place, when at loading and after load removal residual stresses and remainder (plastic) strains occur, in a limit leading to a cracks initiation (see fig. 2).

Fig. 2. The sample of a material. A lateral surface with a flaw after 41 cycles of trials

In Keldysh Center researches are carried out for definition of limiting number of loading cycles for structural materials of LRE units and aggregates with usage of techniques of a numerical analysis nonstationary thermal and a thermostate of stress and mathematical models of plastic behavior of materials. At experimental researches on models the intense-deformed state of structural materials analogous to its state in a regular construction of the LRE aggregate is realised. Calculations testify to large reserves on number of cycles before loss of strength in the form of crack that does not contradict available experimental data on longevity of TPU and chambers of RD-170.

Micrographic research of a surface of a flaw (fig. 3) is conducted on a scanning electronic microscope. The similar relief matches to a relief of thermoshock flaws in heat resisting nickel alloys, for example, thermoshock flaws in samples.

The designed technique of lowcyclical strength research and the endurance failure forecast will allow to use calculative methods for the forecast of resource LRE aggregates.

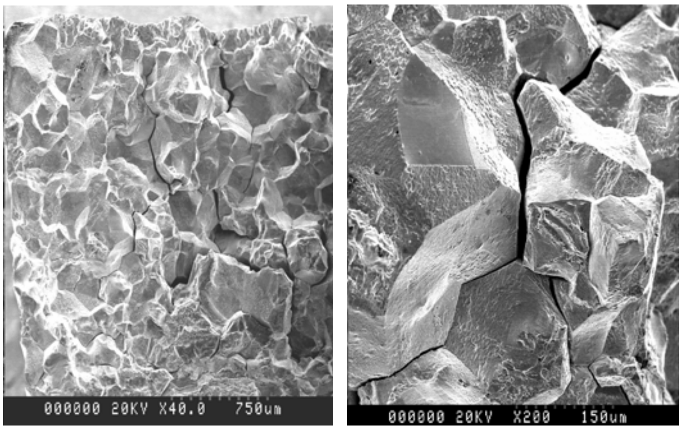


Fig.3.

Methane fuel for a LRE

An introduction of low-cost ecological fuels will allow reducing cost of engines development. Even at usage of the pure methane received by removal of impurity from natural gas, its cost will not exceed kerosene cost. Taking an intermediate place on assemblage of parameters between kerosene and hydrogen, methane will allow receiving increase of power performances, at the expense of higher specific impulse, to raise reserves on cooling, owing to the best, than for kerosene chilling ability. Besides, methane allows designing LRE cycles as with oxidizer rich, and fueling rich gas generator.

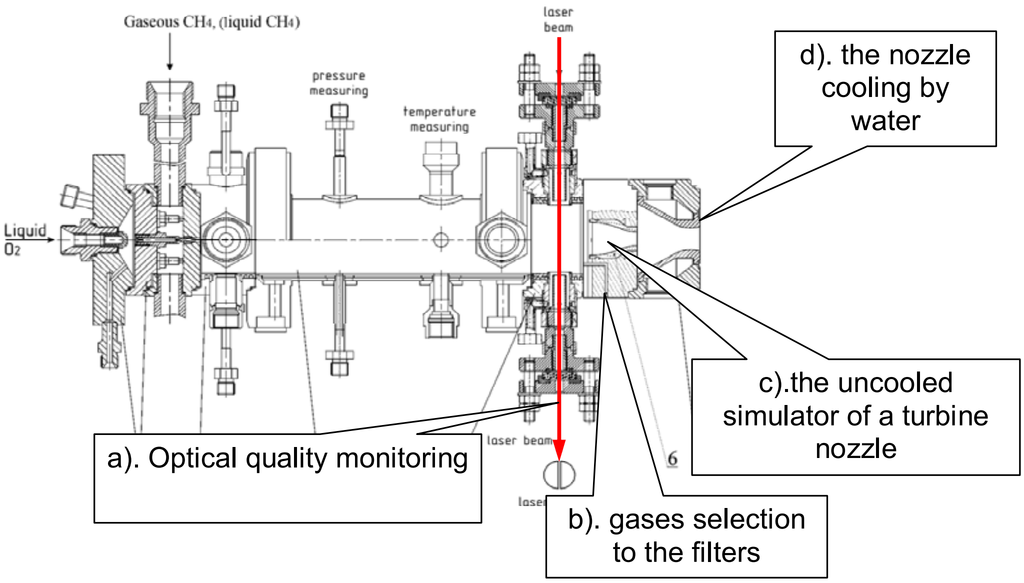


Fig. 4. The modelling gas generator and ways of of combustion products research.

Thus there is a question on catalytic interacting of fuel rich gas products with a wall material. Fuel rich gas of the model gas generator (fig. 4) was researched by an optical method – the emission power after passing in medium (a) was measured; gas samples on special filters (b) were taken; the surface uncooled (c) and cooled (d) insertions was researched. Experimental researches have shown, that in the absence of soot in a generator gas was possible its derivation on hot surfaces, especially in stagnation zones, owing to such gears, as pyrolysis (see fig. 5,). However rate of onset is small and for expandable engines the given problem does not represent troubling. For engines of durable resource special researches as on study of origination, increase and interacting with a material, and in a search area of special materials and the covers reducing catalytic erosion are carried on.

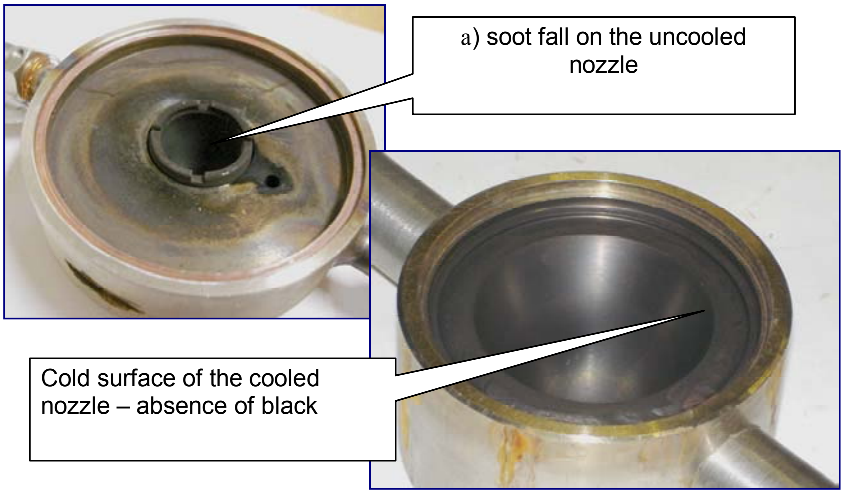


Fig. 5. Surfaces of an uncooled and cooled insertion after tests.

Engine health monitoring and emergency protection

The engine health monitoring and creation of effective protection emergency system represents the independent problem linked as with the hardware (a structure of sensors, selection of diagnostic parameters), and logic of decision making (algorithms of matching of parameters, interacting with a control system of a launcher, absence of a maloperation). The analysis of unnominal situations has shown, that there are crashes with such small time of development, that existing means of the engine shutdown cannot parry them. For example, ignition and corrupting of the oxygen pump in engines of large thrust occurs for 0.02 - 0.06 s, while a total time of registration by the sensor, decision making, valve operation and pressure drop after shutdown several times above. Therefore, presence of emergency protection system does not reduce demands to the engine reliability and only is addition in the common system of safety. Selection of diagnostic parameters allows to determine the most sensitive to change of a regime mode.

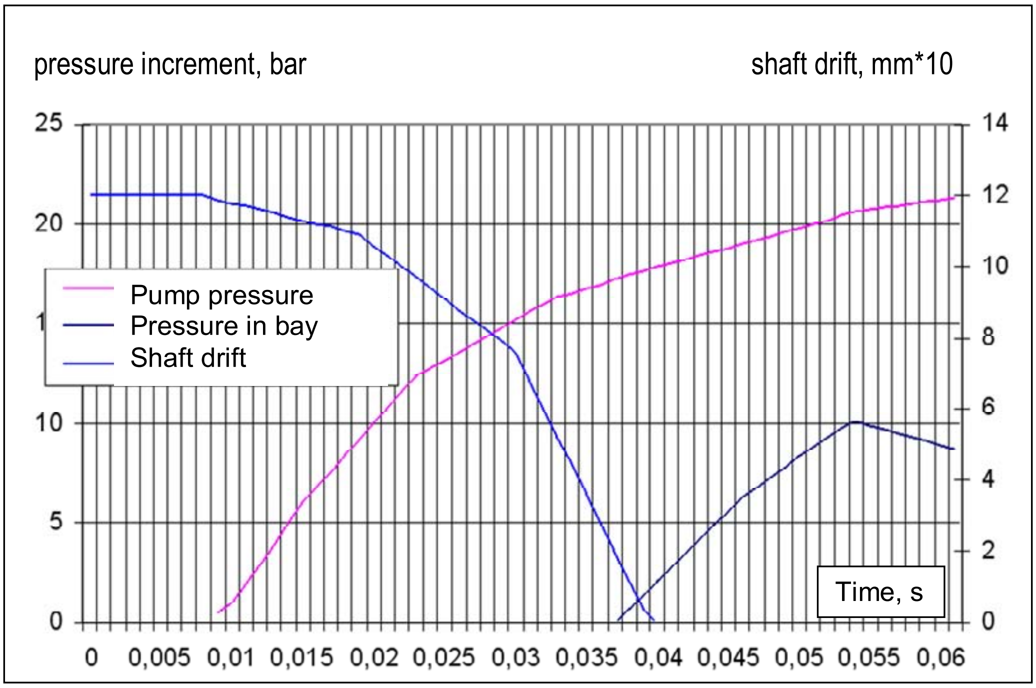


Fig. 6. Creation of diagnostic tags.

So to conventional parameters as temperature, pressure, pressure pulsations, it is possible to add, for example, shaft TPU drift, signaling about an unbalance of the pressures (forces), being to developments of the originated defect or even the crash beginning. On fig. 6 the response of diagnostic parameter «shaft drift» on ignition in a channel of the oxygen pump is presented. Nevertheless, this parameter is inertia and reacts already to defect development, but researches in Keldysh Center have shown, that usage of the inductive pressure sensor registering fast varyingparametres with frequency of interrogation more 10000 Hz and digital registration is possible, at their installation in critical locations of aggregates.

Application of nonmetallic composite materials

One of perspective trends of perfecting engines is application of nonmetallic composite materials (CM) for manufacture of their heat-stressed units and aggregates. CM possess the complex unique thermal-physical, thermochemical and thermal-erosive properties, and substitution of metals traditionally used in a LRE and alloys on lightweight CM supplies significant, to 30-40 % decrease of weight of constructions. Most effectively CM can be applied to manufacture of "hot" constructions, including nozzles and nozzle LRE extantions of large expansion ratios.

The first positive experience of application of nozzles of CM are known – LRE for upper stage DMSL, RL10B2, Vinci. Thin-walled shaped shells of nozzles of these engines are made from carbon-carbon which are in addition protected from oxidation by the carbide covers. Experimental optimisation of these engines has confirmed functionability, efficiency and reliability of constructions. The LRE with the nozzle from the CM which maximum temperature constitutes 1400-1500K, is successfully operated since 2004 (12 flight tests as a part of the launcher Zenith SL).

Now application of nozzles and nozzle extantions of carbon-carbon materials is observed as the most effective engineering solution for variety perspective LRE:

- For cryogenic a LRE: Vinci (ESA), oxygen-hydrogen 7-10 t thrust LRE for perspectiv accelerating stages (Russia);
- For oxygen-kerosene LRE of the first and second stages of the perspective launchers:
  - stationary nozzles of large expansion ratios;
  - telescopic nozzles with "cold" shift;
  - telescopic nozzles with "hot" shift at operation engine.

In most cases the most effective solutions (from the point of view of the minimum weight of the nozzle and the maximum specific impulse of thrust) are attained at enough high levels of temperatures of the nozzles attaining 1900-2000K.

The success of similar developments is linked to the solution of some technological problems.

Support of chemical and erosive durability of materials of nozzles, first of all to chemically active components of products of combustion (H_2O, CO_2, O_2, About, H_2, H, …) for minimization or complete exclusion of ablation (ablation) of a wall.

The solution of this problem is founded on:

- the solution of materials technology problems (reinforcement structure, matrix material, additional covers);
- computational-parametrical researches of processes of interacting of multicomponent high-temperature medium with materials and covers, including the interfaced simulation heat-mass exchange and chemical kinetics;
- experimental researches which are conducted on laboratory-scale device (first of all for definition of kinetic constants of thermochemical interacting) and on bench small-size a LRE with thrust 0,5-2 hardware which are completed with nozzles from composite materials.

The executed researches have shown that the most perspective materials for nozzles and LRE extantions are carbon-ceramic materials with a combined matrix on the basis of SiC, and also carbon-carbon materials with protective multilayer antioxidative covers on the basis of SiC and SiN.

Thermalchemical interacting of these materials is presented by system of the rate equation corresponding to a set homogeneous and heterogeneous reactions (see Table.1)

Table 1.

Material		Components		Interacting products
Si		O_2, O		SiO - gas
SiC	+	H_2O, OH	$\Rightarrow$	SiO_2 – solid, liquid
SiN		CO_2		CO
C_{Graph}		H_2, H		CO_2
$C_{pyrograph}$				N_2, NO_x

Speeds of individual responses essentially depend on temperature (especially at T = 1600-2000K) and pressures (especially at rather low P <10 kPa).

Duration of protective properties of covers, especially on the basis of SiC, depends also on such factors, as

- implementation of "fast" or "slow" kinetics of oxidation of silicon to SiO and SiO_2;
- creations of barrier film SiO_2, its motions and transpiration, and also interacting SiO_2 with the carbon basis of a material.

For support of leak resistance and strength of junctions of units of the nozzles made of heterogeneous composite and metal materials the solution of a problem of their compatibility on temperatures, chemical interacting is necessary.

The solution of this problem is attained

- application of materials with the specified levels thermal physical and physicomechanical properties (for example at the expense of special selection of cycles of CM creation);
- the detailed interfaced simulation of the thermal and is intense-deformed state of constructions, taking into account anisotropy of properties of materials, their relation to temperature and possible change on a time owing to a leakage of active thermochemical processes, features of contact interactings, criteria of corrupting on micro both macrolevels and other facts.

Reliability of computational-theoretical results, including margins of safety and spreads of properties, are confirmed during special experimental researches.

For telescopic nozzles and extantions a key problem is definition and optimization of the passing and reacting against loads acting on the nozzle which assemblage determines shift dynamics, demands to shift devices, to physicomechanical properties of materials, and as a result, weight-dimension performances of a construction. Level of the forces acting on mounting extantion and their nature are generally various:

- external air forces of pressure, F_{p1}, resistances F_1 and friction F_2,
- forces of pressure of an affixed stream of products of combustion F_{p2},
- frictional forceF_3,
- the inertia forcesF_{nx}, F_{ny},
- frictional force in mechanical units of attachment F_4,
- forces of act of the actuator F_5.

Simulation of loads and shift dynamics implements first of all on the basis of the interfaced calculation of external and internal fluid dynamics taking into account change on a time of a configuration of calculation area.

Complex gas-dynamic calculation is under construction on the basis of a number of the physical and mathematical models considering:

- turbulent character of flow of multicomponent gas streams;
- strong is viscous-nonviscous interacting of streams with derivation of developed fly-off allowed bands;
- origination of pressure pulsation owing to development of nonstationarity flows effects.

Calculation simulation is made with usage of specially designed rapid-transfer algorithms in which basis the modified method of "large corpuscles» lies.

Specially executed experimental researches have shown, that accuracy of a numerical simulation is high enough, in particular, lapses of definition axial gas-dynamic loads do not exceed 5 %, and side loads – 10 %.

3. Electric propulsion based on Hall effect thrusters

Keldysh Center's research program in the field of Electric Propulsion (EP) is oriented for solutions of almost all key problems concerned with development of new generation thrusters. In particular the numerical models describing the plasma dynamics in the discharge with crossed ExB-fields are developing, the problem of optimization of magnetic field configuration is investigating, search for new perspective ceramic materials composed of the wall of discharge channel is conducting, reliable methodic for life test duration decrease are developing and experimental equipment for probe and spectroscopic plasma diagnostics inside the channel and in plasma plume are creating.

Optimization of the magnetic field topology. In the course of numerical investigations of the discharge processes in the Hall Effect Thrusters (HET) using fully kinetic 2D3V-model [5] the spatial distributions of the plasma parameters were obtained. Comparing the results of numerical simulations with experimental data enabled to reveal a correlation between the spatial location of the region with maximal plasma density (the so called "ionization core") and configuration of the magnetic field. It was discovered that both radial and axial locations of the ionization core coincide with the location of the maximum of a function $F = \left|\vec{B} \times \nabla\left|\vec{B}\right|\right| / \left|\vec{B}\right|$, which is the projection of the gradient of magnetic field absolute value onto the normal to the local magnetic field line. As an example the contour lines of plasma density obtained in the kinetic model (a) and isolines of the function F (b) for HET with discharge power 200W are shown in fig. 7. Analogous calculations for a set of HET with different discharge power revealed the same regularity.

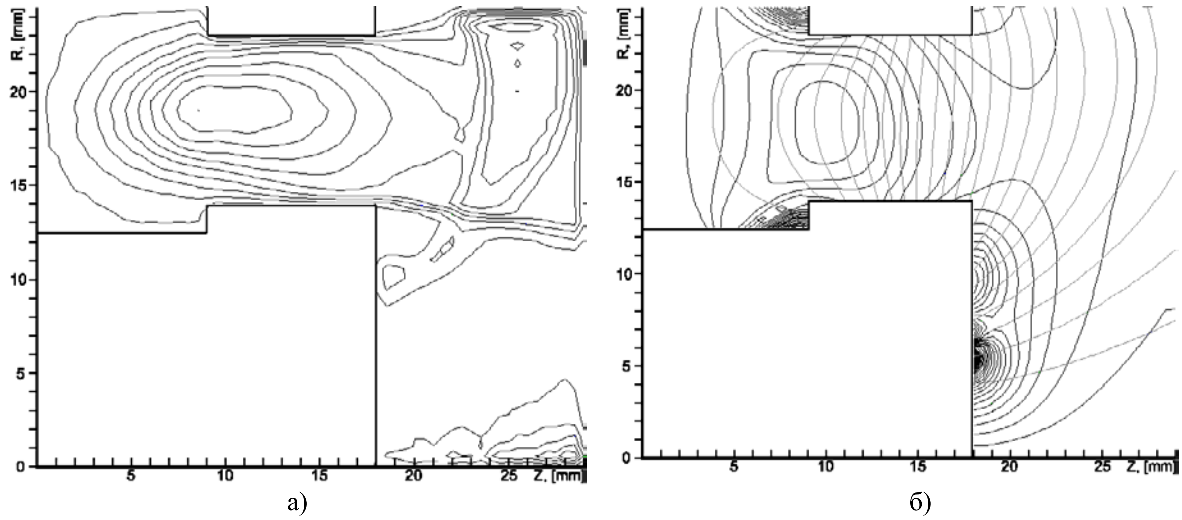


Fig. 7. The contour lines of plasma density (a) and isolines of the function F (b)

The results of numerical modelling have served as an incentive for conducting of a complex of systematic investigations of the magnetic field influence on the HET performance. For that two HET laboratory models were created (with discharge power 900 W and 2 kW) meant for discharge voltage increase up to 1000 V with design allowing changing of the axial and radial location of the maximum of function F and also shape of magnetic flux lines by adjusting of the current ratios in the magnetic coils. The location of the ionization core was investigated using near-wall Langmuir probes that were placed in the external ceramic wall of the discharge channel. A lot of experiments were conducted in which the influence of the magnetic field parameters on the thrust, specific impulse, thrust efficiency, gas utilization efficiency, ion to electron current ratio, average energy of ions and also length and position of the acceleration layer.

Generalization of the obtained experimental data enabled to formulate the quantitative criterion [6,7], characterizing magnetic field from the point of view of the effectiveness of electron keeping ihn the ionization core. The function $\Omega^*(\vec{r})$ was introduced into consideration, which describes the probability of the movement of electrons in the ionization region without collisions with discharge channel walls, and the criterion is the average value of the function $\Omega^*(\vec{r})$ in the region occupied by discharge, calculated with weighting function F: $G^* = \int F(\vec{r})\Omega^*(\vec{r})d\vec{r} \Big/ \int F(\vec{r})d\vec{r}$. The value G^* is dimensionless and allows comparing the magnetic systems of thrusters having different sizes and discharge channel design peculiarities. Calculations of the G^* values for some operational regimes of the HET laboratory model with power 900 W showed the presence of correlation between this criterion and thrust efficiency (Fig. 8).

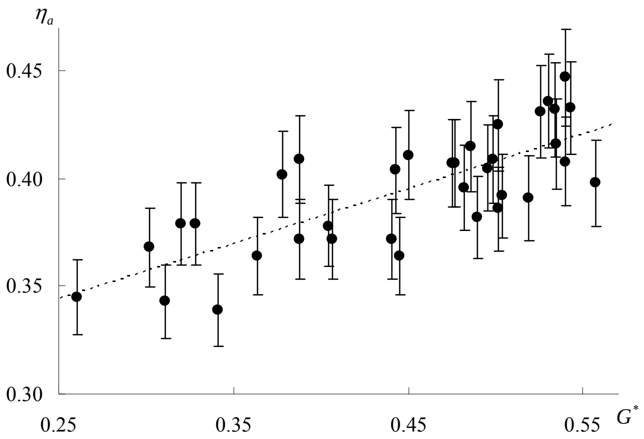


Fig. 8. The anode thrust efficiency as function of the parameter G^* for HET with nominal power of 900 W.

Methodic of shortened life tests. The problem of output parameters confirmation and total lifetime determination is becoming more complicated with increase of HET operation time. With the increase of firing life tests duration to 5÷10 thousands of hours temporal and material expenses on estimation and confirmation of lifetime become very essential. That is why questions of EP lifetime prediction model development and searching for the ways experiments quantity duration decrease become extremely actual. The main reason limiting HET lifetime is discharge channel walls erosion, which occurs due to accelerated ions flow bombardment. The erosion causes changes in the geometry of discharge channel up to total insulators wear, when ion flow starts interaction with magnetic system elements, which sputter resistance is low.

Method of lifetime prediction basing on the semi-empirical model is being developed in Keldysh center [8]. Results of experimental investigations serve as an input data for the semi-empirical models. In particular, during the numerical modeling of discharge chamber erosion data of insulators profiles and their changes in time are used as source experimental information. Basing on these profiles ion current model is developed and further erosion prediction is made up to total lifetime ending. Methodic of shortened life tests defining sequence of actions and tests conditions, allowing considerable decrease of thruster life tests duration was developed basing on the results of described model. The possibility of fivefold decrease of required thruster operation time is experimentally confirmed. Differences in thruster output parameters obtained after direct and shortened life tests are found inside the limits of measurements error. Graphics of specific impulse changing during tests of two KM-60 thruster specimens is presented in fig.9. The specimen #4 passed through direct life tests, while specimen #3 passed through 100-hours tests and basing on the results prediction of insulators condition after 500 hours of operation was made.

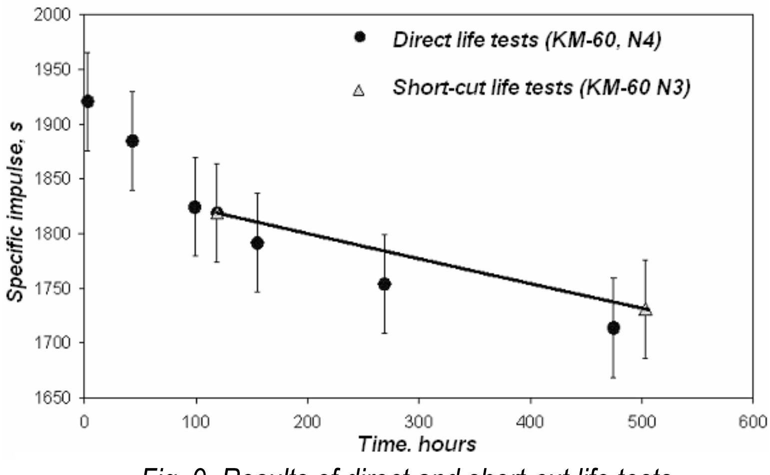


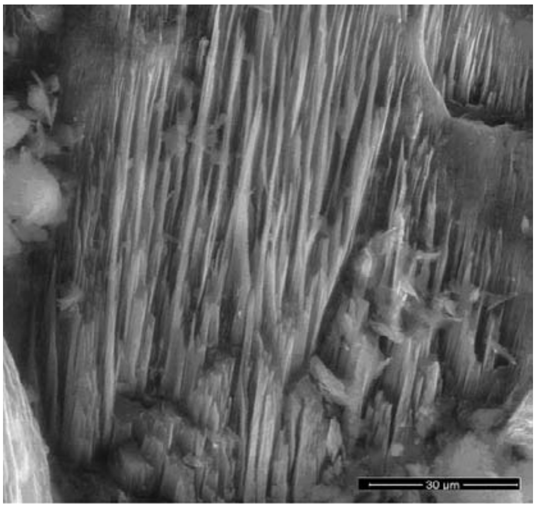
Fig. 9. Results of direct and short-cut life tests

New ceramic materials for HET discharge. Works on the development of high specific impulse thrusters with high lifetime required search for and investigation of new ceramic materials. Choosing of the new material represents rather complicated problem. Such material should be resistant to ionic sputtering, and, at least should not lead to decrease of thruster output parameters decrease..

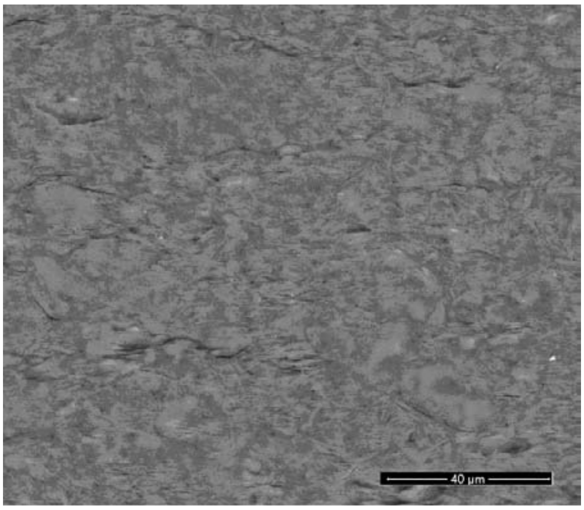
Works on the development of high specific impulse thrusters with high lifetime required search for and investigation of new ceramic materials. Choosing of the new material represents rather complicated problem. Such material should be resistant to ionic sputtering, and, at least should not lead to decrease of thruster output parameters decrease.

Traditional material for the HET discharge chamber walls manufacturing is BGP-10 ceramics, which is composition of BN+SiO2. During the investigations in Keldysh Center it was shown, that ceramics composed of more than 90% BN is more promising at increased discharge voltages (in particular, up to 500 V). The BN-05 material differing from BGP with its lower sputtering yield was investigated in detail [9]. During 500 hours life tests of a HET with nominal power 900 W and 500 V discharge voltage it was shown that that mean value of specific impulse for walls made of BN-05 ceramics is 100-150 s higher than the corresponding value for walls made of BGP-10 ceramics. Yet the prediction of physical wear of both ceramics after 3000 hour of operation turned out to be equal.

Several results of investigations of pure boron nitride ceramics behavior in conditions of HET plasma were presented in [10]. In particular one should mention differences in surface microstructures of different materials observed for the first time. Microstructures formed on the surface of BGP-10 (a) and BN-05 (b) after 500 hours of operation of HET model with 900 W discharge power and discharge voltage 500 V were presented in fig.10. The images were obtained with scanning electron microscope at comparable resolution. It is clearly seen that BGP-10 material is characterized by appearance of “fine structure” consisting of needles with diameter of 50-600 nm and length of 100-1600 nm. X-ray fluorescence analysis showed that needles are composed mainly of Si and O, while in basic material B and N atoms prevail. For BN-05 material such structure was not observed. The investigations of found out peculiarities of ceramics influence on HET operation, including processes of secondary electron emission are continued.



a)



b)

Fig. 10. Microreliefs emerged on the surface of BGP (a) and BN-05 (b) сформированные на поверхности БГП (а) и BN-05 (б) after 500 hours of HET operation at discharge power 900 W and discharge voltage 500 V

Hall thrusters developed in Keldysh Center. A series of thrusters with different sizes and power range from 100 W to 6 kW is developed (see Table 2). Thrusters KM-45, KM-5 and KM-7 are qualified as flight models, thrusters KM-60 and KM-88 are in stage of qualification tests.

Table 2 Hall thrusters developed in Keldysh Center

Thruster	KM-32	KM-45	KM-60	KM-88	KM-5	KM-7
Thrust, mN	5 - 18	10 - 28	30 – 50	50 – 105	75 – 140	200 - 380
Power, kW	0,1 – 0,3	0,2 – 0,45	0,45 – 1,0	1,0 – 2,5	1,35 – 2,5	3,5 – 6,0

Specific impulse, s	850-1400	1250-1500	1200-2200	2000-3000	1600-2100	1700-2650
Development stage	Laboratory model	Flight model	Qualification model	Qualification model	Flight model	Flight model

Hall-effect thruster KM-5 at present time is under flight tests on board of geostationary SC "Express-A4" developed by NPO PM (JSC Reshetnev Applied Mechanics Research), put on orbit on June 10, 2002 [11]. This thruster is used for spacecraft inclination keeping. As of June 2009 the operation time was 2360 hours at 1350 on/off circles. It is worth emphasizing that it is the longest firing lifetime ever reached by Hall thrusters consisting of the orbital spacecrafts. Flight tests of the low power HET KM-45 are planned for 2009 onboard Indian geostationary telecommunication satellite GSAT-4 [12]. The HET with higher power KM-7 was qualified for flight test onboard Russian spacecraft of the "Esxpress-A" series and can be used for orbit correction of heavy geostationary SC (for example on new European space platform @Bus) and also can find application in propulsion system of European inter orbital tow ConeXpress

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