DEVELOPMENT OF ABE THEORY IN RUSSIA: PAST, PRESENT AND FUTURE

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Abstract

This paper is a review of development of theory and practice in the field of air-breathing engine (ABE) creation in Russia. It is natural to break it into three periods: past, present, and future. The development of theoretical concepts of the past is presented accompanied by a comprehensive retrospective review devoted to creation of aviation ABEs in Russia, especially in the favorable period covered the 1950s – 1990s of the last century. The characteristic features of the present period in the theory development are demonstrated with typical examples of different engine components. In the description of the future period in the theory development, some possible directions of more distant future are covered along with quite specific and doubtless directions of the next few years.

1. Introduction

Aircraft engine-building in Russia has deep traditions. The first original domestic versions of aircraft engines were manufactured in 1926 - 1931. The designing of the first engines and subsequent progress of aircraft engine-building in the USSR is closely associated with the Central Institute of Aviation Motors (CIAM) which was established in December, 1930 and this year will celebrate its 75-th. anniversary.

In the first half of the 1930s, CIAM consolidated several design bureaus, which competed in developments of powerful domestic piston engines. Two engines having an interesting history were launched into series production.

The first is M-34 engine designed by A.A.Mikulin (1931), which turned out to be rather promising and had a long life. Its initial power was 850 h.p. Later on, it was modified (AM-38, AM-42) to increase thrust up to 2,000 h.p. In 1937, V.P. Chkalov's and M.M. Gromov's crews onboard an A.N. Tupolev single-engine ANT-25 aircraft powered by this engine made non-stop USSR-USA flights crossing the North Pole. The derivatives of the M-34 engine powered many planes, in particular, the S.V. Ilyushin Il-2 – one of the best old domestic attack aircraft.

The second engine was developed in CIAM by A.D. Charomski in 1932. This is the ACh-30 diesel engine providing initial 1,000-h.p. power. Its high-speed version was successfully used for powering the four-engine Pe-8 aircraft designed by V.M. Petlyakov.

When in the mid-1930s numerous design bureaus (DB) were established in Moscow, Leningrad, Perm, Zaporozhye and other cities, these DBs were headed by CIAM former employees - A.A.Mikulin, V.J. Klimov, V.A. Dobrynin, S.K. Tumanskiy, A.D. Shvetsov, et al. At that time CIAM focused efforts on researches in the field of a theory of operating process in aircraft engines.

In 1947, the USSR government made a decision on extensive expansion of CIAM by establishing a national research test center for testing in simulated altitude-speed flight conditions all engines and their components designed in the Russian design bureaus. The largest in Europe test center came into being in 1955 and became the CIAM's subsidiary . It offers all necessary possibilities for tests of ABEs, including scramjets and ramjets.

The present work highlights the main

stages in this theory evolution and ABE development in Russia as well as gives an overview of promising directions of development in future.

2. The beginning of ABE theory in Russia

B.S. Stechkin, A.M. Lyulka, and V.V. Uvarov - the outstanding Russian scientists were at cradle of ABE theory in Russia .

Boris S. Stechkin (1891 - 1969) worked out the ABE theory fundamentals which were originally stated in the work «Theory of Air–Breathing Engines» [1] published in 1929. In his works he made references to Prof. N.E. Zhukovski works [2, 3] where problems of reactive force in the case of incompressible liquid were studied in details. For motion of a body in air flow (Fig. 1) B.S. Stechkin proposed formulas for jet engine thrust:

$$R = m(V - V_0),$$

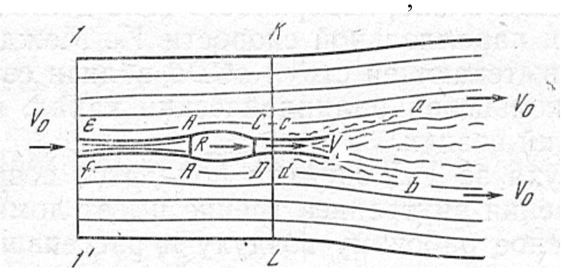


Fig. 1 ABE principal scheme

and efficiency at the presence of heat supply:

$$\eta_e = \frac{2V_0}{V + V_0} \cdot \eta_t,$$

showing that the value of heat jet engine efficiency, η_e , is a product of heat cycle efficiency, η_t, by "propulsive" efficiency, $\eta_p = 2V_0/(V + V_0)$, for a body moving in a uniform flow with V_0 speed and exhausting a jet with V speed. At the end of this work he analyzed the case of isobaric heat input at $p = const$ (Brayton cycle) for which the efficiency is $\eta_t = 1 - T_2/T_0$, where T_0 and T_2 – - temperatures of incoming air flow and air at the end of compression process. It is worth noting that B.S. Stechkin was assigned to be the first director when in 1930 the Central Institute of Aviation Motors was founded.

In the 1930s, structural layouts of turbojets and turboprops came into being in the USSR. The founder and the initiator of turbojet developments in the USSR is Arkhip M. Lyulka (1908 - 1984). In 1940 the development project of the first Soviet turbojet dubbed as RD-1 was completed and launched into production. The engine was equipped with an axial compressor and rated at 5-kN thrust at 920 K gas temperature at the turbine inlet. The engine project, unfortunately, was terminated by war years.

In 1941, A. M. Lyulka patented the turbofan lay-out. Describing the inventive subject matter, he wrote: «A distinctive feature of the bypass engine is air flow splitting at the fan outlet into two streams…».

The shelved development of the first turbojet guided by Arkhip M. Lyulka was resumed in 1943 in CIAM and later on in a specially established design bureau (today it is the Scientific Production Association «Lyulka - Saturn»). Designed by A. M. Lyulka the TR-1 engine providing 11.3-kN thrust, which completed acceptance tests in 1947, became the first Russian turbojet. The engine was equipped with an axial compressor, an annular combustion chamber and a single-stage turbine, i.e. the basic components of up-to-date engines. The engine structure laid the basis for development of the 45-60-kN AL - 3 and AL - 5 turbojets.

Among the scientists who played a key role in the aircraft GTE theory in Russia is prof. Vladimir V. Uvarov (1899 - 1977). In the 1930s he proposed the high-temperature gas turbine concept, which was used in 1939 in GTU-3 experimental turboprop providing 856-kW power (1150 h.p.). This engine tested in 1938 - 1940 had a three-stage centrifugal compressor and a two-stage turbine with water evaporation cooling of rotor blades operating at 1,500K (!) gas temperature. Many years Prof. V.V. Uvarov headed CIAM's turbine department and founded a scientific school of engineers and scientists making turbine researches and contributing significantly to the Russian aircraft engine-building.

3.Russian aircraft GTEs within 1950s – 1990s.

Milestones of theory and practice of ABE and GTE developments can be shown by subdividing into generations [4]. The «aircraft engine generation» is, first of all, characterized by values of cycle parameters, specific features of components (compressor, turbine, combustion chamber) as well as used materials and manufacturing techniques. It is clear that years of I – V ABE generations are approximate but roughly can be dated to the 1950s, 1960s, 1970s, 1980s, and 1990s.

Aircraft powered by the I-st generation engines for the first time overpassed the sonic barrier: they were the Soviet La-176 fighter with the RD-45F turbojet (December 12, 1948) and MiG - 17 fighter with the VK-I turbojet (February, 1950).

The II-d generation of GTEs is distinguished by extensive development and growth in number of new designs of turbojets, turbofans, and turboprops.

Axial single-shaft (with a variable stator) or two-shaft compressors ($\pi_c = 7-13$) and turbines ($T_g = 1{,}150-1{,}275$ K) with cooled nozzle guide vanes and uncooled rotor blades are mainly in use. Improved high-temperature alloys were finding ever-widening use and titanium alloys were coming into use in the engine structure.

The outstanding innovations were implemented in this generation of domestic engines: application of one supersonic stage in the RD9V (A.L. Mikulin), the AL-7F-1 (A.M. Lyulka), the VD-7B (V.A. Dobrynin) turbofan axial compressors and three supersonic stages in the R11-300 (S.K. Tumanskiy) turbojet low-pressure spool. These concepts anticipated future tendencies of aircraft engine development aiming at decreased number of engine core stages (Fig. 2).

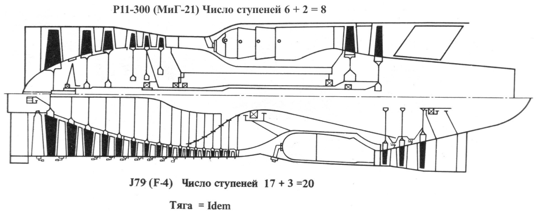


Fig. 2. R11 – 300 and J79

The second generation of engines made it possible to develop the first series of supersonic aircraft (in the USSR it was the MiG - 19 powered by the RD-9B turbojet) and reach flight speeds up to M=2. Below is the list of the most typical domestic engines of the second generation (aircraft models powered by these engines are shown in brackets):

Afterburning turbojets: RD-9B (MiG-19); RII-300 (MiG-21, Su-15, Yak-28, etc.); AL-7F-1, -2 (Su-7, Su-9, Su-11); VD-7M (Tu-22).
Turbojets: RD-3M (Tu - 104); AL-Pd (Be-10); VD-7 (M-4).
Turboprops: AI-20 (Il- 18, An-10, An-12); AI-24 (An-24); NK-12 (Tu-95, An-22, Tu-114).
Turboshafts: D-25V (Mi-6, Mi-10); TV2-117 (Mi-8).

In the 1950s, a system of various engine design bureaus and research institutes was organized: CIAM, VIAM, TsAGI, LII,NIAM. Engineers and designers of aircraft engines were educated and trained in several leading higher schools. Brilliant monographies and textbooks (e.g. [5-8]) were published.

The III-rd GTE generation is distinguished, first of all, by the development of low and or moderate bypass ratio ($m = 0.5-2.5$) turbofans for civil planes, further development of turbofans and emergence of afterburning turbofans. One of the main achievements in this generation was implementation of internal convective air cooling of turbine rotor blades with increased T_g up to 1,350 – 1,450 K. Engine compressors in this generation, mainly, were two-shaft with $\pi_c = 15-20$.

Typical engines models of the III-rd generation were the following:
Turbofans: NK-8-4/2V (Il-62, Tu-154, Il-86); D-20P (Tu-124); D-30 (Tu-134); D30KU/KP (Il-62M, Tu-154M, Il- 76).

<u>Afterburning turbofans</u>: NK-144A (Tu-144); NK-22 (Tu-22M).
<u>Turbojets</u>**:** RD-36-51A (Tu-144D); RD-36-55FV.
<u>Afterburning turbojets</u>: AL-21F (Su-17, Su-24, MiG-23B); R15BF-300 (MiG-25); R27-300 (MiG-23).
<u>Turboshafts</u> : TV - 3-117 (Mi-24, Ka-32).

The IV-th GTE generation is so numerous and diversified that the period of engine launching into production covered the 1970s - 1980s and continued in the 1990s. At the same time, new subsonic turbofans with high by-pass ratio ($m \geq 4-6$) and afterburning turbofans with high gas temperatures ($T_\Gamma = 1{,}500-1{,}700K$) at the turbine inlet (due to use of convective – film cooling of blades) were under development. Total pressure ratio increased up to 25-30 in supersonic turbofans and up to 30-40 in new subsonic turbofans. Thrust-to-weight ratio of afterburning engines reached 8:1 and above.

The most typical engine models in the IV-th generation are listed below:

<u>Afterburning turbofans</u>: AL-31F (Su-27); RD-33 (MiG-29); NK-25 (Tu-22M3); NK-32 (Tu-160); D-30-F6 (MiG-31).
<u>Turbofans</u>: D-18 (An-124 "Ruslan", An-225 "Mriya"); D-36/D-436 (Yak-42, An-72, Tu-334); PS-90A (Il-96, Tu-204, Il-76TM
<u>Turboshafts</u>**:** D-136 (Mi-26).

The V-th generation engines (the 1990s) are characterized by ($T_c = 1{,}850-1{,}950K$) inlet turbine gas temperatures, decreased number of components (in comparison with the previous generations) and thrust-to-weight ratios $\gamma = 10-11$. They were, for the most part, military aircraft afterburning turbofans. The turbofans of this generation demonstrated by-pass ratios $m = 6-10$ and widely used technologies tested in the IV-th generation engines.

Brief mention should be made of s.f.c. of small GTEs for various values of power. Fig. 3 shows

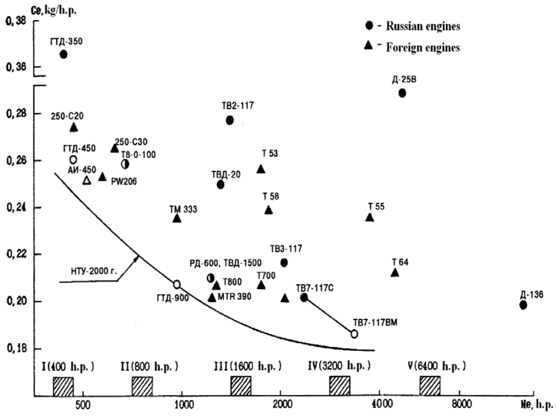


Fig. 3. Specific fluel consumption of small engines

statistical data for numerous engines developed in the USSR (circles) and in the world (triangles). The forecast for new small engines is shown by the solid line.

In 1990 CIAM together with a number of design bureaus developed an experimental axisymmetric dual-mode liquid hydrogen-burning ramjet engine and a guided anti-aircraft missile launcher as well as ground filling and telemetering complexes for flight proving-ground trials. This engine was successfully fired in 1991, 1992, and during following years. The maximum flight speed *M≈ 6.5* and engine operation duration equal to 77 sec were attained.

In our lecture we won't highlight theory and practice of ramjets and scramjets in Russia in the past. The comprehensive information can be found in AGARD-LS-194 series of lectures prepared and delivered by CIAM's employees under the leadership of prof. V.A. Sosunov[9].

4. About the present stage of ABE development

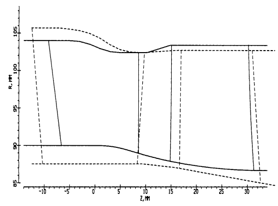
The aircraft engine at the beginning of the new century represents a vivid example of a hi-tech advanced technology product which analogues can be difficult to find among other products of mechanical engineering in view of such parameters as stresses and thermal state of components that ensures its extremely high energy output (specific power per cubic meter of a modern aircraft engine core is 40 - 45 MW).

The up-to-date ABE development is a sophisticated process resting on advanced technologies in many branches of science and engineering (aerogasdynamics, heat-mass exchange, strength, materials, technologies, electronics, etc.). The engine-building in the world is a rather dynamically developing branch of industry providing an improvement of ABE quality: increased efficiency, decreased noise and emissions, improved reliability, and increased service life. The ABE development project is too costly. At the same time the financial capacity of the world engine market was and remains very high. Based on forecasts, ABE deliveries within the nearest 20 years will cost 480 - 500 billion dollars. The required volume of sales of civil aircraft GTEs and ground GTUs in Russia till 2015 is estimated as 400 - 600 billion roubles.

In the last few years the approach to ABE development has been fundamentally changed. The up-to-date methodology is based on a breakthrough scientific and technological background (new technologies, components and demonstration engines) ensuring cost and time cutting of development, certification and launching into manufacturing with a relatively small number of test engines (≤ 8-10). We can illustrate this approach by several typical examples of aircraft ABE development.

At present time the accurate analysis of 3D unsteady flow pattern in all modes allows to design an axial compressor stage with pressure ratio up to 2.5 – 2.6. The main combustors for the advanced engines use is a single zone chamber with a full premixing head part and a segmented flame tube. Main performances are the combustor efficiency 99.5% (cruise regime) and 98% (partial regime), the maximum temperature nonuniformity $\theta_{\max} < 1.25$, the pressure losses 5.5%. CIAM using a section of the modular combustor has demonstrated the possibility of achieving NOx emission levels that are 1.5 ÷ 2 times lower than those of the best modern combustors and showed the feasibility of attaining the goals set by NASA and CIAM.

The important direction in development of advanced GTEs is also a creation of single-stage turbines with high pressure ratios. The intensive calculation and experimental investigations carried out in CIAM have shown the possibility of creating highly efficient single-stage HPTs (including small-size turbines with *G=2.36* kg/s) having π_T up to $\pi_T^* = 4 \div 4.5$. Fig 4 demonstrates the flow path of such a turbine and its efficiency depending on a coefficient of velocity $Y = u / c_{a\partial}$. The efficiency of such a stage in the design mode is $\eta_T^* = 0.875$. For HPT blade with extensive convective - film cooling depth of cooling is $\theta = 0.65 \div 0.75$.



Flow passage

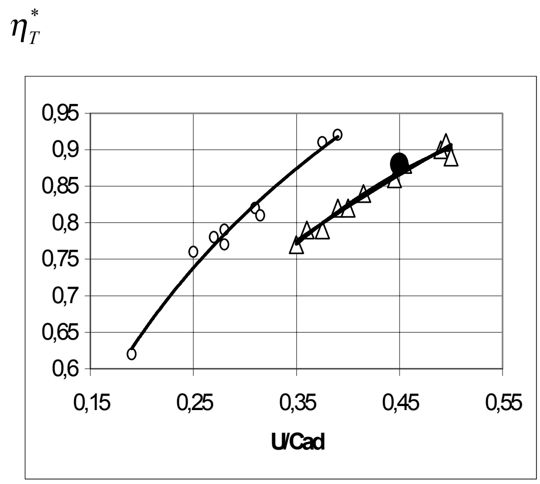


Fig. 4. Total efficiency as function of the velocity coefficient $Y = u / C_{ad}$
○ π^*_T = 3,2 – 3,7; Δ - π^*_T = 4,0; ●- design point

For a new generation engine family in Russia it is important to consider as base the middle thrust turbofan engine (near 12 tons) for a plane with 130-170 passengers. The core of this engine can be used for obtaining smaller (near 7-8 tons) and larger (up to 20 tons) thrust.

5. Near-term outlook

The next step in ABE development will be a natural continuation of development trends of the XX-th century. As regards the GTEs based on Brayton cycle, it is, first of all, a further increase in cycle parameters – the turbine entry temperature and the overall pressure ratio. In the near quarter of the century we should expect mastering the values of the stoichiometric range of maximum gas temperature $T_g^* = 2400 \div 2500\,\text{K}$. The overall pressure ratio of subsonic aircraft turbofans will be gradually growing up to $\pi_\Sigma^* = 70 - 100$.

Mastering the stoichiometric range will demand the development of new high-temperature designs of combustors (double-wall, ceramic, and so on) and the novel systems for cooling the HPT blades. Here, we should expect a wide use of rotor blades with intensive supercooling.

The application of effective thermal with barrier coatings and heat exchangers (in particular, for additional cooling of the secondary air) will become more extensive. The depth of blade cooling will increase up to values $\theta = (T_g - T_b)/(T_g - T_a) = 0.7 - 0.8$. The ecological characteristics of civil aircraft engines will be permanently under improvement.

At present, the advanced developments in theory and practice of ABE creation are being carried out within a number of ambitious programs. Among them we can mention the NASA Glenn Research Center program called UEET (Ultra-Efficient Engine Technology) [11], the European programs VITAL (Environmentally Friendly Aero Engine)[12] and NEWAC (New Aero Engine Concepts). Within the programs mentioned, the ways of significant improvement in efficiency and ecological friendliness of new engines (for example, 15% decrease in specific fuel consumption and 70% reduction of *NOx* relative to ICAO 1996 standard) will be indicative. A rather original advanced design of a counter-rotating low-pressure spool having a two-stage counter-rotating propfan and a counter-rotating multistage turbine without nozzle guide vanes can be considered as a characteristic example of the original design decisions.

6. Common aerodynamics of advanced ABE

Within the next few years the intensive investigations of variable cycle engines and combined turboramjets for advanced supersonic aircraft and aerospace vehicles will be continued. In particular, let us mention the work on a turbine-based combined cycle engine/ revolutionary turbine accelerator (TBCC/RTA) [13], which extends the range of GTE applications up to M=5. For creation of this engine it is necessary to develop methods of solving multidisciplinary, multicomponent, multilevel problems. In this regard, the project aimed at development of the NPSS system that has been carried out at NASA Glenn Research Center since 1994 is quite significant.

Here, we are going to dwell on a more specific question concerning development of a common profound theoretical approach to aerodynamics of the entire ABE flow path [14]. The common mathematical models developed within this cycle of work should be considered as high-level models based on the real 3D geometry of the engine flow path. Modeling of the operating process takes into account all basic real effects, such as viscous losses, fuel supply and burn, cooling air bleed and blowing out, rotor responsiveness, and others. It is a point of importance to be capable of modeling the variations in operating process as well as the variation in geometry and configuration of the ABE flow path that enables to calculate unsteady transitional operating modes of the engine and to determine its performance.

The characteristic examples of modeling the unsteady transitional process throughout the entire turbofan flow path are illustrated in Fig.5.

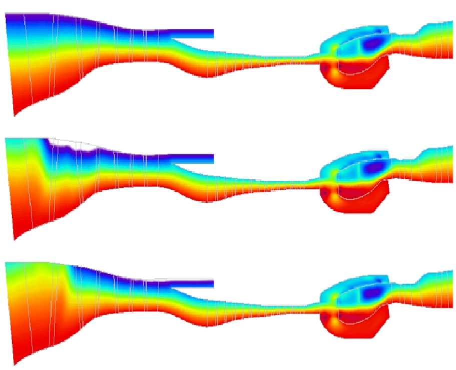


Fig. 5 Unsteady regime with inlet heat disturbance

This process develops under action of a thermal wave coming to the engine inlet. The detailed analysis of transients is very important for solving the problem of integration of a combined turbofan/ramjet engine or an augmented turbofan / ramjet/scramjet engine.

7. Long-term outlook

In conclusion, we will shortly dwell on one ABE theory direction, which possible practical realization could be expected in the very distant future. This direction considers the hypothetical propulsion system, in which the working medium is heated in an annihilation heat exchanger that transfers heat to air. Here, we deal with an ABE that uses antimatter (antihydrogen, antiprotons, positrons) as a fuel. The description of some theoretical features of this process one can find in [15,16].

From the standpoint of the up-to-date science, with the same share of confidence it is possible to offer an annihilation jet engine that uses the air-dark matter (ether) medium surrounding the Earth and the (ether) medium of our galaxy (the Milky Way) as a working medium. In this case, there is no need in a heat exchanger as the energy that releases in annihilation directly warms up the ether medium over the entire volume. So, we consider the air-ether breathing engine –AEBE (with the same configuration that is shown in Fig. 1). We emphasize again that the latest experiments, which demonstrated the presence of dark matter (ether), confirm the principal possibility of creating an AEBE in future and, in particular, a ramjet AEE (RAEBE), and using these engines in intragalactic flights (ether density in (halo) galaxies atmosphere is relatively high and can be enough for realization of the efficient RAEBE [17]. The hydrogen-oxygen mixture also can be used in AEBE/RAEBE as a fuel. In this case, the AEBE realization will not be regarded as a so long-term outlook.

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References

[1] Stechkin B.S., 1929: *Theory of ABE.* Air Flot Technique No. 2, pp. 96-103.
[2] Zhukovski N.E., 1882: About reaction of inlet and outlet fluid. *J. of Phys.-Chem. Soc*., Vol. XIV, No. 8.
[3] Zhukovski N.E., 1908: By theory of ships, driving by water flow out reaction. *Bull. Of Politech Soc.*, No. 8.
[4] Skibin V.A., Solonin V.I., Sosunov V.A., *2004: Aviation Motor – 100 years.* Air Flot technique, vol. 4-6.
[5] Maslennikov M.M., Shalman V.I., 1975: *Aviation GTE*, M., Mashinostroenie, 576 p.
[6] Akimov V.M., Bakulev V.I., Kurziner R.I., Poliakov V.V., Sosunov V.A., Shliakhtenko S.M., 1975: *Theory and calculation of ABE*, M., Mashinostroenie, 568 p.
[7] Shliakhtenko S.M., Sosunov V.A. (eds), 1979: *Theory of bypass turbojet engines*. M., Mashinostroenie, 432 p.
[8] Nechaev V.N., *1990: Theory of aviation engines*. M., VVIA by prof. N.E. Jukovskii, 704 p.
[9] Sosunov V.A., Kopchenov V.I., Rudakov A.S., Tskhovrebov M.M., 1993: Research and Development of Ram/Scramjets and Turboramjets in Russia, *AGARD-LS-194*.
[10] *CIAM 1980-2000, 2000: Scientific contribution in aviation engine development*, M., Mashinostroenie, Vol. 1, 460 p., and Vol. 2, 613 p.
[11] *Ultra-Efficient Engine Technology Program. 2002: Performance Report*. NASA Glenn Research Center.
[12] VITAL, 2004: Snecma Magazine, XI, pp. 28-33.
[13] Turbine-Based Combined Cycle (TBCC), 2003, NASA Glenn Research Center.
[14] Ivanov M.J., Nigmatullin R.Z., 2001: Simulation of steady and unsteady working processes in gas turbine engines. *In «Some*

Aero-Thermo-Fluid Aspects in Airbreathing Propulsion», CIAM, pp. 1-27.
[15] Forward R., 1985: Antiproton annihilation propulsion. *Journal of Propulsion and Power*, Vol. 1, No. 5, pp. 370-374.
[16] Cassenti B., 1989: Conceptual designs for antiproton space propulsion systems. *AIAA paper* No. 89-2333, 8p.
[17] Ivanov M.Ja., Terentieva L.V., 2004: *Gas-dynamics elements of dispersive medium*, M., Informconversion, 152 p.