Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal 2023, 17(1), 267–273
https://doi.org/10.12913/22998624/156985
ISSN 2299-8624, License CC-BY 4.0

Received: 2022.10.16
Accepted: 2023.01.17
Published: 2023.02.01

Usage of Cold Forcing Method for a Gas Turbine Engine of Supersonic Transport

Viktors Gutakovskis[1*], Vladimirs Gudakovskis[1], Ilmars Blumbergs[1], Elina Sarma[1]

[1] Riga Technical University, Ķīpsalas iela 6B,, Rīga, LV-1048, Latvia

* Corresponding author's e-mail: viktors.gutakovskis@rtu.lv

ABSTRACT

The article discusses the current state of development of supersonic transport, analyses the main limitation of the use of gas turbine engines when flying at high supersonic flight speeds, proposes a method for expanding the range of GTE limitations in these flight modes of the aircraft, using cold forcing of the engine, conducts an analytical study of the effectiveness of this approach, proposes one of the possible devices for the implementation of cold forcing, the efficiency of an engine with cold forcing is shown, which may be of significant interest for the application of cold forcing methods in gas turbine engines of supersonic transport.

Keywords: aviation, GTE, supersonic, plane.

INTRODUCTION

General information on the development of promising supersonic transport

Several large American and European companies are engaged in the development of supersonic transport (SST), including Boeing (Aerion AS2 project), Gulfstream (SSBJ Quiet Spike aircraft), Lockheed Martin (X-59 aircraft), supported by NASA, EADS, Virgin Galactic Holdings and etc. Foreign media call the creation of the Lockheed Martin X-59 QueSST (Quiet Supersonic Transport) demonstrator a world technological breakthrough in the field of commercial supersonic aircraft construction.

The SST developers see economic feasibility not only in the sale of aircraft to VIP clients (although they certainly have their own market niche), but also in the creation of breakthrough technologies associated with the development of a virtually new type of aviation technology. It is precisely with this that the desire of many countries of the world, even traditionally far from innovations in the field of aircraft construction, is associated with the desire to engage in such kind of research.

International scientific research in the field of increasing the speed of aircraft allows for the possibility of commercial travel at speeds of Mach 5 and higher, but at present this direction is still at the stage of theoretical development.

From the analysis of existing projects and technical proposals, the following three directions for the development of the SST can be distinguished:

- SST with a flight speed of 1.4–1.6 Mach, the most developed SST projects are designed to carry from 12 to 22 people, the flight speed will be 1.4–1.6 Mach over water surface and 1.2 M over land, the flight range at a speed of 1.4 M will be 7 800 – 10 000 km, the flight altitude is about 18 000 meters (projects of the American company Aerion Supersonic, AS2, as well as a joint project of the Spanish Aernova and the American company Spire Aerospace, S – 512 Quiet Supersonic Jet [1]);
- SST with a flight speed of Mach 2–3, typical representatives of this direction are the project of the Boom Technology company, the flight speed of the aircraft will be Mach 2.2, range of 8 335 km, the number of passengers up to 55 [2] and the project of Virgin Galactic

Holdings, aircraft speed will be Mach 3, the flight altitude is about 20 000 m, the number of passengers will be up to 19 people [3];
- SST with a flight speed of up to Mach 5, a typical representative of this direction is the EADS project – Zero Emission Hyper Sonic Transport (ZEHST), the flight speed will be Mach 4, the flight altitude is over 32 000 meters, the number of passengers will be 50–100 people, this aircraft will use a combined power plant, consisting of ramjet and turbojet engines, one of the main ideas of this project is to reduce SST emissions of exhaust gases [4].

Aviation companies do not disseminate information about engines for SST

An important requirement for the SST engine is the provision of the required thrust and a relatively low (necessary for solving the assigned transport problem with acceptable commercial efficiency) level of engine fuel consumption at supersonic cruising flight speed. At the same time, the maximum values of the engine parameters (gas temperature in front of the turbine, air temperature behind the compressor, the physical speed of the high-pressure rotor) are achieved precisely at the maximum cruising (longest) and maximum prolonged supersonic flight modes, which necessitates the development and use of design and technological solutions ensuring an acceptable thermal state of the structure, the required reliability and service life of the engine and other systems of the SST power plant, including the use of effective cooling systems, structural materials, including composite and non-metallic (to reduce weight and increase the resource). The choice of the type of engine and the characteristics of the power plant and ensuring their coordinated operation at critical points of the trajectory to minimize thrust losses have a key effect on the fuel, economic and environmental characteristics of the SST. General Electric do not disclose the details regarding Affinity, noting only that the new engine will be based on technologies used in the existing GE engine family, which are operated by commercial airlines. [5] One of the main means of expanding the range of speeds and altitudes of modern aircraft is a significant increase in the thrust of the aviation GTE, i.e. its forcing.

By forcing an aviation GTE is meant, as a rule, a short-term increase in the engine thrust in comparison with the thrust at its maximum operating mode. Forcing a gas turbine engine can be used in an aircraft takeoff mode to shorten the takeoff run or in flight for a short-term achievement of the maximum flight speed, climb rate and flight altitude, etc. Engine thrust forcing is carried out in those flight conditions of the aircraft, where it is required to increase the total thrust of the power plant in order to increase the power-to-weight ratio of the aircraft, to ensure its limiting characteristics, for example, flight at supersonic speed. When using a traditional afterburner, the thrust of the gas turbine engine increases by 30–50%, and the specific fuel consumption increases by 2–2.5 times [6,7,8,9].

Features of the use of GTE for SST

When an aircraft is flying at supersonic speeds, due to the adiabatic compression of the air in front of the flying aircraft, the temperature of the complete deceleration of the air in front of the aircraft rises. Full braking temperature T_H^* is defined by expression [6]:

$$T_H^* = T_H + T_H 0{,}2M^2 - 273{,}2\ (^\circ\mathrm{C}), \qquad (1)$$

where: T_H – absolute air temperature (K) at flight altitude H ≤ 11 000 m.

For flying in the stratosphere (H ≥ 11 000 m) the T_H^* is calculated by the formula [6]:

$$T_H^* = 216{,}7 + 43{,}3M^2 - 273{,}2 = 43{,}3M^2 - 56{,}5\ (^\circ\mathrm{C}). \qquad (2)$$

So for SST flying at an altitude of more than 11 000 m at a speed of Mach 1.5–1.7, the temperature at the inlet to the engine air intake will be in the range from 41–68.5 °C; for a flight speed of Mach 2–3, the air temperature at the inlet to the air intake will be in the range from 116.7–333.2 °C; and for a flight speed of Mach 4–5, the temperature at the inlet to the engine air intake will be in the range from 636.3–1026 °C. There are, as noted above, three ranges of supersonic flight.

Flight at a speed of 1.4–1.6 Mach, in this range, the achievement of the indicated flight speeds can be achieved using a gas turbine engine without an afterburner. As a rule, this is a turbojet engine with a low bypass ratio (m = 0.5–1).

To ensure flights at a speed of Mach 2–2.2, afterburning turbojet and reheated double-flow turbofan engine with a low bypass ratio are used (m ≤ 0,5). The main cruising supersonic flight takes place in the afterburner mode.

However, at supersonic flight speeds M>3 GTEs degenerate. The reasons for the degeneration are:

- decrease in the productivity of axial compressors due to the kinetic heating of the working fluid;
- decrease in the useful work of the Brighton cycle due to the limitation of the gas temperature at the outlet from the main combustion chamber.

Therefore, ensuring flight at supersonic speeds of up to Mach 5 at an altitude of over 32 km requires the use of a combined power plant, consisting of a reheated double-flow turbofan engine with a variable duty cycle, a ramjet engine and a liquid-jet engine.

As it can be seen from the analysis above, all three directions of development of modern ATP include a gas turbine engine in the power plant of an aircraft. It was also shown above that with an increase in the aircraft flight speed, the air temperature at the engine inlet rises, which significantly reduces its thrust characteristics, and when certain Mach numbers are reached, the gas turbine engine degenerates and a transition to another jet engine scheme, the ramjet VRM, is required. In this regard, a contradiction arises between ensuring high economic characteristics of a gas turbine engine and its real capabilities. The solution to this contradiction is the creation of various ways to increase the engine thrust characteristics, providing lower fuel consumption for creating a unit of thrust, i.e. forcing a gas turbine engine.

Forcing a gas turbine engine to obtain high traction characteristics

It is known from the theory of aircraft engines that to identify the main parameters of the working process, flight altitude, and speed, as well as other factors for the thrust of a gas turbine engine, the following approximate expression for the engine thrust can be used:

$$\mathrm{R} \approx G_A(C_J - V_F), \tag{3}$$

where: G_A – air flow through the engine,
C_J – rate of gas flow from the nozzle,
V_F –flight speed.

Formula (3) is obtained from the following conditions:

- on the assumption of equality of the second air flow rate at the engine inlet and the second gas flow rate flowing out of the jet nozzle.
- it is also assumed that there is a complete expansion of the gas in the nozzle and the gas pressure at the nozzle exit is equal to the atmospheric air pressure.

The rate of flow of gases from the nozzle is determined by the expression:

$$C_J = \varphi_J \sqrt{\frac{2k_g}{k_g - 1} R_g T^*_{gJ} \left[1 - \left(\frac{P_\mathrm{H}}{P^*_J}\right)^{\frac{k_g - 1}{k_g}}\right]}, \tag{4}$$

where: φ_J – velocity factor, takes into account internal losses in the nozzle,
T^*_{gJ} –temperature of gases flowing out of the nozzle,
P_H – static pressure in the surrounding atmosphere,
P^*_J – total pressure in front of the nozzle,
R_g – gas constant,
k_g – adiabatic exponent.

From formula (3) it follows that the amount of thrust is affected by the air flow through the engine and the speed of the gas flow from the nozzle. Air flow through the engine (G_A) is practically determined by the operation of the compressor, and the gas flow rate C_J temperature of gases during fuel combustion in the main and afterburner combustion chambers. Thus, an increase in thrust (forcing) of a gas turbine engine can be carried out in two ways:

- increase in air flow through the engine at maximum gas temperature – cold forcing;
- an increase in the gas temperature by using additional fuel combustion – hot forcing.

Hence, it can be seen that all methods of forcing a gas turbine engine are reduced to two groups, which are fundamentally different from each other, this is an increase in the mass of the working fluid and an increase in its temperature before leaving the engine.

An increase in the temperature of the working fluid to increase the rate of its outflow from the engine is associated with significant fuel consumption, which greatly impairs the efficiency of the engine and is limited by the heat resistance of the materials used in the design of the gas path of the engine.

The most common way of forcing a gas turbine engine is additional heat input behind the turbine. Another frequently used method of forcing a gas turbine engine is to increase the rotor speed due to an additional short-term increase in the temperature of the gases in front of the turbine. The disadvantages of these methods are described above. Additionally, it should be noted that with an increase in the supersonic flight speed of the aircraft, the temperature of the air (working fluid) at the engine inlet increases, as noted above. Considering the limitation of structural details in terms of heat resistance, it is impossible to increase the amount of heat input with an increase in the air temperature at the engine inlet. As a result, the total amount of supplied heat decreases, which leads to a decrease in the traction and economic characteristics of the GTE at supersonic flight modes.

Another group of methods for forcing a gas turbine engine is based on an increase in the mass of the working fluid passing through the engine. This group of forcing methods is attractive in that it does not require additional fuel consumption to increase the air consumption through the engine, and, consequently, the engine thrust. This fact is very important for the economic indicators of the SST.

Cold forcing GTE

At present, cold forcing as a direction for increasing the thrust of a gas turbine engine has been little studied and this has been one of the reasons for underestimating the capabilities of a gas turbine engine as a gas-dynamic scheme for use in power plants of aircraft with high supersonic flight speeds.

The main idea is to use a high cooling resource of promising cryogenic fuels, in particular, hydrogen. The system of heat exchangers, built into the structural elements of the compressor and its channels, allows to reduce the temperature of the working fluid and thereby increase the air flow through the compressor.

The requirement of time, and modern technological capabilities make it possible to take a fresh look at the introduction of intercooling of air during its compression in a gas turbine engine.

The main parameters of an axial compressor are known from the theory of aircraft engines:

- adiabatic work of compression, i.e. work of rotation of the compressor shaft (L_C)

$$L_C = \frac{k}{k-1} \mathrm{R}T_A^* \left({\pi_C^*}^{\frac{k}{k-1}} - 1 \right) \tag{5}$$

where: k – adiabatic exponent,
R – gas constant,
T_A^* – inhibited air temperature at the compressor inlet,
$\pi_\mathrm{C}^* = \frac{P_C^*}{P_A^*}$ – compressor pressure rise (P_C^* inhibited pressure behind the compressor, P_A^* – inhibited pressure at the compressor inlet)

- the specific performance of the compressor, i.e. air flow through a unit of total front area at the compressor inlet (G_{AC})

$$G_{AC} = m \frac{P_A^*}{\sqrt{T_A^*}} q(\lambda_A)(1 - \overline{d}_{sl}^2) \tag{6}$$

where: m – dimensional factor depending on the type of gas,
$q(\lambda_\mathrm{A})$ – relative current density,
T_A^* – inhibited air temperature at the compressor inlet,
P_A^* – inhibited pressure at the compressor inlet;
$\overline{d_{sl}}$ – relative diameter of the impeller sleeve at the compressor inlet.

As it can be seen from formulas (5) and (6), by increasing air temperature at the compressor inlet $(\mathrm{T}_\mathrm{A}^*)$ the specific performance of the compressor decreases (G_{AC}) and the work required to rotate the compressor shaft increases L_C.Therefore, to reduce L_C and increase G_{AC} it is necessary to reduce the air temperature $(\mathrm{T}_\mathrm{A}^*)$.

Water injection at the compressor inlet

One of the best-known methods of cold forcing is by injecting water into the compressor inlet.

The heat that is taken away from the air stream by atomized water consists of three components:

- the heat spent on heating water droplets to the boiling point

$$Q_1 = \mathrm{C}_{PW} g_W (T_B - T_0), \tag{7}$$

where: C_{PW} – specific heat capacity of water,
g_W – relative flow rate of injected water,
T_B – boiling point of water,

T_0 –temperature of injected water at the compressor inlet;

- the heat of vaporization

$$Q_2 = q_W, \tag{8}$$

where: q_W – specific heat of vaporization of water;
- heat spent on heating the steam to the air temperature in the compressor

$$Q_3 = C_{PV}\, g_W (T_C - T_B), \tag{9}$$

where: C_{PV} - specific heat of water vapor,
T_C – temperature behind the compressor.

The total heat removed by the water from the air flow will be determined by:

$$Q_\Sigma = Q_1 + Q_2 + Q_3 = C_{PA}\,(T_{CC} - T_C), \tag{10}$$

where: C_{PA} – specific heat capacity of air,
T_{CC} – temperature behind the compressor without water injection.

The amount of water injected into the compressor is limited and does not exceed 3% of the total air flow. Water injection not only increases engine thrust, but also reduces (NO_x).emissions

Refrigerated axial compressor applications

The authors propose a method for forcing a gas turbine engine for high supersonic flight speeds by removing heat from the working fluid through a cooled axial compressor.

Compressor operation determines the air flow through the engine (G_A) and, consequently, the thrust of the gas turbine engine. As the flight speed increases, so does the air temperature at the compressor inlet (T_A^*), which leads to a decrease in the reduced speed ($\overline{n}$),

$$\overline{n} = n\sqrt{\frac{288}{T_A^*}}, \tag{11}$$

where: n –the physical speed of the compressor rotor.

At constant temperature of gases in front of the turbine T_{CC}^* = const and a constant rotational speed n = const, it leads to a decrease in the degree of pressure increase in the compressor (π_C^*) and the degree of heating in the engine $\left(\Delta = T_{CC}^* / T_A^*\right)$.

Accordingly, the air temperature behind the compressor also rises (T_C^*), which reduces the amount of heat input (Q_C) in the thermodynamic cycle, because.

$$Q_C = C_{Pg}\,(T_{CC}^* - T_C^*), \tag{12}$$

where: C_{Pg} – specific heat capacity of gases.

Figure 1 shows the change in the position of the design point on the operating line of the compressor characteristic with an increase in the temperature at the compressor inlet (T_A^*). 1st -2nd, -3rd – line of operating modes in the compressor characteristic field. 4th – line of the boundary of stable operating modes of the compressor. 5th – line of the direction of reduction of the reduced speed of rotation with an increase in the temperature of the working fluid at the inlet to the compressor ($\overline{n_2} < \overline{n_{opt}}$). 6th – line of direction of increasing the reduced speed of rotation during the operation of the cooling system of the working fluid, i.e., decreasing its temperature.

Figure 2 shows the dependence of the work of the thermodynamic cycle (L_{TC}) on the degree of pressure increase (π_C^*) and the degree of heating of the working fluid (Δ) with increasing temperature at the compressor inlet (T_A^*). With an increase in the temperature of the working fluid, the degree of its heating decreases, while the optimal value of the degree of pressure (π_C^*) increase also decreases and the work of the thermodynamic cycle also decreases. When the working fluid cooling

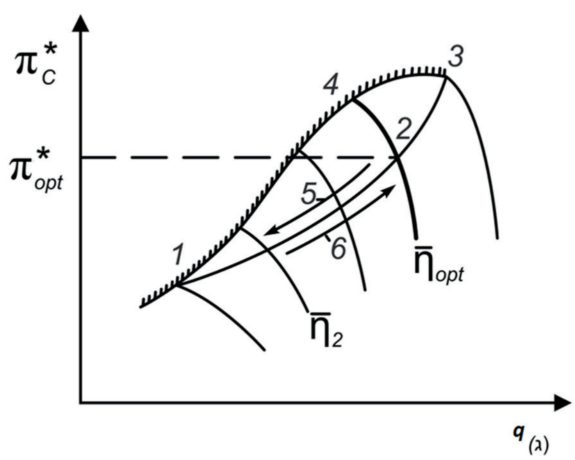

Fig. 1. Compressor characteristics

system is operating, all parameters of the thermodynamic cycle tend to return to optimal values.

As follows from the above, in order to improve the characteristics of an axial compressor, it is necessary with an increase in the temperature at the compressor inlet (T_A^*), i.e. with an increase in flight speed, apply measures to reduce the temperature of the working fluid, i.e. reduce T_A^*.

In this method, when the GTE thrust increases at large numbers M of the aircraft flight (M> 2.5), it is done by cooling the air in the compressor using the cooling resource of the fuel by supplying the refrigerant to the compressor casing and the stator of each stage, and the amount of refrigerant supplied from the first to the last stages for each flight mode are increased according to the law of increasing the temperature of the air flow along the compressor path. When changing the flight mode using the cooling control system, the maximum possible reduced speed ($\overline{n}$) near its optimal value ($\overline{n_{opt}}$) (Fig. 1) is maintained by changing the amount of supplied refrigerant (liquid hydrogen).

Additionally, a heat exchanger can be installed in front of the high-pressure compressor (for reheated double-flow turbofan engine). The heat exchange elements are the hollow blades of the guide vanes of all stages of the axial compressor and its casing.

The amount of heat removed from the working fluid is determined by the expression:

$$Q_\Sigma = \kappa\, F_\Sigma\, T_Q, \tag{13}$$

where: κ – heat transfer coefficient
F_Σ – the total area of the surface washed by the working fluid,
T_Q – average temperature head.

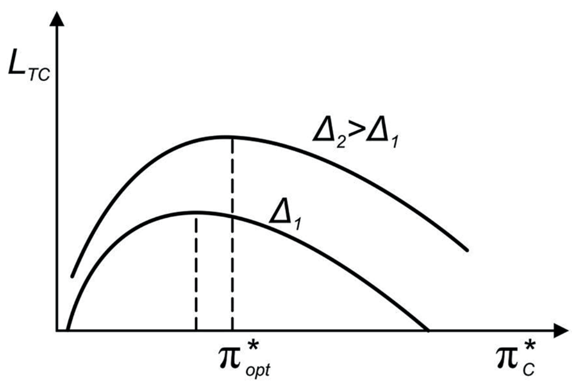

Fig. 2. Dependence of the work of the thermodynamic cycle (L_{TC}) on the degree of pressure increase (π_C^*) and the degree of heating of the working fluid (Δ)

The automatic control system provides refrigerant supply from the first stages to the last according to the law of increasing air flow temperature along the compressor flow path. In Figure 3 the authors have presented a diagram of one of the possible variants of a hypothetical GTE (reheated double-flow turbofan engine) for an SST with a cold forcing system.

In the Figure 3: 1 – aircraft fuel tank (hydrogen fuel); 2 – control unit with temperature values coming from sensors at the engine inlet Ta and temperatures behind the compressor Tc 3 – block of injection pumps; 4 – cooler distributor for consumers; 5 – block of supplying fuel pumps to the main and afterburner combustion chambers; 6 – block of pumping out pumps from cooling elements; 7 – cooled fan guide vanes; 8 – cooled fan case; 9 – heat exchanger for cooling the air entering the high pressure compressor; 10 – cooled high pressure compressor; 11 – main combustion chamber; 12 – afterburner combustion chamber.

The order of operation of the device: depending on the temperature at the inlet to the engine and the temperature behind the compressor, the control unit (3) regulates the supply of coolant by the injection pumps (3) to the cooling elements (7,8,9,10) from the aircraft fuel tank (1), then the refrigerant is pumped out of the cooling elements by the pumping out pump unit (6) and supplied to the fuel supply pump unit (5), which distributes the fuel supply between the main (11) and afterburner (12) combustion chambers.

In a gas turbine engine for high supersonic flight speeds, as a rule, low-pressure axial compressors are used, which makes it possible to place cooling channels in the guide vanes of an axial compressor.

CONCLUSIONS

The use of cold forcing at high flight speeds will expand the range of flight speeds (Fig. 4). In the figure, line 1-1 is the limitation of engine operation according to the maximum permissible temperature of the working fluid at the engine inlet (T_A^*). Line 2-2 shows the displacement of the limitation on the maximum allowable temperature at the engine inlet when implementing (turning on the cold forcing system) the method of cooling the working fluid in the gas turbine engine to higher values of the M flight numbers.

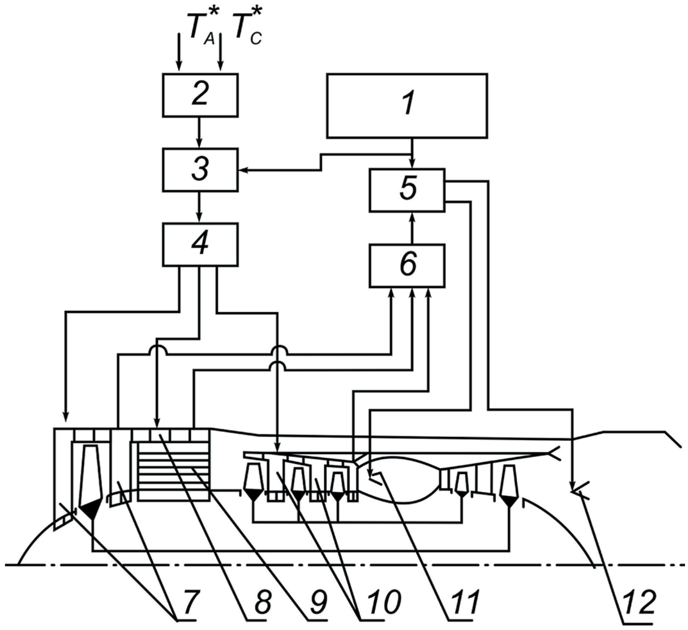

Fig. 3. Diagram of a hypothetical GTE for SST with a cold boost system.

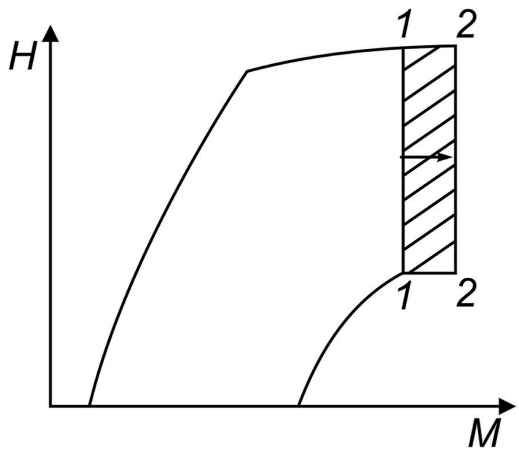

Fig. 4. The area of limitation of the operating modes of supersonic transport

It should be noted that the specific fuel consumption (C_R) will decrease with cold forcing, because increased thrust (R) occurs not due to an increase in fuel consumption, but due to the use of its cooling resource:

$$C_R = \frac{G_F}{R}, \tag{14}$$

where: G_F – hourly fuel consumption.

Thus, the direction of cold forcing of a gas turbine engine may be of interest when creating promising power plants for SST due to its economy, which does not require additional fuel combustion with an increase in engine thrust.

REFERENCES

1. Aerion AS2 Supersonic Business Jet, https://www.aerospace-technology.com/projects/aerion-as2-supersonic-business-jet/, 6.06.2022
2. Supersonic takes shape, https://boomsupersonic.com/, 6.06.2022.
3. Virgin Galactic takes off with Mach 3 passenger aircraft design, https://www.theengineer.co.uk/virgin-galactic-mach-3-passenger-aircraft-rolls-royce/, 6.06.2022.
4. The ZEHST Is The 3,000 MPH, Zero emissions airplane of 2050 https://techcrunch.com/2011/06/20/zehst/, 20.06.2011.
5. GE refines Affinity supersonic engine, plans for 2020 performance tests, https://www.flightglobal.com/engines/ge-refines-affinity-supersonic-engine-plans-for-2020-performance-tests/138508.
6. Eger S.M., Mishin V.F., Liseytsev N.K. et al. Aircraft Design: A Textbook for High Schools, 3rd ed. Yegera S.M. (Ed.), Mashinostroenie, 1983.
7. Blumbergs, I., Kleinhofs, M. Strength determination and prediction of destructive processes of composites. Aviation 2015; 19(2): 67–71.
8. Hauka, M., Pavelko, V., Kubuliņš, R., Blumbergs, I. Automated sensory monitoring system prototype for continuous monitoring of material and structure state. In: Environ. Technol. Proc. of the 13th International Scientific and Practical Conference. Rezekne Higher Education Institution, Latvia 2021; 2: 58–61.
9. Arnautovs, A., Bikovens, O., Gribniak, V., Nasibulins, A., Blumbergs, I., Hauka, M. Investigation on fracture of epoxy-filled composites by acoustic emission. Journal of Civil Engineering and Management, 2016; 22(5): 683–689.