Research of Propulsion Engines for Advance Reusable TSTO Aerospace System

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Abstract

The last thirty years investigations have shown that the most technically attractive class of advanced RSTS with horizontal take-off and landing is the Two-Stage-To-Orbit aerospace system. One of the main problems for these RSTS, which deliver payloads to low earth orbit, is creation of vehicle-accelerator propulsion. This paper details Russian research experience in the field of conceptual design, as well as structural and technological solutions for the advanced TSTO combined propulsion systems.

Abbreviations

ABE	- air breathing engine,
ASS	- aerospace system,
CPS	- combined propulsion system,
CS	- cooling system,
EF	- endothermic fuel,
FAHE	- fuel-air heat exchanger,
HECT	- heat exchanger-reactor of coil type,
HEST	- heat exchanger-reactor of shell type,
HCF	- hydrocarbon fuel,
HVA	- hypersonic vehicle-accelerator,
LRE	- liquid rocket engine,
RJ	- ramjet,
RSTS	- reusable space transportation system,
SSTO	- single-stage-to-orbit,
TCE	- turbocompressor engine,
TDP	- thermal decomposition product,
TFAB	- turbofan with afterburning,
TRJ	- turboramjet engine,
TRJcabr	- TRJ with the common afterburning and ramjet combustor,
TRJsep	- TRJ with separation flow path for TCE and RJ,
TSTO	- two-stage-to-orbit

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Introduction

The process of space exploration is characterized by an increase in cargo traffic on the "Earth-Space-Earth" route and expansion of tasks behind space activities. The success of this process should be facilitated by creation of RSTS, designed to open new opportunities for work in space, radically (5-10 times) lowering the unit cost of payload transportation and eliminating the shortcomings of one-time carrier rockets.

Given the high technical risks and costs of development programs for such systems, different variants of RSTS are being considered worldwide, among which a notable place is occupied by RSTS with horizontal take-off and landing - SSTO and TSTO, using air as the working mass of their engines up to the hypersonic flight velocity ($M_f \geq 5$).

Active design studies of various variants of SSTO and TSTO are being carried out worldwide since the 1960s, and the largest projects include- NASP in USA, HOTOL in Great Britain, «Sanger» in Germany and JASP in Japan– during 1980s-1990s **[1-4]**.

In Russia, during the last decade of the twentieth century, the studies of SSTO and TSTO combined propulsion systems were concentrated in the framework of the “Oryol” R&D program of the Russian space agency (RSA), started in 1993 with the aim of determining development strategy for RSTS and accumulation of a scientific and technical “know-how” for their creation in the 21st century. Development of recommendations for selection of the priority RSTS concept was carried out based on a comprehensive analysis of Technical Proposals for RSTS alternatives with vertical and horizontal launch and landing, developed by leading Russian experimental design bureaus according to technical tasks provided by top-level Research Institutes of rocket and space industry (TSNIIMASH and Keldysh Research Center) and aviation industry (TsAGI and CIAM). In this program, CIAM was responsible for the development of CPS for hypersonic SSTO (Tu-2000) and TSTO (MIGAKS) [5,6].

Deterministic calculations have shown that the SSTO with base CPS and a starting mass of 350 tons is capable of bringing about 7 tons of payload into a low orbit (200 km). But, given that in the process of creating the SSTO, design parameters and characteristics may change, the probability of fulfilling the task was about 35%, and for the probability to be≈100%, it is necessary to have more than 5 tons of reserve fuel, which is comparable to the weight of the payload [7].

Therefore, since 1998, by the decision of the RSA, the studies in the field of RSTS with horizontal take-off were focused on the concepts of TSTO and their propulsions. At that point, TSTO projects with stage separation Mach numbers ranging from 0,8 to 12 were being developed worldwide (fig.1) [8,9].

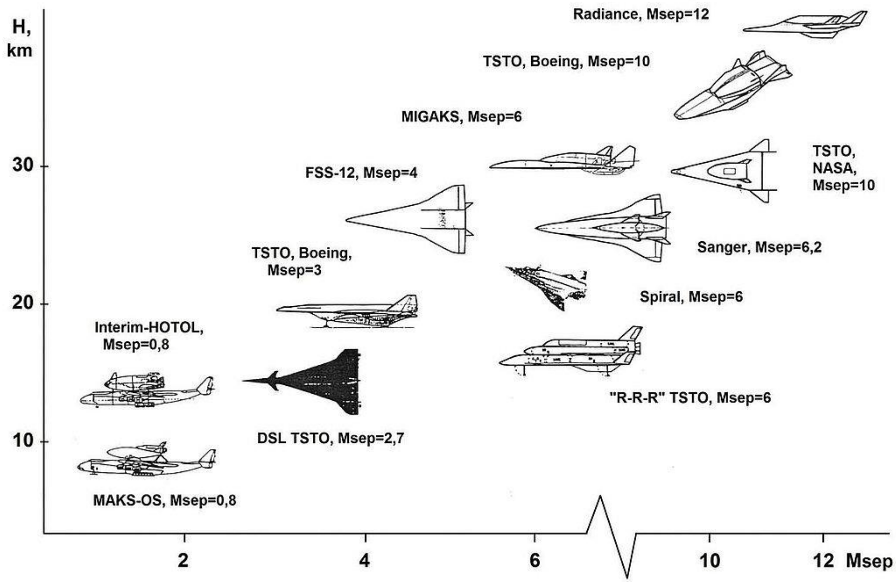


Fig. 1.TSTO projects and concepts

1. Basis of the technical appearance of the CPS for the vehicle-accelerator of an advanced TSTO

1.1. Choosing CPS scheme and parameters

Early 1990s-2000s estimations have shown that development and creation duration of the advanced TSTO vehicle-accelerators could range from 10 to 20 years and the cost – from $20-25 billion, nearly 30-40% of which should be dedicated to CPS activities. Evidently, currently these cost values may increase further. This circumstance points to the particular importance of the correct choice and validity of the CPS base variant, its components and key technologies.

The complexity of the CPS design for TSTO vehicle-accelerators is due to a wide range of flight conditions and CPS operating regimes, its variance, multi-factor and multi-criteria choice of its scheme, including the dependence of the CPS composition and scheme on the type, function and take-off mass of RSTS, on restrictions related to materials and fuels, the state and development prospects of the production, technological and experimental base, the need to take into account the probabilistic nature of the problem, etc. Selection of CPS options should be carried out according to the criteria of the upper level systems - RSTS, space fleet, etc. in deterministic and probabilistic statements.

CIAM studies have shown that, with the level of near-future technologies, the maximum relative mass (ratio of the payload mass to the take-off mass of the TSTO) of the TSTO payload (regardless of the fuel used in the jet engine and the presence of parallax) corresponds to M_{sep}=6-7. With the technology level forecasted for a more distant future, the maximum shifts to the M_{sep}=8-10 area and slightly exceeds the efficiency with separation of stages at M_{sep} = 6 (fig.2) [9]. This means that the structure of a vehicle-accelerator glider with M_{sep}=6 can be made uncooled, using existing materials and diffusion combustion of fuel in a subsonic air stream [8,9].

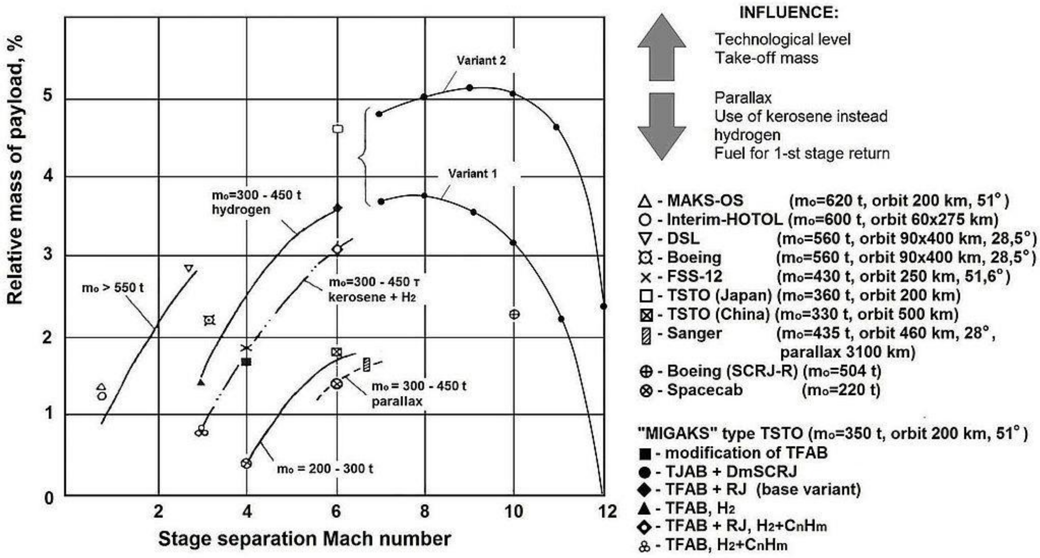


Fig. 2. Relative TSTO payload mass

Currently, similar designs are being carried out by Lockheed Martin (USA) in the framework of the hypersonic aircraft SR-72 project [10], as well as in the studies of China. [11].

It is known that for flights withM_{Max} ≤6 the most suitable are turboramjet CPS. Schemes of these CPS are differ depending on M_{max} and for M_{max} = 6 the optimal scheme is the one with separate ducts for turbocompressor engine and ramjet. Formation of a scheme and a choice of main elements' dimensions of a turboramjet CPS must be carried out taking into account three typical flight zones of a vehicle-accelerator:

- transonic zone (M_f=1.1-1.3, H=8-11 km) with increased aerodynamic resistance to CPS and TSTO also imposes higher requirements on thrust (and hence the choice of dimensions) of TCE;
- the zone of switching from TCE regime to RJ regime at supersonic flight speeds (M_f=2.5-4, H=15-20 km), which determines the size of RJ combustor chamber: higher values of M_f, corresponding to the switching to RJ regime, the smaller the cross-sectional area of the RJ combustor chamber should be, however, the difficulties of a TCE creating increase in this case [12];
- the "hill" maneuver zone for separation of stages with maximum HVA speeds (M_f=6-6.5, H=28-35 km), where the requirement of a large thrust of a CPS determines the size of the CPS air inlet area.

In article [5], with reference to the TSTO HVA of the MIGAKS type with a take-off mass of 350 tons and the separation of the stages at M_{sep}=6, is given a comparative evaluation of the

CPS variants based on the TRJ with separate ducts for TCE and RJ (TRJsep) and TRJ with common afterburner-ramjet combustion chamber (TRJcabr), formed on the basis of the same turbo-compressor (**fig. 3, table. 1**).

The four main requirements for designed TRJ were formulated:

- flight Mach number in M_f=0...6 range;
- TRJ thrust level corresponds to Russian test facilities capabilities (existing or near future);
- usage of kerosene for main TCE combustor (for maintenance of wide operational capabilities of TSTO) and hydrogen - for afterburning and ramjet combustors;
- qualities of structural materials and technology level should correspond to 2020-2025 level.

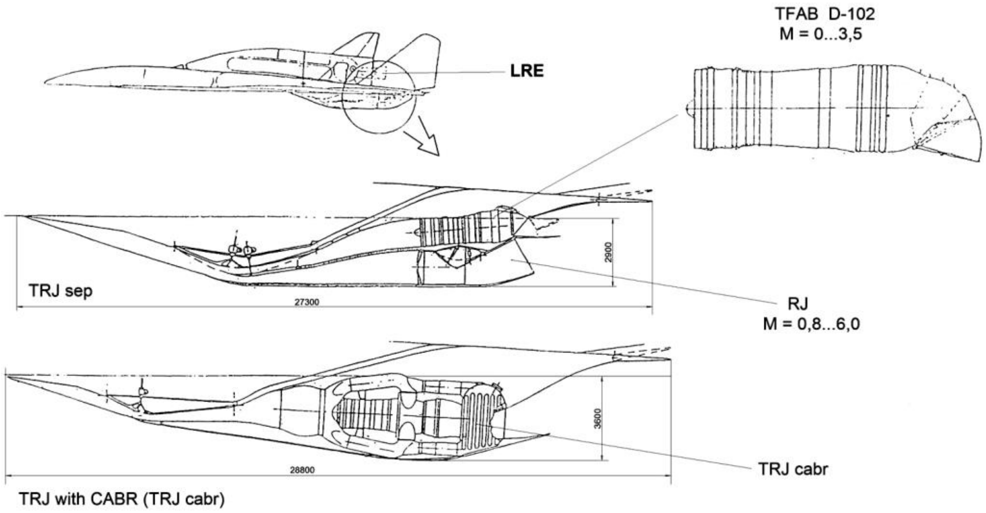


Fig. 3.Alternative variants of TSTO (MIGAKS type) HVA CPS

Table 1

M_f	TRJ_{sep} main regimes	TRJ_{cabr} main regimes
0 - 0.8	TFAB(α_Σ≈1.0) (on take-off regime RJ duct is closed, with flight speed increase it open)	TFAB(α_Σ≈1.0) (RJ ducts are closed)
0.8 - 3.2	Joint work TFAB (α_Σ≈1.0) and RJ (on limited heating regime)	TFAB (α_Σ≈1.0) with bypass of the air part from inlet to nozzle
3.2 – 3.5	Switching of CPS working to RJ regime, TFAB duct is hermetically closed	Switching of CPS to RJ mode, TFAB duct is closed, air bypass is begun from inlet to the common afterburning-ramjet combustor, air bypass from inlet to nozzle is closed
3.5 - M	RJ ($\alpha_\Sigma \approx 1$)	
M= 4-4.5	RJ (α_Σ> 1)	
M = 6.0	RJ ($\alpha_\Sigma \approx 1$)	
6.0 - 0	CPS operate on partial-thrust regimes for HVA returning	

Based on these requirements, a two-shaft TFAB was chosen as the TCE with an ideal thrust of 30 tons (M=0, H=0), an ideal specific impulse of 3390 sec, a pressure ratio - 20, bypass ratio - 0.3, gas temperature before the turbine at the level of the 5th generation engines, total excess air ratio α_Σ = 1.0, specific weigh - 0.10, maximum diameter of 1.5 m and motor length of 5.1

m. TRJsep CPS has dual streams inlet and nozzle, and TRJcabr CPS – single stream.

According to the complex analysis for TRJcabr, in which at M=0.8-3.5 part of the air consumption from the, and at M=3.5-6 - the whole inlet air consumption, bypassing the TCE, is fed into the common afterburner-ramjet combustion chamber. The option of air bypass through four pipes connected to the collectors in front of the fan and in front of the common afterburner-ramjet combustion chamber was chosen.

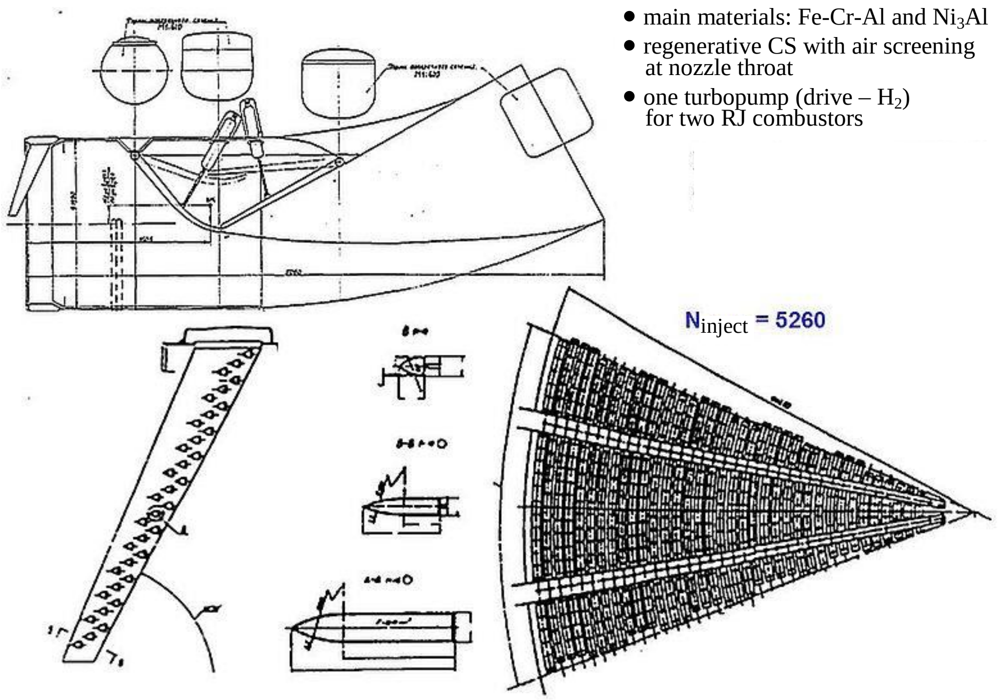


Fig. 4. Hydrogen RAMJET of turboramjet CPS

With M = 3.2-3.5 when switching TRJcabr into ramjet regime, the TCE is closed in front by a moving central body, and at the rear - diaphragm damper plates.

The TRJsep hydrogen RJ of (**fig. 4**), operating in a wide range of Mach numbers M=0.8-6 (at M=0.8-3.5 together with TFAB, at M>3.5 - independently), consists of a cylindrical combustion chamber (diffusion combustion) and adjustable 3D nozzle, which have a fuel wall cooling system. As a result of optimization, a variant with one turbo pump for two RJ combustion chambers has been chosen.

Comparison of the thrust-economic and weight-dimension characteristics has shown that TRJsep-based CPS has an advantage in all characteristics. Due to the absence of losses in bypass ducts and the possibility of joint operation of the TFAB and RJ, its thrust is higher in all regimes: at M=0 by 6.7%, at M_f=1.4 by 22%, at M_f=6 by 2.7%. The weight of the CPS with the TRJsep is less by 14.3%, the length by 5.5%, the width by 28.6%.

The basic vehicle-accelerator CPS included TFAB D-102K (M=0-3.5), hydrogen ramjet (M = 0.8-6), dual streams inlet and nozzle **[8,9,12]**. Application of the O_2-H_2 LRE has been considered for the second stage of TSTO.

Fig. 5 shows the change in the TRJsep air inlet consumption coefficient on the flight trajectory with the optimum coordination of operating regimes of the air inlet, TFAB, ramjet and nozzle, and **fig. 6** shows gas flow in a dual streams TRJsep nozzle in main regimes.

Complex nature of the gas-dynamic flow in the nozzle in transonic flight conditions leads to a significant increase in the CPS thrust losses and to a change in the angle of inclination of the thrust vector of the nozzle (**fig. 6**, **table 2**).

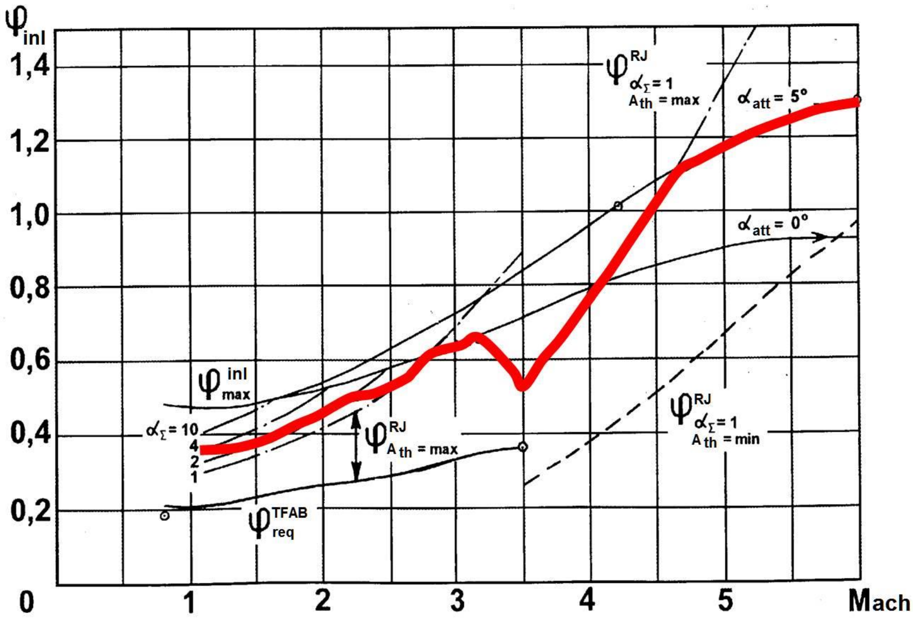


Fig. 5. Change in the TRJsep air inlet consumption coefficient on the flight trajectory

Table 2 (for **fig. 6**)

M_f	1.1	3.5	3.5	6.0
Regime	TFAB+RJ	TFAB+RJ	RJ	RJ
ΔRin x %	17.6	6.5	8.9	11.0
ΔRin_{Σ} %	12.0	4.9	8.1	10.0
$\Delta Reff_{\Sigma}$ %	22.6	7.2	9.5	11.2
δ, dgree.	- 20	10.7	7.4	8.5

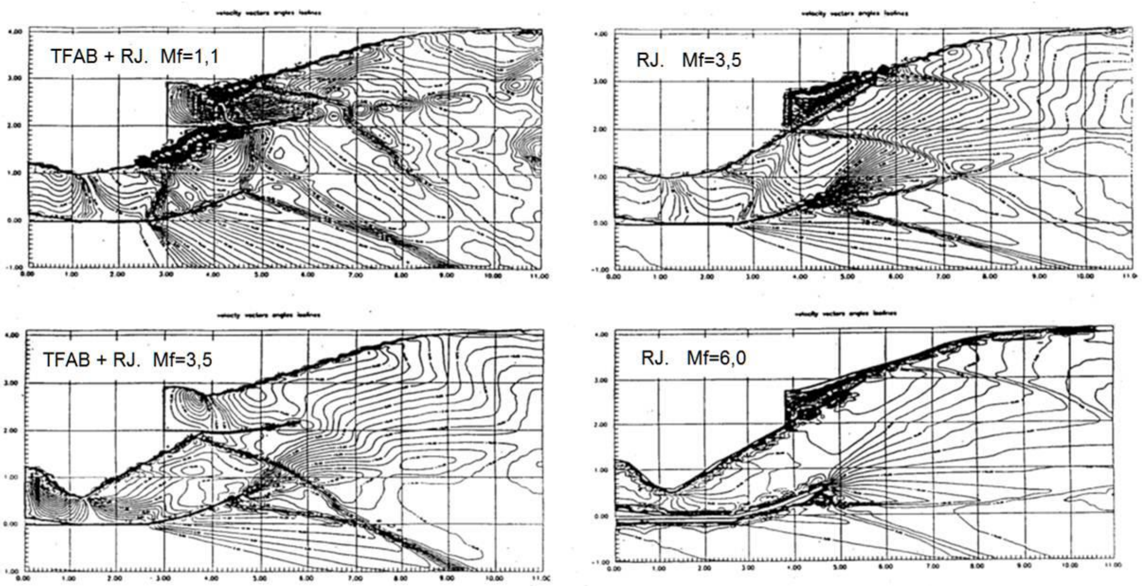


Fig. 6. Operating regimes of the dual streams TRJsep nozzle

1.2. Environmental assessment

The first assessment of the impact of RSTS CPS on the atmosphere gave encouraging results that this influence is insignificant: for the troposphere, NOx emission from one TSTO flight is equivalent to two flights of a regional aircraft, and for the ozonosphere, the effect is 30 times less than the effect from one flight of the Space Shuttle.

1.3. Efficiency of methane and endothermic fuels using

In the case of the MIGAKS-type TSTO, the possibility of replacing liquid hydrogen (base version) with promising hydrocarbon fuels (HCF) has been investigated: liquefied natural gas (methane) or hydrocarbon endothermic fuel (EF). As expected, the largest payload delivery is achieved by using the liquid hydrogen CPS.

However, it is shown that both new versions with HCF, provided that the design of the CPS is operational, have a sufficiently high efficiency up to M_{max}=6. So, in the base version, the relative payload mass is 3.6% of the take-off mass of the TSTO, and when methane is used in TFAB and ramjet, this value is 2.7%, for the option with EF - 2.3-2.5%.

This conclusion is important for the choice of the future direction of research, especially in view of the possibility of using methane or EF on high-speed transport aircraft with M_{max} up to 5.

This result is also important because when the hydrogen is replaced with methane or with non-cryogenic hydrocarbon endothermic fuel in vehicle-accelerator, the operation of the first stage of the TSTO is much simpler and cheaper **[3, 8-9]**.

2. Researches of possibilities of non-cryogenic endothermic HCF application for ABE

The definition of the technical appearance of the base CPS for accelerator aircraft ASS allowed to form a program of key technologies, an important part of which were the research works on the creation of a new technologies demonstrator – experimental RJ with endothermic fuel. This works were carried out in the 1996-2003 period within the research project "Oryol" and "Grif" **[13-15]**. The creation problems for high-speed hydrocarbon TCE, which must be serviceable up to M=4-5, and RJ for large supersonic and hypersonic flight speeds were considered.

Endothermic effects and processes at HCF heating are known, and there are studied long ago. Without a detailed review of these studies, we note a several classical publications on these problems with description of the main results obtained in Russia and the United States **[16-18]**. The possibility of using an endothermic, non-cryogenic HCF in the high-speed ABE defines the following main problems.

The first is to determine the value of the total heat sink (physical+chemical) and control the dependence of the heat sink on the fuel heating temperature.

The second is the creation of combustion chamber with effective mixing, flame stabilization and full burning at a short length of gasified, evaporated or liquid HCF.

The third is the organization of the cooling system of structural elements and/or the working substances. In this CS the fuel heat sink is realized and the liquid (in the initial state) fuel is converted into gaseous without or with thermal destruction reactions.

The fourth – and may by the main, when the HCF is heated - one is the coke formation and coke deposits on the fuel channels walls. These coke processes impair the heat exchange and leads to an increase in the wall temperature up to the wall burn-out. There are differed usually of the two type coke and two stage coke formation. The low-temperature stage with liquid-phase coke formation limited HCF temperatures, which near critical and, as a role, they are below start fuel thermal decomposition temperatures. The high-temperature stage realized at HCF heating up to start of fuel thermal decomposition with formation of pyrocarbon, which is base of the high-temperature coke.

It should be noted especially that the pyrocarbon coke problem in the CS fuel channels can be solved by using special structures that reduce heating and the degree of decomposition of ET (see, for example, [19]).

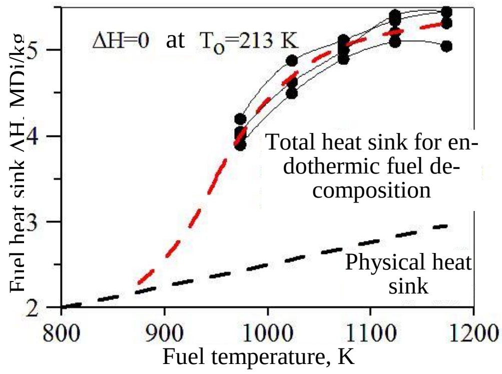
However, the more difficult problem is a reduction of the low-temperature liquid-phase coke deposition and it requires special fuel treatment, in particular, the elimination of undesirable impurities and dissolved oxygen [17].

For complex experimental studies of these problems in M=3-7conditions the design of a demonstration dual-mode RJ, which operating on endothermic HCF, was made. The engine realize full fuel cycle: liquid fuel, heating and decomposition HCF in fuel CS, injection and burn of fuel thermal decomposition products (TDP) in combustor.

2.1. Total heart sink of HCF with the thermal decomposition processes

Creation of advanced high-temperature and high-speed CPS with ABE for ASS is defined in many respects not only by energy parameters (mass H_u and volume H_v combustion heat), but also by heat sink and operational properties of fuels. Therefore, although the study of EF carried out at the second half of the last century, not well understood properties and, apparently, the cost of ET is largely constrain their use.

At the same time, just increased EF heat sink is the most attractive characteristic of advanced HCF. This increased heat sink appears when HCF are heating up to temperatures exceeding the thermal stability limits and reaching a level, where chemical reactions are taking place of the thermal destruction processes with the endothermic effect. The products of these chemical reactions have lower molecular weight than the hydrocarbons of intact fuel. Consequently, the total heat sink at a given temperature T sums up the physical cold resource corresponding to the heat needed for heating the intact fuel to T from the initial temperature (for example, the fuel temperature in the tank), and the chemical heat sink corresponding to the endothermic reactions heat of the thermal destruction processes of the initial fuel. Thus, the increased heat sink hydrocarbon fuels can be named the any HCF, including aviation kerosene, when their heating more to the thermal stability limit temperature and to the temperature level T_{td}, at which the thermal destruction processes begin. And endothermic fuels should be called the special formulations HCF, for example, which providing a minimum of coke deposit.



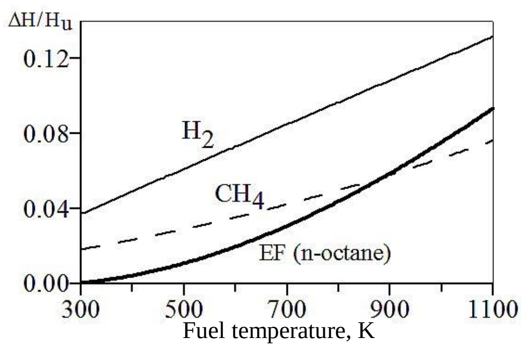


Fig. 7. Heat sink of ABE fuels
(T_o for H_2 – 20 K, CH_4 - 112 K, EF - 300 K)

An experimental data with large heat sink values of kerosene shows fig. 7. The comparison of ET, hydrogen and methane [20] shows ibidem for the real heat capacity values, which can be

characterized by a quotient of the fuel heat sink of 1 kg $\Delta H(T,T_o)$ to the H_u. Here $\Delta H(T,T_o)$ is the amount of heat that can take the fuel when heated from T_o up to T. A comparison of the EF and cryogenic fuels was showed that the EF heat sink at T=1000 K is equal the 9% from H_u, and 72% from the hydrogen heat sink, and this value is noticeably more that one is for methane.
The calculation of the maximum heat sink of the normal hydrocarbons from n-octane (C_8H_{18}) to n-ethane (C_2H_6), with take into account of the thermal decomposition processes in an equilibrium ideal-gas approximation, showed that all hydrocarbons have the significant "chemical" heat sink values. For T=1000 K these values are constituted near half of the heat sink for propane, butane and n-octane, and for ethane and hexane the effect of fuel decomposition on the total heat sink is less. The calculations showed that the relative heat sink (to H_u) of more lighter hydrocarbons than n-octane, is on 10-30 % lower of the n-octane maximal value and one is near at the kerosene fuel level. However, taking into account the smaller amount of carbon condensate in the decomposition products of light hydrocarbons, the possibility of their use as the ABE fuels requires studies of their properties at heating up to T=900-1000 K.

2.2. Researches of combustion processes

The combustion chamber of the demonstrator is made with a cylindrical burning section and with combustion according to the diffusion scheme. Heated and gasified fuel or of thermal destruction products (TDP) are supplied through jet injectors located on the fuel supply pylons and on the combustor walls. Stabilization of the combustion is fulfilled at the fixed separation zones after the back walls pylons and in the circular niche stabilizer. An electric spark plugs are used for ignition.
Development of the ignition and stabilization processes were carried out in external blow-out conditions on the planar model analog of the pylon + niche stabilizer system. Fuel (kerosene RT) was heating in special fuel-gas heat exchanger.
The main regime parameters were following: blow-out air total temperature and Mach number - T^*_{air}=520-620 K and M_{air}=0.1-0.6, fuel temperature and decomposition degree - $T_{топл}$=420-900 K and Z=0-0.7, the equivalent fuel-air excess coefficient - ϕ=0.12-1.4. The obtained regimes of stable combustion with gasified fuel and TDP on the model stabilizers (**fig. 8**) testify about the possibility of organizing a stable combustion in high-speed subsonic flow in the combustor of demonstration dual-mode RJ, **[15]**.

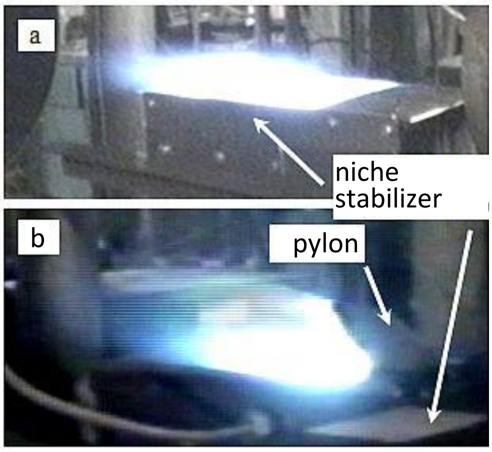


Fig. 8. The torches of stabilized combustion on model stabilizers: a - niche stabilizer, gasified kerosene; b - fuel supply-pilon-stabilizer + niche stabilizer

Features of the mixing and burning processes of gaseous HCF has been considered previously at the study of methane combustion (as an analog of the gasified kerosene or TDP) in a model ramjet combustor with the multiple-rows fuel injection system. Experimental studies have shown possibilities effective combustion of the HCF in small lengths combustor with large subsonic speeds (M=0.5-0.7) when the of combustion efficiency was high level η=0.92-0.96 at ϕ_Σ=0.7-0.83, **[21,22]**.
Taking into account the obtained data, an axisymmetric model combustor of the demonstration hydrocarbon RJ with a multiple-rows fuel supply system for heated and gasified kerosene and with uncooled walls is prepared for testing (**fig. 9**). The tests were carried out at direct connect scheme with the simulation at the

combustor entrance of air flow parameters, fuel-air excess coefficient ϕ and parameters of the heated gasified kerosene RT, which must be appropriate RJ operating conditions at the flight Mach numbers M_f=2.4-4.2. Typical distributions of static pressure along the combustor flow path corresponding to the subsonic combustion modes, a combustor scheme and external view of the combustor during the test is shown in **fig. 9**.

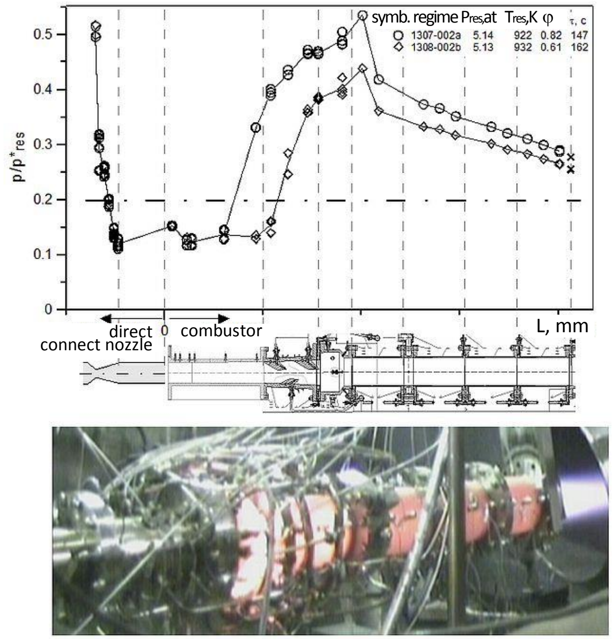


Fig. 9. Uncooled combustor of the demonstration hydrocarbon RJ with burn of gasified kerosene as EF analog

It was determined that reliable combustor starting is carried out along the full investigated range of $\phi_{\text{КС}}$ with a throttling flow path and ignition of fuel-air mixture by two electric spark plugs in the niche stabilizer cavity.

In tests without oxygen compensation, the combustion of gasified kerosene was carried out in an air-gas flow with stoichiometric coefficients L_o=17.5-18.5 with combustion coefficients η=0.94-0.98 at ϕ=0.6-0.82. A good agreement between the experimental and calculated data was become for these conditions. Consequently, when the same combustor will be to operate at stoichiometric conditions with "clean" air the η values will not be lower level η=0.9-0.92.

It should be noted that when optimization of multi-fuel injection system is possible due to the distribution of fuel consumption by injector rows, increasing of the injectors number and the positive impact of fuel pre-injection **[23]**. As a consequence, the combustion efficiency increase is possible at ϕ→1.0 up to the minimum level of η=0.95.

2.3. The cooling systems of ABE with HCF and the coke problems

The cooling systems of advanced ABE, working on the increased heat sink HCF, have been investigated in the calculated analysis of the high-speed TFAB and RJ for CPS. It was assumed that for the TFAB applications of the HCF heat sink for cooling of the working substance, i.e. for air cooling in fuel-air heat exchangers (FAHE) of the intermediate air cooling in the compression flow path before the compressor and the turbine air cooling system must be possible. The plate types of these FAHE was considered.

In addition, HCF heat sink was used for convective cooling of the walls of the main and afterburner combustion chambers. It was assumed that these CS are made in the form of double wall shells or panels with the between the same walls. The inner wall had a finning that formed fuel channels with a variable along length cross-section (in general case). It was assumed also that for full-scale RJ with HCF, working at M=6.0, the cooling system of flow path walls will be made with the even straight-line fuel channels.

Experimental large-scale model heat exchanger-reactors the coil (HECT) and the shell (HEST) types (**fig. 10**) have been developed and tested for the study of heating ET and their use in the form of cooling systems of various design schemes These researches were a preliminary stage before using the same heat exchangers as elements of demonstration RJ cooling system.

Experimental researches of the HECT (**fig. 10a**) were carried out at heating and thermal decomposition of kerosene RT with the pressures 4-8

MPa and temperatures heating gas T_{gas}=650-1300 K [20]. The maximum fuel temperatures reached T_{fuel}=1070 K and the decomposition degrees - of level Z=0.8. In experiments the heat engineering performances of HECT were determined, the peculiarities of the process of heating and decomposition of the fuel were explored, and the resulting data for the mathematical models improvement were got.

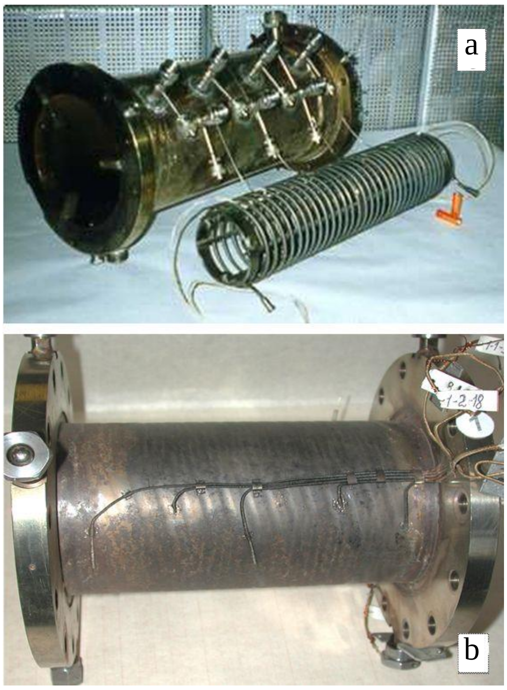


Fig. 10. Large-scale coil(a) and shell(b) types of experimental heat exchanger-reactors

Analysis of the HECT thermal-hydraulic parameters and of the TDP liquid phase samples showed that intense decomposition of kerosene in HEST occurs when T_{fuel} above ≈870 K. These temperatures is near to the data [24], which were received during the laboratory tests with the small consumption straight-line tubes under electric heating. This important result substantiates the possibility of using the EF properties that were obtained in experiments with the small-size models for the development of real objects.

Prototypes of the HEST corresponded a fuel-cooled sections of demonstration hydrocarbon RJ (**fig. 10b**). During the HEST test fuel (kerosene RT) was heated up to temperatures much higher limit of thermal stability, with coke deposit in the ranges of low-temperature liquid-phase fuel oxidation (T_{fuel}=450-600 K) and of the high-temperature coke (T_{fuel}>850 K). A calculation of the parameters for the test conditions showed satisfactory agreement of the calculated and experimental data on the fuel flow path and the temperatures of the HEST walls. For example, the difference of the HEST walls temperatures was not more 5-10 K for level Tw=480-800 K and the one can be considered as satisfactory.

An important result of the HEST hot tests is the determination of the maximum operating time (resource) of the prototype in special resource tests. These tests were carried out for two modes with parameters corresponding to the HEST parameters in the demonstration engine combustor. First mode was at T_{fuel}= 790-830 K, T_w=820-850 K, a stationary regime duration τ_{stat}=34 minutes and second mode - at T_{fuel}=960-970 K, $T_{w,max}$=1030-1050 K и τ_{stat}=5 minutes with the decomposition degree of level Z=0.7-0.8. The HEST destructed at this regime end and the analysis showed that the same destruction was due to insufficient development of technologies for manufacturing of the thin-walled soldered HEST shells. Thus, summary hot working life of one from the HEST prototype products, as CS of experimental RJ, was obtained near 5 hours, from which at T_w≥800 K – near 1 hour, and at T_w=1000-1050 K – 5-9 minutes.

In principle, obtained working life is sufficient for a beginning of the demonstration hydrocarbon RJ with kerosene fuel CS. But the engine parameters calculations for M=6-7 showed that using of kerosene as coolant is advisable not for all the operating regimes of engine under consideration scale. Therefore, to improve the CS performance of the demonstration RJ, calculated studies of the heat fluxes decrease when using HEST with thermal insulating inserts from composite materials C-C or C-SIC (CM) were carried out. The various schemes of heat transfer from CM-insert to the HEST metal walls was considered (**fig. 11**): “full contact”, “radiation” and combined scheme "radiation + full contact".

It was ascertained that combined heat transfer scheme “radiation + full contact” (**fig. 11d**) is a most effective using of the inserts. This scheme made possibility to decrease of the fuel and the metal walls temperatures of the HEST by alternating grooves and ridges on the outer surface of insert **[19]**. It was showed that kerosene decomposition degree is not more Z=0.1 at stoichiometric regime for M≥6.0. Therefore, the pyrocarbon coke deposition and the risk of engine deterioration may be practically fully to prevent.

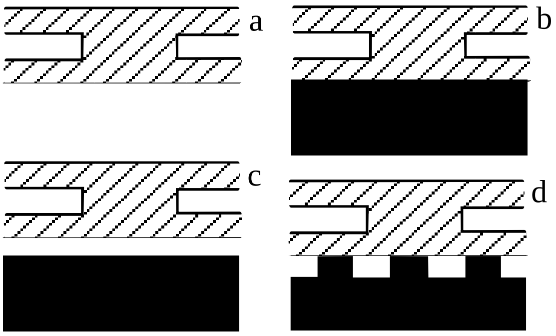


Fig. 11. Schema of HEST with insulating inserts: a - initial metal construction; b – “full contact” scheme; c - “radiation” scheme; d - “radiation - full contact” combined scheme

The low-temperature coke problem, which produced at liquid-phase oxidation of HCF and at fuel heating up to temperatures above the thermal stability limit, is critical nevertheless for all types of CS. The same problem need first of all accumulation of experimental data on intensity of coke deposit and on working life of hydrocarbon CS with the heating fuel channels. To obtain such data, experimental studies of model kerosene tubular heat exchangers (tube 3.0×0.5mm, length ≈1 m, material is stainless steel, electric heating) in the liquid-phase oxidation range without thermal destruction were carried out. Fuel was kerosene RT and TS-1 at supercritical pressures, thermal and hydraulic operating parameters correspond to heat exchangers in TCE and RJ. In these tests the maximum temperatures of the outer surface walls increased from T_w≈550-600 K up to 900-980 K in depending on the operating modes due to coke deposition and deterioration of heat transfer during the maximum operating time exceeding the possible operating time of the demonstration RJ. For an example at **fig. 12** the T_w distributions along the tubular channel length is shown at different operating times.

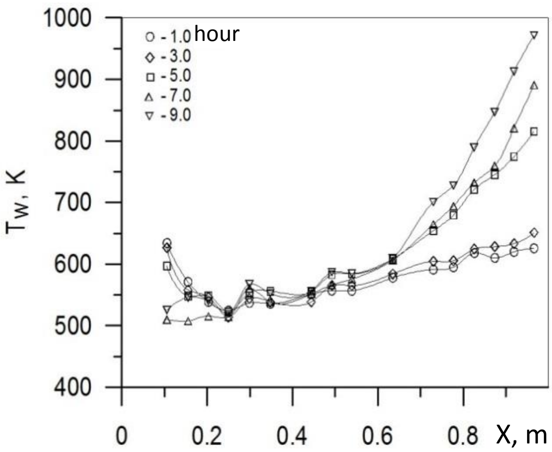


Fig. 12. Outside tube surface temperatures at different of working life times

Based on the experimental data, an empirical approximation model of the working life up to the limit temperatures of the fuel channel wall $T_{w,max}$ was developed. The generalized view of the approximation model as functional relationship of two complex parameters $F(\tau_{Hap},\rho U)$ and $Q(T_{w,max},q_{w,o})$ are illustrated in **fig. 13**, where τ_{Hap} is the working life, ρU is the current density, $T_{w,max}$ is the maximum temperature of the fuel channel wall, and $q_{w,o}$ – specific heat flux in a "clean" fuel channel. A photo of the cross-section slice of the fuel channel with a coke layer view after the working life is illustrated also on the same figure.

A computational model for the dynamics of coke deposits on the channel walls in the range of liquid-phase coke deposition is also developed. The model is based on one-dimensional conservation equations of consumption and energy for the kerosene flow and on the empirical relationships temporal variation of the thermal resistance for the coke layer ($R_c = \delta_c / \lambda_c$) at liquid-phase oxidation from parameters of the fuel and of the fuel channel wall.

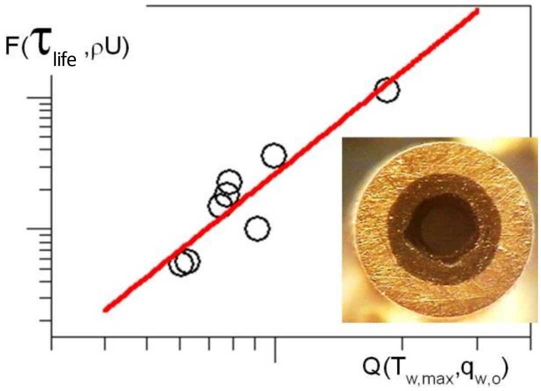


Fig. 13. Generalized model of working life time for fuel channel with heating of aviation kerosene at the liquid-phase oxidation

Both models allow to estimate the heat exchanger parameters during to heating kerosene time, the thickness of the coke deposit layer of and the maximum working life times for maximum structurally allowable temperature of the fuel channels walls. These estimating models shall be most reliable for heat exchanaers manufacturing from stainless steels, for kerosene RT under supercritical pressures 4-6 MPa and temperatures below the start temperature of the thermal destruction process 850-870 K, for the walls temperatures $T_{w,max}$=650-1200 K, current densities ρU=600-2000 kg/(s·m^2) and heat flux q_w=0.15-0.85 MW/m^2.

2.4. The using of hydrocarbon fuel heat sink at TCE of the combined propulsions

With regard to the CPS which one consist of the endothermic fueled TFAB and RJ (n-octane), for advanced TFAB D-102T with T^*_{comb}=2250 K, it is shown that the use of the HCF heat sink in TFAB turbofan in combination with the high-temperature composite materials fan and hybrid bearings can extend the range of its operational activities up to M_{max}=5. Such extension of the operating Mach number TFAB allows to reduce the sizes and weight of RJ.

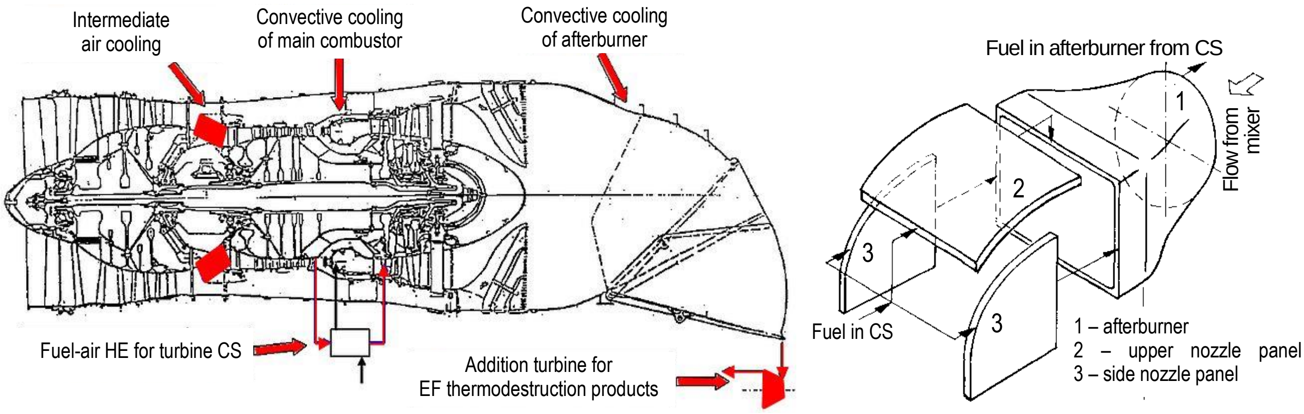


Fig. 14. Places for realization of the hydrocarbon EF heat sink and power production and CS scheme of afterburning combustor chamber for high-speed TFAB D-102T

Following most efficient areas for realization of HCF heat sink (**fig. 14**) in cooling systems of structural elements and fuel-air heat exchangers (FAHE) are identified when limiting the HCF flow in the TCE (no more than 1/15 of the air flow):

- FAHE in turbine CS and fuel CS of main combustor (main combustor fuel),

– FAHE of the air cooling system at HPC inlet to reduce the required compression work of the HPC and afterburner fuel CS (afterburner fuel).

Parameters of TFAB with the indicated heat exchangers are calculated up to M_n=5.0 based on the unifying mathematical model. It is ascertained that realization of turbine cooling system FAHE for turbine cooling prolongs effective operation of TFAB up to M_{max}=3.5-3.7 while maintaining the cooling air flow, maximum blade temperature $T_{b,max}$=1120°C and required service life. At the same time, the fuel is heated to 900 K with a degree of decomposition Z=0.9. And realization of FAHE for air cooling in front of the compressor improves the engine parameters (an increase in the total degree of pressure increase by 21% and thrust by 13%). Under these conditions, the temperature of the main CC wall did not exceed $T_{w,max}$≈1000 K with insignificant heating ($\Delta T_{топл}$=8 K) and additional EF decomposition (ΔZ=0.07), and for the afterburner - $T_{w,max}$ ≈830 K at $T_{топл}$=530 K at the jacket outlet without noticeable decomposition.

The analysis of the convective cooling of both CC walls has shown the adequacy of the EF heat sink and the constructive realizability of such chambers. In general, maximum use of HCF heat sink extends the TFAB performance range to M_n=5. However, if M_n=5 the maximum fuel temperature reaches ≈1100-1200 K and EF heat sink (physical + chemical) is depleted almost completely.

2.5. Realization of hydrocarbon heat sink in RJ CPS

A comparative design study of large-scale ramjet parameters (scheme of duct - **fig. 4**) with a fuel cooling system has been carried out at M=6 for hydrogen, methane and n-octane options as typical representatives of endothermic HCF **[20]**. Calculations have shown the possibility of organizing almost complete combustion of gasified fuels with total temperatures of the combustion products at 2810-2880 K. And for such CS, dimensions of straight fuel channels were determined from the condition hot walls temperatures not exceeding T_w=1100-1200 K. It was determined that width of the channels varied in range of 5-30 mm in different sections of the CS, height 4-25 mm, and rib thickness 5-8 mm.

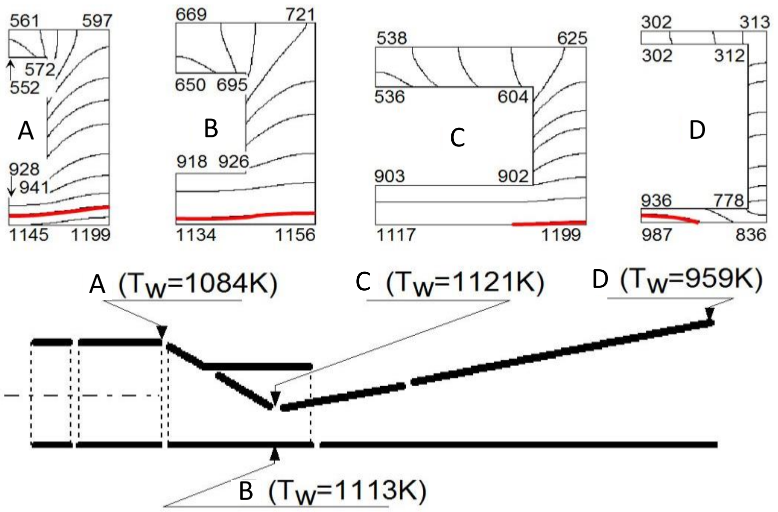


Fig. 15. Cooling system scheme, types of fuel channels and 2D temperature fields in the typical cross sections of the EF ramjet flow path for ASS "MIGAKS"

Fig. 15 illustrates the CS scheme, fuel channel types, and the cooled walls thermal state data. The satisfactory match of Tw values calculated with an approximate ribbing and data of 2D calculations of the temperatures of two-walled shells with ribbing should be noted – in fig. 15 the isotherms with Tw are shown by red lines in 2D fields.

Calculations have shown the possibility of cooling system realization for RJ CPS of a vehicle-accelerator with structural temperatures less than $T_{w,max}$=1200°C, allowing the use of modern high-temperature nickel alloys.

In these conditions, the CS ensures preservation of a large reserve of available EF heat sink – no less than 50% with respect to the maximum realized degree of decomposition Z=0.5. Thus, if necessary, a decrease in $T_{w,max}$ up to 100-150°C is possible. Comparison of heat sink reserves for the considered fuels under the condition of maximum permissible heating up to $T_{fuel,max}$=1000 K is shown in fig. 16.

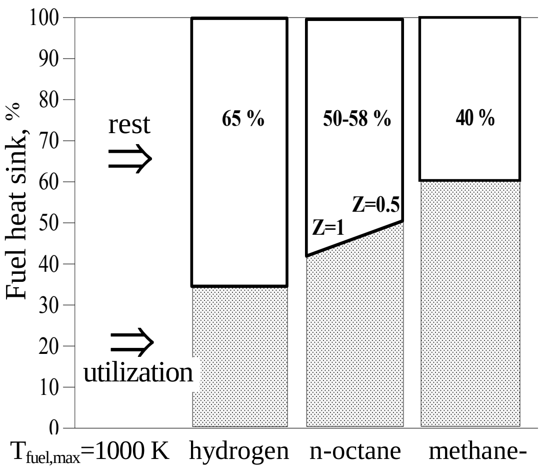


Fig. 16. Different fuels heat sinks at cooling of full-scale ramjet

Conclusions

Based on conducted unifying studies of various TSTO concepts, the most promising type of TSTO is defined as a two-stage system and the technical appearance of a basic combined propulsion system of a hypersonic vehicle-accelerator is determined. Key Technologies Program has been formed to further development activities, principal place in which belongs to demonstrator of new technologies – experimental RJ running on endothermic fuel, works on which were conducted from 1996 to 2003 in the framework of R&D projects "Oryol" and "Grif".

The development of dual-mode ramjet demonstrator working on endothermic HCF was carried out. The engine is designed for practicing operating procedures with implementation of complete fuel cycle: liquid fuel – heating and decomposition in cooled combustion chamber compartments – injection and burnout of products of thermal destruction of fuel in the chamber. During model testing of the demonstrator's units and CC, matters of ignition, stabilization and burn-out of gaseous HCF with high combustion completeness were studied. Possibility of cooling systems realization of jet engine's structural elements and working bodies using HCS heat sink has been shown. Mathematical models of promising high-speed Jet engines have been developed taking into account endothermic effects during HCF heating, as well as models of heat exchangers taking into account influence of coke deposits.

These developments can be used to design CPS for advanced TSTO, as well as for high-speed aircrafts of other types, such as experimental aircrafts, high-speed transport aircrafts, etc.

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