Chapter

Performance Assessment of the Thermodynamic Cycle in a Multi-Mode Gas Turbine Engine

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Abstract

This chapter discusses the direction of development of promising multimode aviation gas turbine engines (GTE). It is shown that the development of GTE is on the way to increase the parameters engine workflow: gas temperatures in front of the turbine (T^*_G) and the degree of pressure increase in the compressor (P^*_C). It is predicted that the next generation engines will operate with high parameters of the working process, T^*_G = 2000–2200 K, π^*_C = 60–80. At this temperature of gases in front of the turbine, the working mixture in the combustion chamber (CC) is stoichiometric, which sharply narrows the range of stable operation of the CC and its efficiency drops sharply in off-design gas turbine engine operation modes. To expand the range of effective and stable work, it is proposed to use an advanced aviation GTE: Adaptive Type Combustion Chamber (ATCC). A scheme of the ATCC and the principles of its regulation in the system of a multi-mode gas turbine engine are presented. The concept of an adaptive approach is given in this article. There are two main directions for improving the characteristics of a promising aviation gas turbine engine. One is a complication of the concepts of aircraft engines and the other one is an increase in the parameters of the working process, the temperature of the gases in front of the turbine (T^*_G) and the degree of increasing pressure behind the compressor (π^*_C). It is shown how the principles of adaptation are used in these areas. The application of the adaptation principle in resolving the contradiction of the possibility of obtaining optimal characteristics of a high-temperature combustion chamber (CC) of a gas turbine engine under design (optimal) operating conditions and the impossibility of their implementation when these conditions change in the range of acceptable (non-design) gas turbine operation modes is considered in detail. The use of an adaptive approach in the development of promising gas turbine engines will significantly improve their characteristics and take into account unknown challenges.

Keywords: thermodynamic cycle, gas turbine engine, combustion chamber, adaptation principle, aviation

1. Introduction

This chapter analyses the main trends in the development of an aviation multi-mode gas turbine engine (GTE) of direct reaction, examines its thermodynamic cycle and determines the influence of the multi-mode GTE on its efficiency, analyses the multi-mode operation of a multi-purpose aircraft and analyses ways to improve operation of the thermodynamic cycle in non-design modes of GTE operation. The energy capabilities of traditional aviation fuels for the implementation of high thermodynamic characteristics in non-design gas turbine engine operation are studied. The adaptive approach is determined as the main one in the creation of promising aviation GTEs. The concept of an adaptive approach is given. There are two main directions for improving the characteristics of the promising aviation GTE.

One is the sophistication of the schematic diagrams of aircraft engines and the second one is an increase in the parameters of the working process, the temperature of the gases in front of the turbine (T_G^*) and the degree of pressure rise behind the compressor (π_C^*).

It is shown how the principles of adaptation are used in these areas. The application of the adaptation principle in resolving the contradiction of the possibility of obtaining the optimal characteristics of the high-temperature combustion chamber (CC) of the GTE under the design (optimal) conditions of operation and the impossibility of their implementation when these conditions change in the range of permissible (non-design) operating modes of the GTE are considered in detail. The use of an adaptive approach in the development of promising gas turbine engines will significantly improve their characteristics and take into account unknown challenges.

2. The main trends in the development of aviation gas turbine engines

The world leaders in aircraft engine manufacturing prefer the traditional ("soft") direction of the development of aircraft gas turbine engines. In accordance with the theory of aircraft engines, the development of the traditional direction of aircraft gas turbine engines occurs in accordance with the following priorities:

- ensuring high efficiency;
- stable operation in a wide range of speeds and flight altitudes of the aircraft;
- ensuring high dynamic characteristics;
- reliable high-altitude and ground launch;
- ensuring high environmental performance (reducing harmful emissions and reducing noise levels);
- ensuring acceptable performance under icing conditions and other difficult climatic conditions;
- widening of the range of work due to ensuring the operation of the engine with a minimum degree of stability;
- the ability to operate on various fuels (alternative).

At present, aviation GTEs has reached a high level of development and has:

- a high level of thermodynamic perfection;
- high aerodynamic loading of blades (compressors, turbines);

- marginal combustion intensity and ecological perfection of combustion chambers;
- effective thermal protection of the elements of the hot path of the engine;
- low specific gravity;
- multi-mode operation;
- new materials in engine design (steel and composite materials);
- highly efficient constructive and technological solutions.

The main regularity in the development of aviation GTEs is the consistent improvement of the indicators of technical perfection and the efficiency of their use on aircraft. This pattern is continuous and progressive, reflecting the need to accumulate the required amount of knowledge, understanding the experience of previous developments and operation, mastering new technologies for creating highly efficient units and elements of aviation GTE.

The traditional way to improve the efficiency and traction characteristics of a GTE is to increase the efficiency of the thermodynamic cycle of the engine:

- increase in the total degree of pressure increase in the cycle (1):

$$\pi^*_{C\Sigma} = {}^{P^*_C}/_{P^*_A}, \tag{1}$$

where:
($P^*_C -$ pressure behind the compressor, $P^*_A -$engine entrance pressure);

- increase in turbine intake temperature(T^*_G);
- reduction of total pressure losses in the air intake and outlet devices.

Within the framework of the traditional approach of improving the efficiency of aircraft gas turbine engines, there is also some reserve associated with improving the main components of the aircraft engine.

However, it should be stated that further improvement of the characteristics of aviation GTEs within the framework of traditional layouts is associated with ever-increasing difficulties.

The main qualitative changes, in accordance with thermodynamics and heat exchange, are associated with the creation of turbines and combustion chambers capable of operating at turbine intake temperature which is at the level of 2100–2400 K, bringing the turbine inlet temperature closer to the maximum energy potential of aviation fuel, and requiring new solutions for realization of such temperatures in aircraft gas turbine engines.

As noted earlier, the development of aircraft gas turbine engines follows the path of a constant increase in the parameters of the working process, an increase in the turbine inlet temperature ($\mathrm{T^*}_\mathrm{G}$) and an increase in the total of pressure increase degree in the engine ($\pi^*_{C\Sigma}$).

An increase in $\mathrm{T^*}_\mathrm{G}$ with a simultaneous increase in $\pi^*_{C\Sigma}$ leads to an increase in the specific engine thrust $\mathrm{R_S = R/G_A}$ (R - engine thrust, $\mathrm{G_A}$ - air flow through the engine) and frontal thrust $\mathrm{R_F = R_{TO} / F_m}$ ($\mathrm{R_{TO}}$ - engine thrust at take-off, $\mathrm{F_m}$ - the area of the mid-section of the engine) .

GTE generation	I	II	III	IV	V	VI
T_G*, K	1000–1150	1150–1250	1300–1450-	1500–1650	1700–1900	2100–2200
$\pi^*_{C\Sigma}$	3–5	7–13	14–20	20–35	20–50	60–80

Table 1.
The growth trend of T^*_G *and* $\pi^*_{C\Sigma}$ *for different generations of aviation gas turbine engines.*

The higher R_F, the smaller the frontal dimensions of the engine and the specific gravity of the engine $Y_{ENG} = G_{ENG}/R_F$ (G_{ENG} - engine mass). Parameters R_F and Y_{ENG} – characterize the level of perfection of the engine.

An increase in the values of T^*_G and π^*_C lead to an increase in the work of the thermodynamic cycle and efficiency. **Table 1** shows the growth trend of T^*_G and $\pi^*_{C\Sigma}$ for different generations of aviation gas turbine engines [1].

One important feature of a promising multi-mode aircraft is flight at supersonic cruising modes, which should be carried out at non-boosted engine operating modes.

A promising direction for meeting this requirement is the creation of the so-called stoichiometric motors. In these engines, all of the oxygen in the air entering the gasifier is used to burn fuel in the main combustion chamber to obtain a high T^*_G.

Obtaining T^*_G = 2000–2200 K in the combustion chamber of a promising gas turbine engine requires that the excess air ratio of the combustion chamber $\alpha_{CC} = G_A/G_F L_O$ (G_A - the air flow rate entering the combustion chamber, G_F - the fuel flow rate entering the combustion chamber, L_o - the theoretically required amount of air for complete combustion of 1 kg of fuel, for aviation kerosene $L_O = 14.8$) was α_{CC} = 1.1–1.2 (to describe the fuel composition a description of the following dependence is used: air / fuel ratio).

The urgency of creating high-temperature (stoichiometric) gas turbine engines, in the direction of increasing the efficiency of the thermodynamic cycle and ensuring their multimodality, poses a number of new problems. These tasks are associated with the peculiarities of the organization of the fuel combustion workflow to obtain high turbine inlet temperature and the efficient use of the energy potential of the fuel in the entire range of the GTE operation.

3. Thermodynamic cycle of the direct reaction aircraft GTE

As mentioned above, the parameters of the working process of aviation GTE $\pi^*_{C\Sigma}$ and T^*_G with the development of engines are constantly increasing. Such a tendency in the development of aviation GTE as a heat engine, in accordance with the theory of aircraft engines, is natural. Put simplistically, the main components of a modern aviation GTE are:

- a heat engine operating according to a thermodynamic cycle with heat supply to the working fluid (implementing the Brighton cycle);

- propulsion device - a device for converting the available work, obtained as a result of the thermodynamic cycle, into thrust, depending on the type of gas turbine engine;

- automatic control system (ACS), which ensures the maintenance of the necessary engine operating modes.

Based on the basic provisions of the theory of aircraft engines, the energy balance of aviation GTE of a direct reaction can be represented in a simplified way by a diagram that displays all stages of the process of converting the chemical energy of fuel into useful work.

In a direct reaction GTE, atmospheric oxygen is used to convert the chemical energy of the fuel into thermal energy. Air serves as the main component of the working fluid for the thermodynamic cycle, in which thermal energy is converted into mechanical energy. Receiving acceleration in the propulsion system, it creates a thrust force, i.e. serves as a propulsion device. Direct reaction engines are turbojet engines and turbofan engines. **Figure 1** shows a simplified diagram of the energy balance of a direct reaction GTE.

In the diagram on the **Figure 1**:

$Q_0 = \frac{G_F H_u}{G_A}$ - the amount of thermal energy introduced into the engine with fuel per 1 kg of working body (chemical energy of the fuel);

G_F –fuel consumption;

G_A –air consumption;

H_u –lower calorific value of fuel;

Q - the actual amount of heat energy received during fuel combustion.

The real process of heat release is accompanied by losses and is characterized by the fuel combustion efficiency (η_g = Q/Q$_0$).

L_C – the work of the thermodynamic cycle of the engine, which results in an increase in the kinetic energy of the exhaust gases, can be represented for multimode aircraft real cycle in the following formula (2) [1]:

$$L_C = C_p T_H \frac{e-1}{\eta_c}\left(\frac{\overline{m}\Delta\eta_c\eta_e}{e} - 1\right), \tag{2}$$

where: η_c, η_e – the efficiency of the compression and expansion processes, i.e., they characterize the technical perfection of the compression and expansion process;

$\Delta = \frac{T_G^*}{T_H}$ – working body heating degree;

T_H – ambient air temperature;

$\overline{m}$ – coefficient taking into account the difference in the physical properties of air and gas;

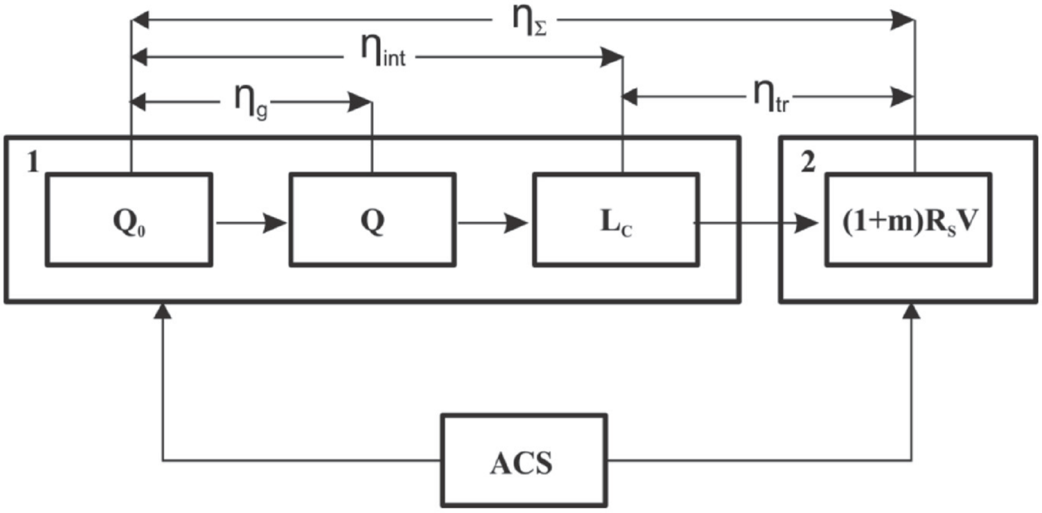

Figure 1.
Simplified diagram of the energy balance of a direct reaction GTE: 1- heat engine; 2 - propulsion device; ACS - automatic control system.

e = $\pi_{k\Sigma}^{*\frac{k-1}{k}}$;

C_p – specific heat of heat supply at constant pressure.

The operation of the actual thermodynamic cycle of a GTE depends both on the parameters of the working process $\pi_{C\Sigma}^{*}$, Δ, and on the technical perfection of the compression and expansion processes $(\eta_{c,}\ \eta_e)$.

$\eta_{int} = \frac{L_C}{Q_0}$ - internal coefficient efficiency of the GTE thermodynamic cycle (motor thermodynamic efficiency), i.e. the efficiency of the engine as a heat engine serves to assess the efficiency of heat conversion into cycle work, is given in the following relation: $(\eta_{int} = \frac{L_C \eta_g}{Q})$.

The internal efficiency of the GTE thermodynamic cycle takes into account the inevitable heat losses associated with the costs of overcoming hydraulic losses, as well as heat losses due to incomplete fuel combustion and recoil to the engine walls.

$\eta_{tr} = \frac{2}{1+\frac{C_j}{V}}$ - propulsive efficiency, which characterizes the operation of a direct reaction gas-turbine engine as a propulsion device [1]:

where:

C_j – nozzle flow rate;

V – flight speed.

(1 + m)R_SV – effective work (jet thrust),

where: m = $\frac{G_{A2}}{G_{A1}}$ - bypass ratio (G_{A2} – air flow through the second engine circuit, G_{A1} – air flow through the gas generator).

$\eta_{\Sigma} = \eta_{int}\eta_{tr}$ – the overall efficiency of the direct reaction GTE, which characterizes the share of chemical energy of the fuel converted into effective work, takes into account all the losses in the process of converting heat into effective work, and thus most fully characterizes the efficiency of the GTE .

ACS - automatic engine control system that regulates the operation of the GTE of both the heat engine and the propulsion unit in various flight modes of the aircraft, in order to obtain maximum performance.

Figure 2 shows the values of the level of efficiency of GTE for some engines of civil aviation, considering the degree of bypass (m) [2, 3].

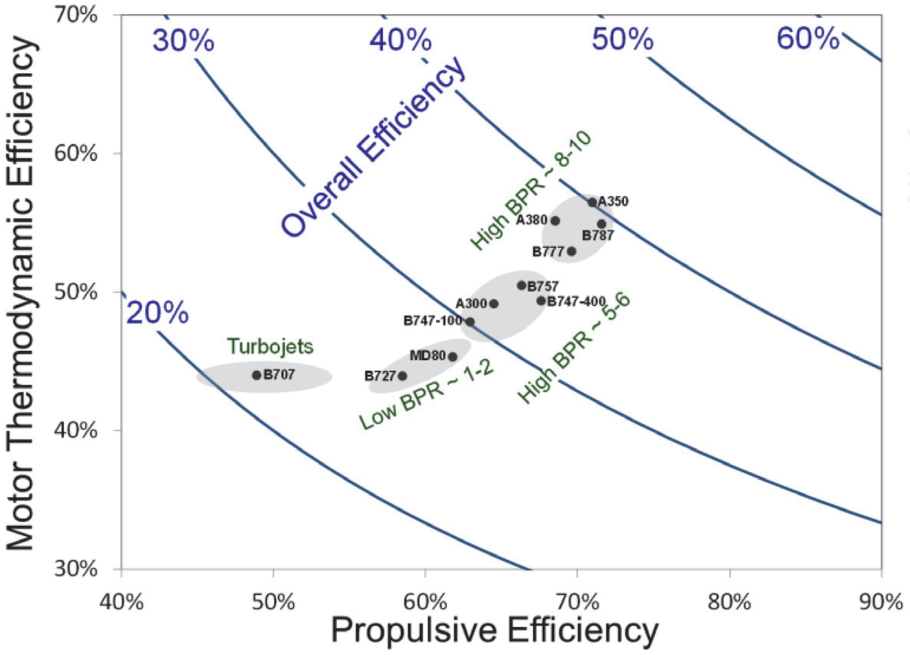

Figure 2.
Commercial aircraft gas turbine engine efficiency trend BPR, bypass ratio. Reproduced with the permission of United Technologies Corporation, Pratt & Whitney [2, 3].

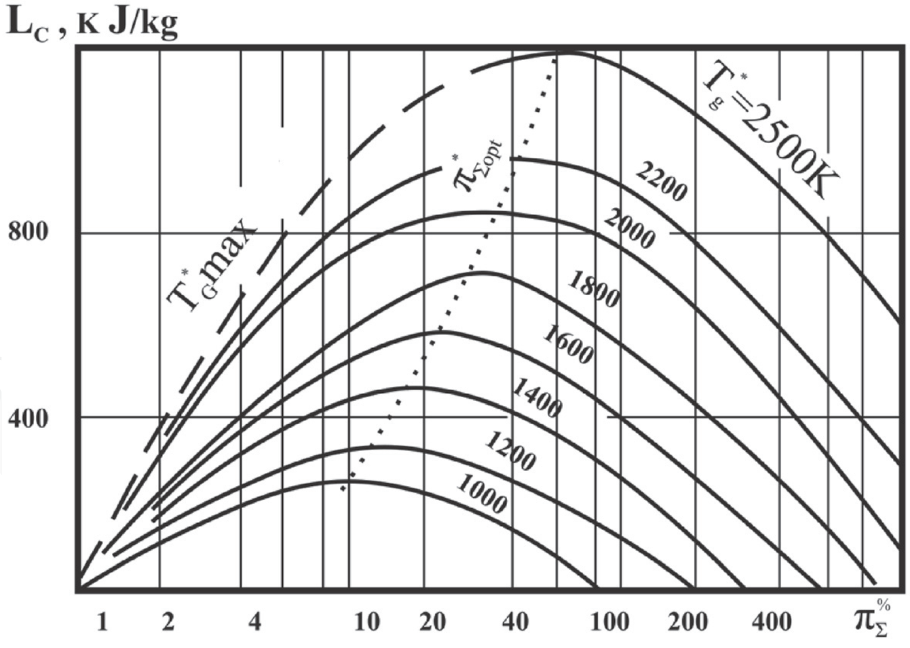

Figure 3.
Dependence of the cycle L_C *from* $\pi^*_{C\Sigma}$ *if* T^*_G *= var. and* T^*_H *= const.*

Figure 3 shows the dependence of the cycle L_C on the parameters of the working process of the direct reaction gas turbine engine. The graph shows that for a promising multi-mode bypass turbofan engine at $\pi^*_{C\Sigma} = 28$ the turbine inlet temperature will be $T^*_G \approx 1700$ K, while the degree of bypass is m ≈ 0.57.

4. Multi-mode aviation GTE of direct reaction

As a rule, aviation GTEs are designed for the maximum power mode, which provides the maximum parameters of the thermodynamic cycle and which are optimal. The geometry of the gas-turbine engine flow path also optimally corresponds to this mode and the parameters of the thermodynamic cycle. Other modes of GTE operation, which have their own optimal parameters of the thermodynamic cycle and which must correspond to their own geometry of the GTE flow path, are taken as compromises with the engine flow path unchanged. Engines of multipurpose supersonic aircraft differ from engines of subsonic aircraft in the requirement of multimode.

In a certain sense, any aircraft is multimode, but the most multimode is typical for military aircraft, the aircraft which must perform a wide range of varied tasks, which are characterized by a wide range of speeds and flight altitudes. Thus, the fighter's engine must provide high thrust when accelerating and intercepting supersonic targets at high altitudes and when conducting air combat at medium altitudes in a wide range of aircraft flight speeds, as well as having high efficiency when flying at subsonic speeds at high altitudes and near the ground. Since each flight mode of an aircraft is characterized by its own optimal parameters of the thermodynamic cycle, compromise decisions are made in the design of the engine and its control systems.

The provision of supersonic flight in non-afterburner mode is especially acute for engines of military multipurpose aircraft. Provision of supersonic cruise flight in non-afterburner mode requires the creation of a large thrust from the engine. One of the ways to solve this problem is to increase the turbine inlet temperature (T^*_G), in the future to stoichiometric. The result of analyzing the main flight modes of a

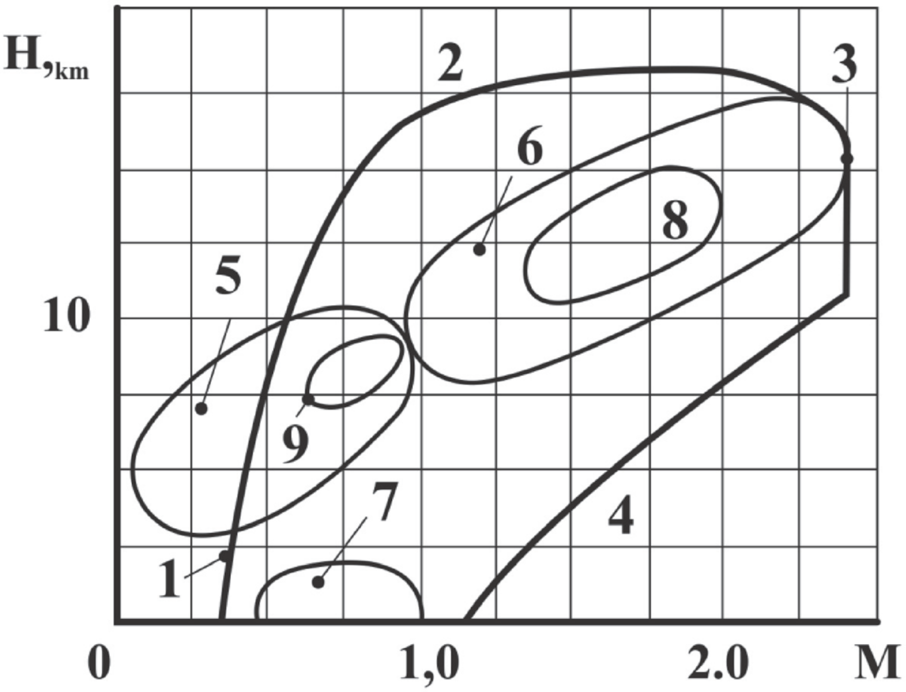

Figure 4.
Areas of the main flight modes of a multi-mode aircraft: 1- on the bearing properties of the wing, 2- on the thrust capabilities of the engine (static ceiling), 3- on kinetic heating, 4- on the strength of the aircraft (high-speed head); flight modes: 5- subsonic maneuverable combat, 6- interception, 7- attacks of ground targets, 8- supersonic cruising flight, 9- subsonic cruising flight.

multi-mode aircraft [4, 5] is represented in **Figure 4**, it shows the areas of the main flight modes of a multipurpose aircraft.

The engines of multi-mode aircraft have high values of the parameters of the working process. This is due to gaining an advantage over a potential enemy. Engines of civil aircraft with high parameters of the working process have an advantage in the combat, because their efficiency will be better. It becomes important to create aviation gas turbine engines that work effectively in all flight modes of aircraft, i.e. adapt the engine to the appropriate operating mode. The higher the thrust-to-weight ratio of the aircraft, the more it is necessary to throttle the engine in cruise mode, especially for stoichiometric engines.

When the engine is throttled, its internal efficiency decreases sharply due to a strong decline $\pi^*_{C\Sigma}$ when decreasing T^*_G . This leads to a decrease of L_C at this engine operating mode.

To increase L_C at throttle modes (non-design modes of GTE operation), as can be seen from formula (1), it is necessary to increase the efficiency of compression (η_C) and efficiency enlargement (η_e) of the thermodynamic cycle.

5. The main directions of increasing the efficiency of GTE of direct reaction in non-design (throttle) modes

Increasing the efficiency of the GTE of direct reaction in off-design modes is achieved by regulating the elements of its flow path. To increase the efficiency of compression (η_C) in non-design modes, regulation elements are used:

- air intake device for supersonic aircraft;
- rotation of the engine fan blades with a high bypass ratio;

- rotation of the guide vanes of the compressors of individual stages or a group of stages;
- the use of a bypass GTE scheme, which makes it possible to redistribute the air flow between the gas generator by the second or third circuits (regulation of the degree of bypass (m));
- the use of two or three compressor stages in the design of a gas turbine engine, while there is a spontaneous change in the rotational speed of individual stages;
- the use of a slotted air bypass above the rotor blades of the first compressor stages;
- regulation of the radial clearance in the last stages of the compressor;
- bypassing air from individual sections of the compressor flow path to the atmosphere, the second circuit, or into any section of the gas-air duct with reduced pressure (as a rule, it is not used in advanced engines).

A characteristic feature of promising aircraft gas turbine engines is the use of complex schemes with high parameters of the working process, in which several methods of compressor control are used. To increase the efficiency enlargement (η_e) the following regulation elements are applied:

- regulation of gas turbines GTE by turning the nozzle apparatus;
- regulation of radial clearances of working blades of gas turbines;
- regulation of mixing chambers (for gas turbine engines with mixing flows);
- regulation of output devices.

It should be noted that in modern and promising gas-turbine engines, the regulation of the flow path occurs in a complex manner according to regulation programs, depending on the properties of the joint operation of the elements of the flow path of the aviation GTE. At the same time, the greatest effect of obtaining high values of efficiency of compression and expansion processes at non-design modes of GTE operation is observed.

6. Influence of the GTE operating mode on the energy characteristics of the fuel

The source of thermal energy for the implementation of the thermodynamic cycle of aviation GTE is aviation fuel. In connection with the aforesaid, there is an acute issue of the efficiency of fuel use, reduction of its consumption while obtaining the maximum possible thermal energy. The main aviation fuel, today, for jet aviation is aviation kerosene, obtained from oil. Despite the development of alternative fuels, aviation kerosene will remain the main fuel for jet aircraft in the near future. The most common brands of aviation kerosene used in civil and military aviation, and their main characteristics, are presented in the source [6, 7].

An important parameter characterizing the energy capabilities of fuel for a multi-mode GTE is the fuel heat output. Heating capacity characterizes the energy capabilities of the fuel-air mixture, taking into account the efficiency of the organization of the working process in the engine combustion chamber. Fuel heating capacity (Q_t) is determined from the relation (3):

$$Q_t = \frac{H_u \eta_g}{1 + \alpha_{cc} L_0}, \tag{3}$$

where:
Q_t –heating capacity (lowest), kJ/kg;
H_u - lower calorific value, kJ/kg;
L_0 – stoichiometric coefficient, kg air/kg fuel;
η_g – fuel combustion efficiency;
α_{cc} – excess air ratio in the combustion chamber.

From formula (3) it follows that the fuel heat output depends on the operating mode of the gas turbine engine.

Thus in non-design modes α_{cc} will take on larger values than in the design mode of operation of the GTE, then the heat output of the fuel in these modes will decrease. This will lead to an increase in fuel consumption in these engine operating modes.

The results of previous research in the field of changes in α_{cc} can be represented in the following way in **Figure 5**. It shows the range of variation of the excess air ratio in the combustion chamber of a turbojet engine of a maneuverable aircraft. For a turbofan engine the excess air ratio will vary in a smaller range. This is due to the fact that part of the air will be bypassed into the second circuit, bypassing the gas generator (first circuit).

A typical change in the excess air ratio can be shown schematically in the following form in **Figure 6**. It shows a typical change in the excess air ratio in the combustion chamber when changing the operating mode of the gas turbine engine. Point 2 corresponds to the maximum operating mode of the engine (design mode), point 1 corresponds to the operating mode of the minimum power, which is

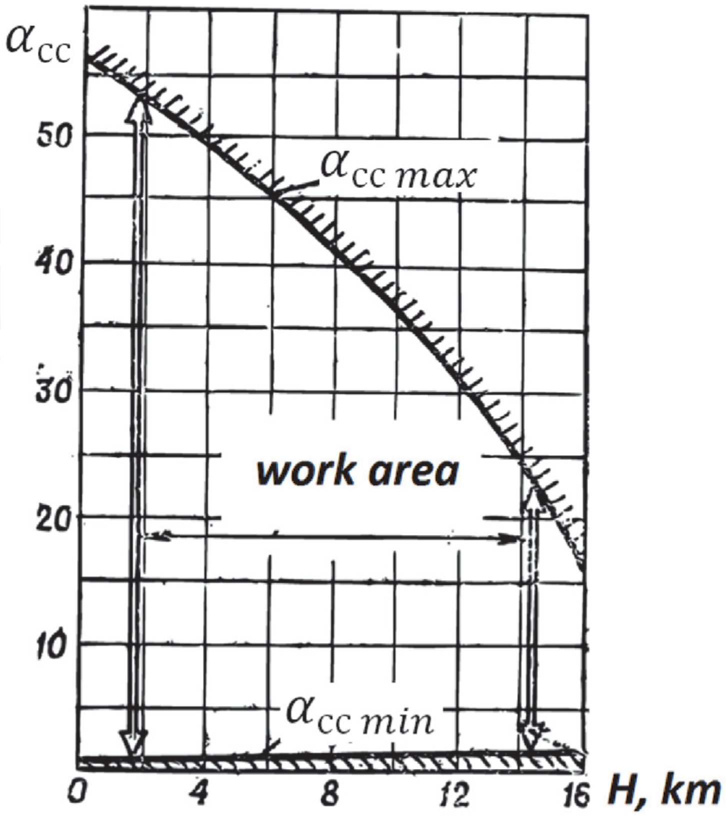

Figure 5.
Range of α_{CC} variation in GTE multi-mode (maneuverable) aircraft.

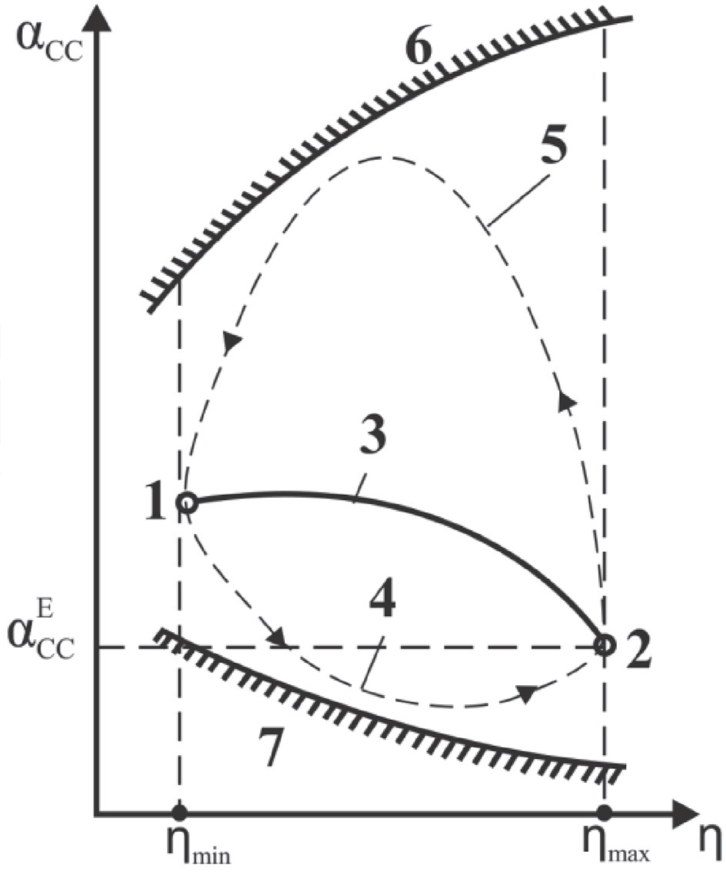

Figure 6.
Typical change in excess air ratio α_{cc} in the combustion chamber of a gas turbine engine when changing its operating mode.

characterized by increased values of the excess air factor in the engine compressor, 3- steady-state modes of GTE operation, 4- throttle response, 5- gas discharge, 6- lean flameout in the combustion chamber, 7- rich flameout in the combustion chamber, α_{cc}^{E}– the calculated value of the excess air ratio in the combustion chamber.

As it can be seen from **Figure 6**, a change in the operation of a gas turbine engine leads to a strong change in the excess air ratio in the combustion chamber, which greatly affects the efficiency of fuel combustion efficiency (η_g)this also reduces the heat output of the fuel (Q_t), which, accordingly, reduces the coefficient of the GTE thermodynamic cycle η_{int}, and in the end full efficiency of the engine (η_Σ) decreases. This situation is typical for any direct reaction aircraft GTE, and the parameter values depend on the specific engine and its purpose.

At the design operating mode of the GTE (maximum power mode), α_{cc} = 2.0–2.5, η_g= 0.98–0.99, which corresponds to the modern level of development of aviation gas turbine engines, the heat output of aviation kerosene is 1103–1385 kJ/kg - design modes, fuel heating capacity (Q_t) less than 500 kJ/kg.

For promising high-temperature (stoichiometric) aviation GTEs in the design mode (maximum power mode),

α_{cc} = 1.0, η_g= 0.99, the heating capacity will be approximately 2682 kJ/kg. Thus, the multimodality of aviation GTE significantly determines the efficiency of fuel use in an engine. As noted earlier, each mode of operation of aviation GTE also corresponds to its own optimal parameters of the thermodynamic cycle, which are characterized by the effective operation of the engine in this mode. Therefore, it is important to ensure optimal and efficient use of fuel in all modes of GTE operation to obtain these parameters, taking into account that the geometry of the engine is optimally designed for efficient operation only at the maximum power mode. Fuel properties play one of the key functions in the formation of the technical appearance of an aviation GTE and its design.

Flight technical and operational characteristics of an aircraft to the greatest extent depend on such fuel properties as density (ρ), and heat of combustion (H_u). Influence of the type of fuel on the working process and the main parameters of the GTE, thrust (R) and specific fuel consumption (C_R), is (mainly) due to the calorific value of the fuel and the thermophysical properties of combustion products with air. Maximum possible theoretical turbine inlet temperature (T_G^*) (in the first approximation) for aviation kerosene can be determined by the relation (from the basic course in the aviation engine technology):

$$T_{Gmax}^* = T_C^* + \frac{H_u \eta_g}{\alpha_{cc} L_0 C_p}. \tag{4}$$

From the Eq. (4) it follows that T_{Gmax}^* generally depends on T_C^*, excess air ratio in the combustion chamber(α_{cc}) and the relation H_u/L_0 . By increasing α_{cc} the temperature T_{Gmax}^* decreases.

As follows from **Figure 7**, the maximum gas temperature $\left(T_{Gmax}^*\right)$ is achieved at α_{cc} = 1.0, thus, at the stoichiometric value. The range of maximum value of T_G^* is very narrow and by increasing α_{cc}, T_{Gmax}^* will decrease rapidly. This leads to a decrease in the possibilities of full use of the energy potential of the fuel, and in some cases it can lead to the impossibility of the combustion process.

Figure 8 shows a typical characteristic of the combustion chamber from which it follows that in the entire range of variation of the excess air coefficient in the combustion chamber (α_{cc}) there is a single value α_{cc}^E at which the combustion

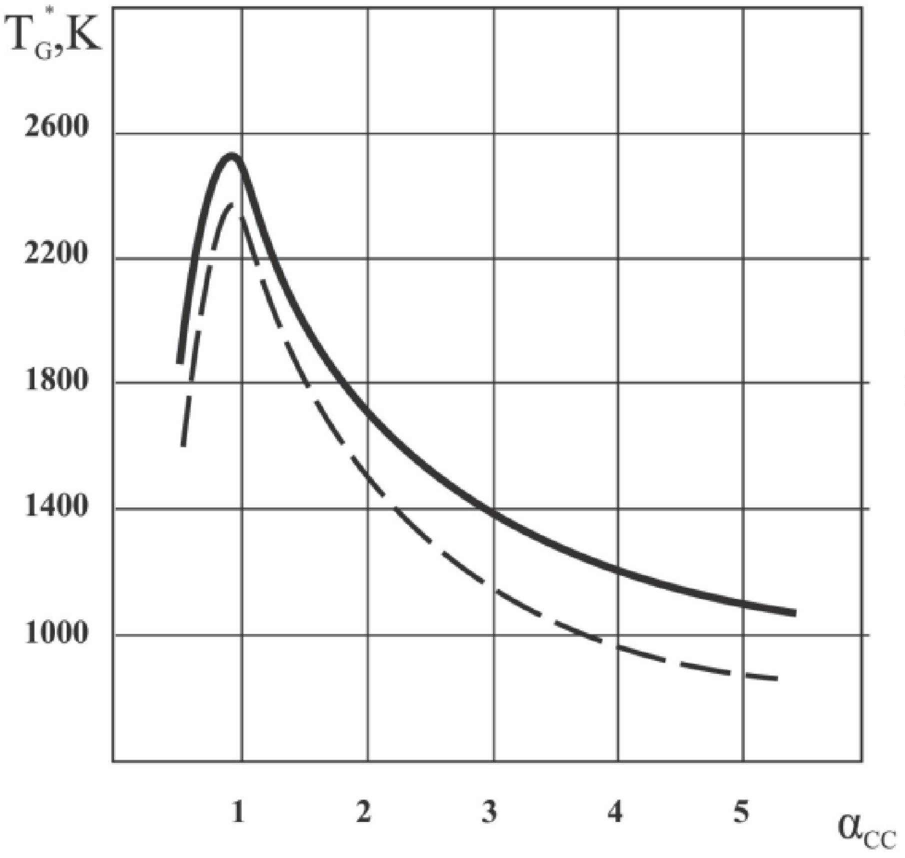

Figure 7.
Calculated dependence of the temperature of fuel oil combustion products on the excess air ratio: —— at T_C^* *= 600 K; - - -* T_C^* *= 300 K.*

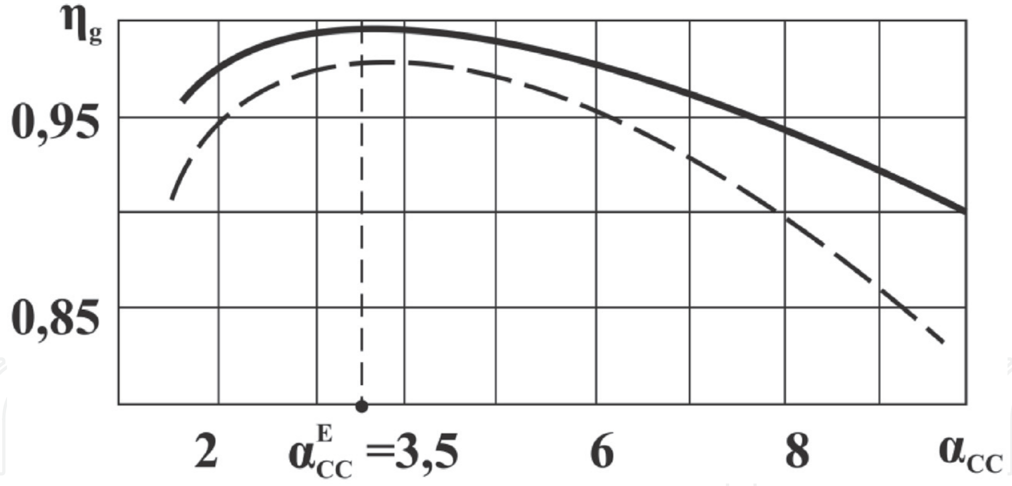

Figure 8.
Typical characteristic of the combustion chamber is represented in the following way: The dependence of the fuel combustion efficiency (η_g) from the excess air ratio in the combustion chamber (α_{cc}). The calculated excess air ratio for a given combustion chamber is α^E_{cc} = 3,5, ——————— T^*_{Cmax}, - - - - T^*_{Cmin}.

efficiency (η_g) has a maximum value. This is true for all combustion chambers of a conventional GTE.

Thus, it follows from the above analysis that the maximum energy characteristics of jet fuel can be obtained in a very narrow range of operation of traditional (non-regulated) combustion chambers. And the optimal operating mode of the compressor station at which the maximum heat release occurs corresponds only to a single value of the excess air coefficient (α^E_{cc}) in the combustion chamber and it corresponds to the calculated (maximum) value of the engine operating mode.

To evaluate the operation of the compressor station with control elements in the multi-mode GTE system, we introduce the coefficient of fuel heat output (q_t) (5):

$$q_t = \frac{Q_{ti}}{Q_{tr}}, \tag{5}$$

where:

Q_{ti} - fuel heating capacity at the i-th mode of GTE operation;

Q_{tr} - heating capacity of fuel at the design (maximum) mode of operation of the GTE.

The coefficient of fuel heat output shows the use of the thermal capabilities of the fuel depending on the operating mode of the GTE. Each mode of GTE operation corresponds to its own excess air ratio in the combustion chamber (α_{CCi}). For high-temperature (stoichiometric) combustors with elements for regulating the geometric dimensions and composition of the mixture in the combustion zone, the coefficient of heat output shows their technical perfection, i.e. obtaining the maximum possible heating capacity of the fuel in throttle (non-design) modes of the GTE.

The above analysis shows that, aviation kerosene still has a sufficient reserve for the implementation of high thermodynamic characteristics for promising GTEs for the near future. However, in order to realize the great thermodynamic capabilities of fuel in a multi-mode GTE, a new approach to the development of promising GTEs is required.

7. The principles of adaptation of a promising multi-mode GTE

The essence of the approach for realizing the large thermodynamic capabilities of the GTE should be based on the fact that each operating mode of the engine should be optimal (calculated). This means that the gas path of the GTE and the engine automatics must correspond to obtaining the maximum engine characteristics in these modes. In other words, the gas path of the GTE and the automatic engine control system must adjust (adapt) to each operating mode of the engine in order to increase the work of the thermodynamic cycle in these modes, i.e. increase in total efficiency of GTE.

Adaptation refers to the ability of technical devices or systems to adapt to changing environmental conditions or to their internal changes, which leads to an increase in the efficiency of their functioning. For promising aircraft gas turbine engines, this is expressed in the application of regulation of the elements of its flow path, depending on the mode of its operation, as well as the use of an adaptive control system for its operation. The means of adaptation are the adjustable elements of the GTE flow path (part 5) and the engine control system. Continuous increasing requirements for the flight performance of maneuverable aircraft necessitate continuous improvement of the characteristics of the aviation GTE. As already noted, the improvement of the characteristics of the aviation GTE goes along two” soft “directions.

The first is the complication of the schematic diagrams of aviation GTEs, with the simultaneous implementation of regulation of the elements of its flow path, in accordance with the operating mode of the engine, that is, the use of its adaptation.

The second is to increase the parameters of the GTE working process, the turbine inlet temperature $\left(T_G^*\right)$ and the degree of compressor delivery pressure$\left(\pi_C^*\right)$.

Moreover, in these areas of development of aviation GTE, the adaptation process is widely used in order to obtain high performance in all modes of GTE operation.

If the adaptation of promising aircraft GTEs is carried out mainly by adjusting the elements of the flow path of the engine, as is customary, according to rigidly specified programs, depending on the operating mode, then it is clear that automatic control according to a given rigid program does not implement extensive adaptation and automation capabilities. In other words, there is a shortage of potential capabilities of the characteristics of the GTE, from this it follows that the evolution of the means of adaptation of the GTE comes into conflict with the control methods.

The operational ranges of changes in the characteristics of promising multimode aircraft are so wide that the control of the GTE without adaptation means becomes more and more difficult.

The rigidity of the program for regulating the elements of the GTE reduces the achievable effect of automation of maintaining the constraints. With tough regulation programs, the engine does not pick up its potential capabilities, i.e. its potential for gas-dynamic stability in the area of possible operation is not fully used.

The contradictions between the completeness of using the capabilities of the GTE and its limitations can be resolved only on the basis of the use of adaptive multi-parameter control systems with the simultaneous development of regulation of the elements of the GTE flow path in accordance with the mode of its operation, i.e. engine adaptation.

8. The application of adaptive approach in complicating the concept of aviation GTEs

Figure 9 shows a hypothetical adaptive GTE with control elements for its flow part, where: 1-rotary guide vanes of the fan; 2- air bypass into the second circuit; 3-rotary guide vanes of the compressor; 4-adjustable radial clearances in the last

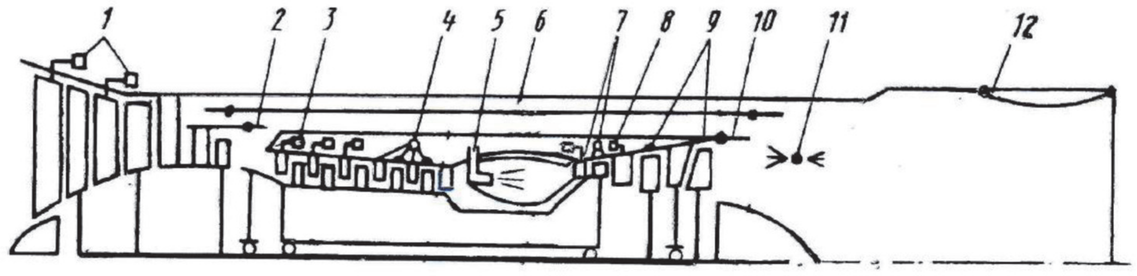

Figure 9.
Hypothetical adaptive GTE: Source [8, 9] provides information about the Adaptive Versatile Engine Technology (ADVENT) program, which later switched to the Adaptive Engine Technology Development (AETD) program, which provides for the creation of a new type of aviation GTE for aircraft of the 5th and 6th generation.

stages of the compressor; 5-fuel supply to the adaptive combustion chamber; 6-adjustable third circuit; 7- adjustment of the compressor turbine (rotary blades of the nozzle apparatus and adjustable radial clearance of the impeller); 8-rotary blades of the nozzle apparatus of the fan turbine; 9-adjustable radial clearances of the fan turbine; 10- adjustable mixing chamber; 11-fuel supply to the afterburner; 12-adjustable nozzle.

The overall goal of the programs is to create a promising GTE, which consumes 25% less fuel, creates 10–20% more traction than existing GTEs.

Such a significant improvement in the parameters is achieved due to the complexity of the concept of a GTE and the use of various adaptation mechanisms.

The bypass turbofan engine provides for the availability of an adjustable third circuit (**Figure 9**, item 6), which is included in the operation only in the cruise (economic) flight mode, while significantly increasing the overall bypass ratio (m).

At high and maximum power modes, the circuit switches to low bypass levels, which allow increasing the traction characteristics of the engine in these modes.

Analyzing changes in specific thrust (R_S) and specific fuel consumption (C_R) depending on the bypass ratio, we calculate (from the basic aviation engine technology theory) (6):

$$C_R = \frac{3600 * Q_1}{(1+m) * \eta_g * H_u * R_S}, \tag{6}$$

where:
m – bypass ratio;
Q_1 – the amount of heat supplied to the primary circuit (core engine circuit);
η_g – fuel combustion efficiency;
H_u – thermal conductivity of fuel;
R_S – engine specific thrust.

$$R_S = \sqrt{\frac{2 * L_{C1}}{1+m} + V^2} – V, \tag{7}$$

where:
L_{C1}– inner loop operation;
V – flight speed;
M – bypass ratio.

Eqs. (6) and (7) show that an increase in the bypass ratio (m) in the cruise aircraft flight modes leads to a decrease in specific fuel consumption (C_R), while a decrease in the bypass ratio at the maximum power modes leads to an increase in specific thrust (R_S).

This example also shows that the use of an adaptive approach to increasing the complexity of the schematics of an aircraft GTE provides a significant boost to improving the performance of promising engines.

9. Increasing the parameters of the GTE workflow using the adaptation approach of high-temperature main combustion chamber

The above mentioned graph also shows that, to ensure the possibility of a stable and efficient operation of high-temperature stoichiometric combustion chamber (CC) and T^*_G = 2000–2200 K in a multi-mode GTE, it is necessary to use elements of the control of the combustion chamber (from the previous information analysis).

In [6] various methods of regulating the main CC of a multimode GTE are described. Although these methods of regulating the main CC were mainly aimed at obtaining better characteristics for the emission of pollutants, they can also be used to improve the characteristics of the high-temperature main CC.

Adjustment in the main CC is aimed at maintaining the specified composition of the fuel-air mixture in the combustion zone. Maintaining the required composition of the mixture in the CC can be facilitated by the supply of fuel, distributing it to the combustion zones. Several combustion zones are created that operate on the corresponding GTE operation modes. **Figure 10** shows the sample CC by the [6, 7] with two zones of combustion chamber areas. The main drawback of such burning is the inefficient use of the volume of the CC. In some modes of operation, the GTE of the zone type uses only half of its working volume.

Another way to maintain a given composition of the mixture in the CC is the redistribution of air entering the CC, depending on the mode of operation of the GTE. Air is distributed by using, for example, an adjustable front device. **Figure 11** shows CC with an adjustable head.

By means of changing the flow area of the holes in the flame tube, it is possible to vary the air supply to the combustion zone in various combinations to maintain a given α_{CC} [7].

Currently, the adjustability of the elements of the CC is sufficiently broadly developed.

Various adjustable nozzles, swirlers with adjustable blade installation angle and a change in the cross-sectional area, heads with preliminary organization of the air mixture fuel and control of its supply, adjustment of the CC volume with redistribution of air throughout the flame tube, etc., may be applied [10].

Based on the above, it is possible to schematically present a hypothetical high-temperature CC for a multi-mode perspective GTE. **Figure 12** shows a hypothetical

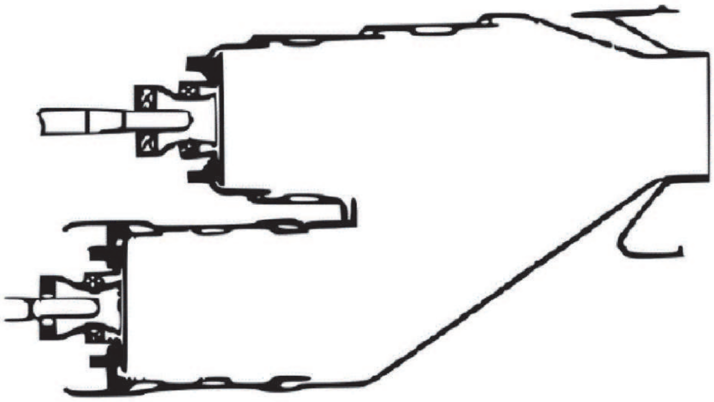

Figure 10.
Double zone CC [6, 7].

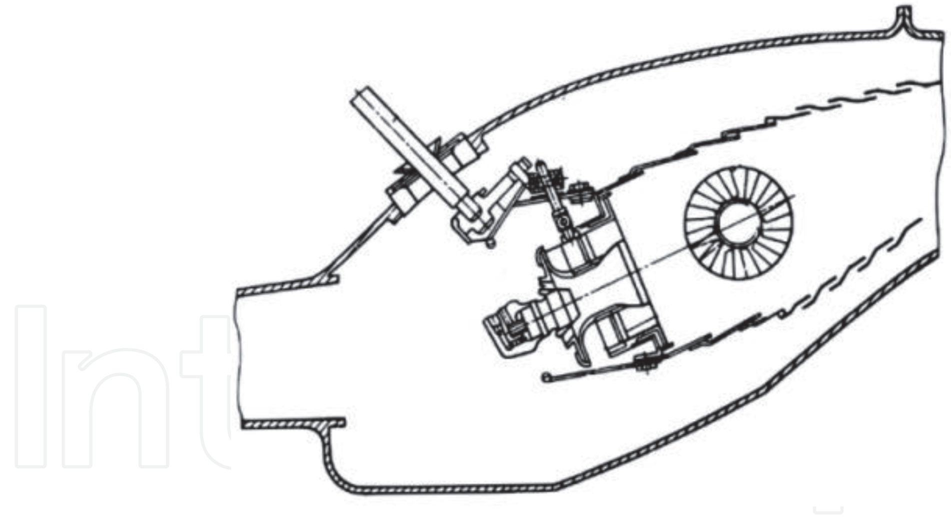

Figure 11.
The possible CC scheme with an adjustable head.

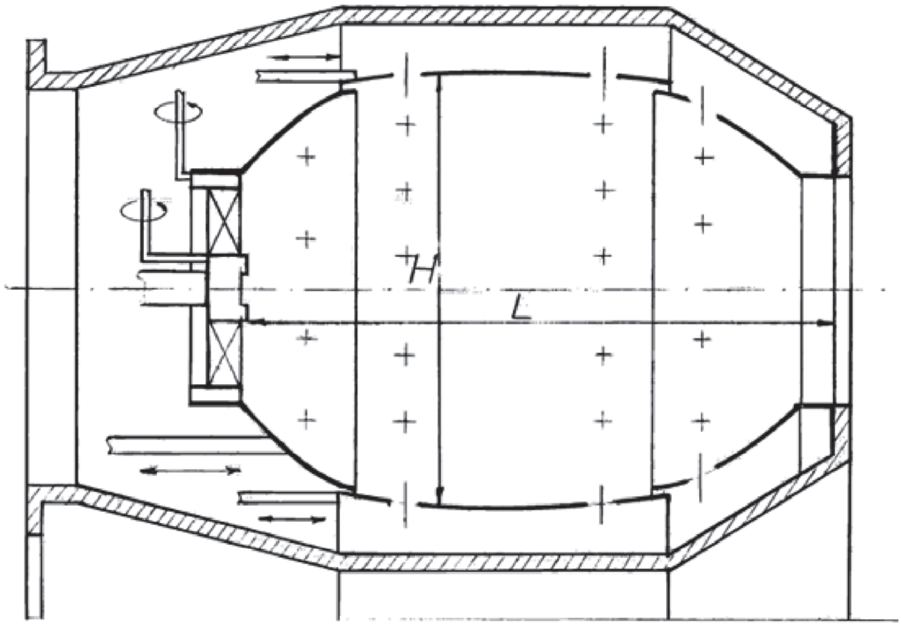

Figure 12.
Diagram of a hypothetical adaptive type combustion chamber (ATCC).

high-temperature CC with workflow control element or adaptive type CC (ATCC). A combustion chamber in which elements of adjustable geometric dimensions are used in accordance with the operation mode of the GTE, as a rule, the volume of CC and, accordingly, redistribution of air supply to the combustion and mixing zone, is called an adaptive type CC (ATCC).

An obstacle for use of effective control of multi-mode CC of the GTE is the design complexity of the controlled CC, high-temperature GTE operation modes and limitations in the level of development of modern materials science and technology.

The application of adjustability in a high-temperature ATCC is aimed at maintaining a given $\alpha_{CC,}$ at which the combustion chamber operates quite efficiently, with a high fuel combustion efficiency (η_g) and a high coefficient of fuel heat output (q_t) (4) which also leads to the expansion of its range of stable operation.

Table 2 shows the adjustable parameters, control actions and the achievable control goals for a hypothetical ATCC multi-mode GTE. The implementation of the ATCC control is an adaptive control system.

No	Adjustable parameter	Designation	Control action	The purpose of regulating GTE modes
1.	Air supply to the fuel injector	F_{IA}	The area of the orifices of the air flow through the nozzle	Coordination of the spray angle of the geometry of the CC
2.	Spinning the air in the head	φ_S	Swirl blade installation angle	Coordination of the sizes of the zone of processing currents of the geometry of the CC
3.	Air flow through the head	F_S	The area of the orifices of the flow sections of the air supply through the swirler	Maintaining a given α_{CC} in the primary combustion zone
4.	Changing the geometric dimensions of the CC	V_C	The volume of the flame tube CC (change in length-L and height - H)	Coordination of the volume of the flame tube CC and its dimensions to the mode of operation of the GTE
5.	Supply of secondary air flow along the length of the CC	F_{SA}	The area of the orifices of the flow areas of the secondary air supply to the flame tube	The distribution of the secondary air supply throughout the volume of the CC to maintain a given α_{CC}
6.	Fuel supply to the CC	G_{FJ}	Adjustable fuel supply through the nozzle	Specified fuel supply, depending on the mode of operation of the GTE

Table 2.
The adjustable parameters, the control actions and the achieved adjustment objectives for the hypothetical ATCC of multimode GTE.

An adaptive control system for a high-temperature CC of a multi-mode GTE can be implemented in two directions:

First - an adaptive choice of options, as the simplest [11].

Second - a self-adjusting adaptive system, as a more complex [12].

Adjustment by the method of adaptive choice of options is a choice of control actions (variant of the CC) under conditions of a priori uncertainty.

In this direction, the ATCC has several fixed positions of all control actions distributed over the GTE operation modes. Where for each range of GTE operation mode there is “its own” version of the CC, which in these conditions realizes the best performance. Each variant of the CC corresponds to a fixed position of the control action. In this way (8):

$$\alpha_{\mathrm{CCi}} = \mathrm{f}(\mathrm{G}_{\mathrm{FJi}}; \mathrm{F}_{\mathrm{IAi}}; \varphi_{\mathrm{Si}}; \mathrm{F}_{\mathrm{Si}}; \mathrm{V}_{\mathrm{Ci}}; \mathrm{F}_{\mathrm{SAi}}). \tag{8}$$

Graphically the characterization of the relative fuel combustion efficiency $\overline{\eta_g} = \eta_g/\eta_{g\,\max}$ (where η_g– current fuel combustion efficiency, $\eta_{g\,\max}$ – maximum fuel combustion efficiency) depending on the α_{CC} for ATCC with an adaptive choice of options can be represented in the following form in **Figure 13** $\overline{\eta_g} = f(\alpha_{CC})$.

The generalized characteristic of the ATCC is the curve of the peaks of the options. Thus, given the formula (7) we get (9):

$$\overline{\eta_g} = \mathrm{f}\left(\sum_{i=1}^{n} \alpha_{CCi}^{E}\right). \tag{9}$$

When using the self-regulated adaptive system ATCC, the rule for determining the control actions changes in the course of GTE operation. In this case, the adaptive

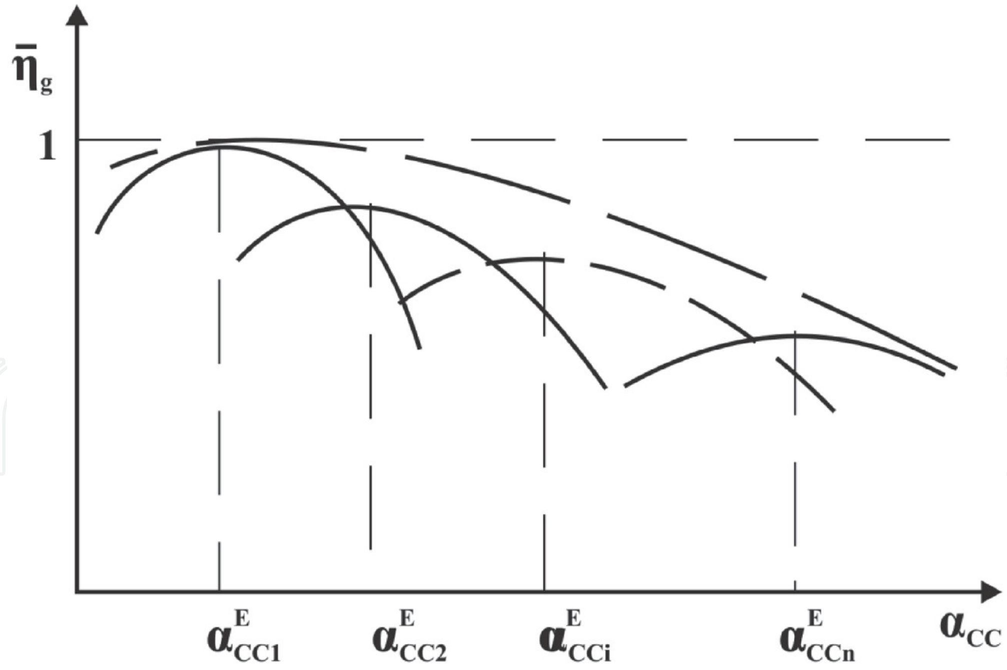

Figure 13.
Graphical characteristic of the ATCC with an adaptive choice of options.

control algorithm will be a combination of adjustment and adaptation algorithms. The adaptive control system will be a dynamic system consisting of an ATCC and a device implementing an adaptive control algorithm, with the control algorithm to be determined over the entire range of operation of a multimode GTE. In this case, the ATCC characteristic will appear as follows, see **Figure 14**.

In this way:

$$\overline{\eta_g} = \mathrm{f}(\alpha_{CC}(\overline{u})), \tag{10}$$

where:

$\overline{u}$– vector of control actions.

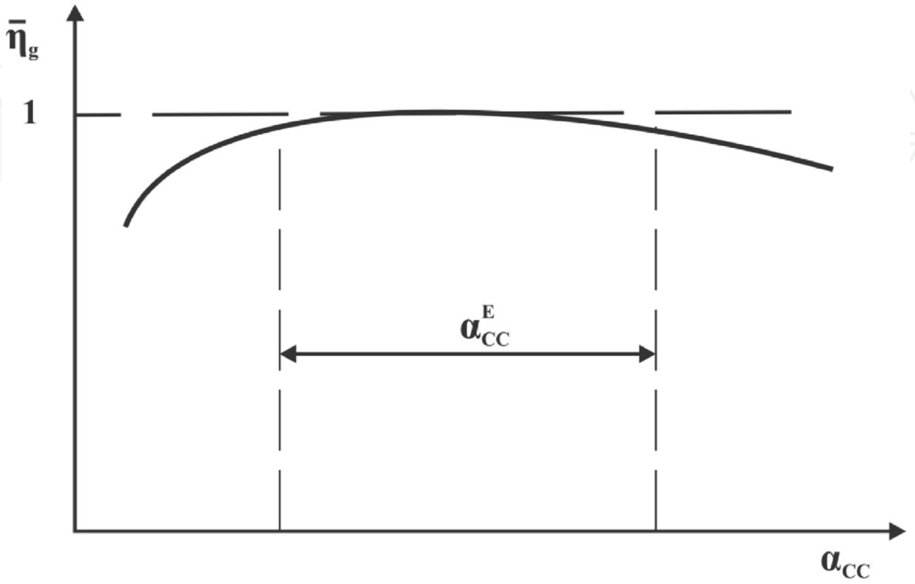

Figure 14.
The characteristic of the ATCC with a self-adjusted adaptive system of regulation, where α^E_{CC} – The range of calculated modes of the excess air ratio in the combustion chamber for this method of controlling the organization of the combustion process.

It is necessary to clarify the definition of CC of the adaptive type (ATCC). Based on the above, the ATCC of a multi-mode GTE is a CC with a large number of control actions on the organization of the working process (developed control) and an adaptive control system.

Figures 13 and **14** show that, the use of ATCC in a high-temperature multi-mode GTE will significantly reduce its specific fuel consumption C_R in all operating modes. Since an increase in the fuel combustion efficiency (η_g) and the coefficient of thermal performance of fuel (q_t) lead to a decrease of C_R (6). At the same time, the task of expanding the range of stable work is being solved.

10. Conclusions

To meet the requirements for promising aviation GTEs, it is necessary to increase the parameters of the thermodynamic cycle of the engine, while simultaneously applying complications of the GTE concept and its elements. This will make it possible to apply the principles of adaptation of the engine in non-design modes of operation, and to obtain the best characteristics of the GTE in these modes.

The use of adaptation principles in the development of future-generation aviation GTEs makes it possible to quite effectively resolve the contradictions of the possible obtaining of the best (optimal) characteristics under certain (calculated) conditions of GTE functioning and the impossibility of their implementation when these conditions change (non-design modes) in the range of permissible (or necessary) engine operating modes.

The use of an adaptive approach in the development of promising aviation GTEs will allow to take into account many uncertainties of the challenges of the future, which at the time of the start of work are not known or only assumed. This is due to the fact that the creation of an engine is characterized by a significant time interval within which various influencing factors can appear or change, and the adaptive approach takes into account the uncertainty and limited information of many influencing factors.

List of the acronyms

C_j	nozzle flow rate
C_p	specific heat of heat supply at constant pressure
C_R	specific fuel consumption
F_{IA}	the area of the orifices of the air flow through the nozzle
F_m	the area of the mid-section of the engine
F_S	the area of the orifices of the flow sections of the air supply through the swirler
F_{SA}	the area of the orifices of the flow areas of the secondary air supply to the flame tube
G_A	air flow through the engine
G_{A1}	air flow through the gas generator
G_{A2}	air flow through the second engine circuit
G_{AC}	air flow rate entering the combustion chamber
G_{ENG}	engine mass
G_F	fuel flow rate entering the combustion chamber
G_{FJ}	adjustable fuel supply through the nozzle
H_u	lower calorific value of fuel
L_o	theoretically required amount of air for complete combustion of 1 kg of fuel

L_C	work of the thermodynamic cycle of the engine, which results in an increase in the kinetic energy of the exhaust gases, for a real cycle has the following form
L_{C1}	inner loop operation
m	bypass ratio
$\overline{m}$	coefficient taking into account the difference in the physical properties of air and gas
P_A^*	engine entrance pressure
P_C^*	pressure behind the compressor
Q	the actual amount of heat energy received during fuel combustion
Q_0	the amount of thermal energy introduced into the engine with fuel per 1 kg of working body
Q_t	fuel heating capacity
Q_{ti}	fuel heating capacity at the i-th mode of GTE operation
Q_{tr}	heating capacity of fuel at the design (maximum) mode of operation of the GTE
Q_1	the amount of heat supplied to the primary circuit (core engine circuit)
q_t	the coefficient of fuel heat output
R	engine thrust
R_F	frontal thrust
R_C	specific engine thrust
R_{TO}	engine thrust at takeoff
T_C^*	air temperature behind the compressor (at the inlet to the combustion chamber)
$T^*{}_G$	gas temperature in front of the turbine
T_{Gmax}^*	the maximum possible theoretical turbine inlet temperature
T_H	ambient air temperature
$\overline{u}$	vector of control actions
V	flight speed
V_C	the volume of the flame tube CC
Y_{ENG}	the specific gravity of the engine
α_{CC}	air ratio of the combustion chamber
α_{cc}^E	the calculated excess air ratio for a given combustion chamber
α_{CCi}^E	the calculated excess air ratio for the current position of the control elements of the adaptive type combustion chamber
Δ	working body heating degree
η_e	the efficiency of the expansion processes
η_c	the efficiency of the compression
η_g	the fuel combustion efficiency
η_{int}	internal coefficient efficiency of the GTE thermodynamic cycle
$\eta_{g\ max}$	the maximum fuel combustion efficiency
η_{tr}	propulsive efficiency
η_Σ	the overall efficiency of the direct reaction GTE
$\overline{\eta_g}$	the relative fuel combustion efficiency
π_C^*	compressor pressure rise
$\pi_{C\Sigma}^*$	cumulative pressure rise in the engine
ρ	density
φ_S	swirl blade installation angle

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