MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE

National Aerospace University
“Kharkiv Aviation Institute”

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AFTERBURNERS AND EXHAUST SYSTEMS OF TURBINE ENGINES

Tutorial

Kharkiv «KhAI» 2014

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Y-44

Розглянуто одні з найважливіших вузлів газотурбінних двигунів – форсажні камери згоряння і вихідні пристрої. У першій частині навчального посібника наведено відомості про призначення, роботу і конструкцію форсажних камер згоряння, у другій частині - про призначення вихідних пристроїв ГТД і вимоги до них. Показано різницю між вихідними пристроями двигунів прямої та непрямої реакцій. Описано вимоги до цих вузлів ГТД і засоби їх забезпечення. Подано відомості про матеріали, які використовуються для виготовлення елементів форсажних камер і вихідних пристроїв. Для практичного закріплення знань сформульовано завдання, розв'язання яких потребує вивчення макетів двигунів, креслень і плакатів. Для перевірки знань кожний розділ завершується контрольними запитаннями.

Для студентів, що навчаються за напрямком «Авіаційна і ракетно-космічна техніка», при виконанні лабораторних робіт, підготовці до екзаменів з дисциплін «Конструкція авіаційних двигунів і енергетичних установок», «Двигуни літаків і вертольотів», а також при виконанні курсових і дипломних проектів.

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Tutorial addresses operation and construction of afterburners and exhaust systems of turbine engines. First part of the tutorial contains information about purpose, operational process and construction of afterburners. Second part concerns exhaust systems. Difference between exhaust systems of direct-reaction engines and indirect-reaction engines is shown. Requirements to these components of engines and methods to meet these requirements are given. Materials used to manufacture parts of these components are named. The tutorial contains practical tasks which performing needs studying engine mockups, drawings and posters. There are questions for self-testing in the end of each part.

This book is profitable for students studying "Aerospace Engineering" to prepare for laboratory activities and examinations on disciplines "Construction of Aero Engines and Power Plants", "Engines of Airplanes and Helicopters", and to make course and diploma projects.

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CONTENT

INTRODUCTION

Exhaust system is one of major components of turbine engines.

Engines of high-velocity airplanes contain afterburners. Afterburning is the most rational method of thrust augmentation; it increases specific thrust essentially at moderate increasing of mass and size.

Afterburning mode is not economical, but essential improvement of aircraft performances compensates increasing specific fuel consumption.

Exhaust systems of turbine engines have some significant functions:

- transforming energy of exhaust gas into energy of jet thrust;
- providing set direction of thrust force;
- supporting operational mode of turbocompressor;
- transporting gas into fuselage or nacelle;
- decreasing engine noise;
- screening direct infrared radiation of engine etc.

Afterburners and exhaust systems play significant role in engine integration with aircraft.

This tutorial considers main problems of afterburners and exhaust systems construction. It contains realized constructive decisions reasoning.

The tutorial saves learning engine components at laboratory training. For practical hardening problem area knowledge a text of the manual contains Tasks (Exercises) which carrying out assumes studying mockups, drawings and sketches of predetermines engines. For checking knowledge concerning each of parts, the lists of control questions are applied.

1 AFTERBURNERS OF AIRCRAFT ENGINES

1.1 General information about afterburners

Flight of high-speed aircrafts includes such characteristic stages as short takeoff, high-speed climb, fast acceleration, sound barrier overcoming, supersonic flight. All of these stages need essential thrust augmentation (to 45…60 % during takeoff and to 130…170 % during supersonic flight). The device that provides this augmentation is afterburner.

Afterburner is placed after last stage of turbine and serves burning additional fuel. This burning increases heat capacity and velocity of gas, thus increasing engine thrust.

In afterburning turbojet engines (ATJE), mixture of gas going from main combustion chamber, and air that returns to gas path from turbine cooling system, is supplied to afterburner. New portion of afterburning fuel is added here, thus creating afterburning fuel-air mixture, which composition is close to stechiometric composition (the excess air/fuel ratio α_Σ= 1.05…1.3), therefore temperature in combustion zone is high – about 2050…2200 K.

Afterburning turbofan engines (ATFE) have low bypass ratio and are equipped with mixing chamber. So besides mentioned above flows of cooling air and main combustion products, air from secondary duct enters afterburner also. This initiates essential non-uniformity of temperature and air/fuel ratio in gas flow, thus decreasing stability of burning.

Construction of afterburner must provide:

- stable burning of fuel at all flight conditions (required range of stable mixture composition is from $\boldsymbol{\alpha_{\Sigma\, min} = 0.7 \ldots 0.9}$ to $\boldsymbol{\alpha_{\Sigma\, max} = 2.0 \ldots 2.5}$);
- reliable starting of afterburner in all range of flight altitude and velocity that enables for afterburning;
- excluding influence of afterburner operation on turbine inlet parameters, to prevent turbine blades overheating during afterburning switching-on and switching-off, and also during operation at afterburning mode;
- minimal hydraulic and heat losses;
- minimal mass.

1.2 Main elements of afterburners

Scheme of afterburner is presented in Figure 1.1. Main elements of afterburner are diffuser 1, mixing system containing manifolds with nozzles 2 and flame stabilizers 3, combustion chamber itself 4, heat-proofing and acoustic liners 5 and 6. Variable nozzle 7 with governor 8 is placed at afterburner exit.

The unit containing flame stabilization system and fuel manifolds with fuel nozzles is named as combustor dome of afterburner.

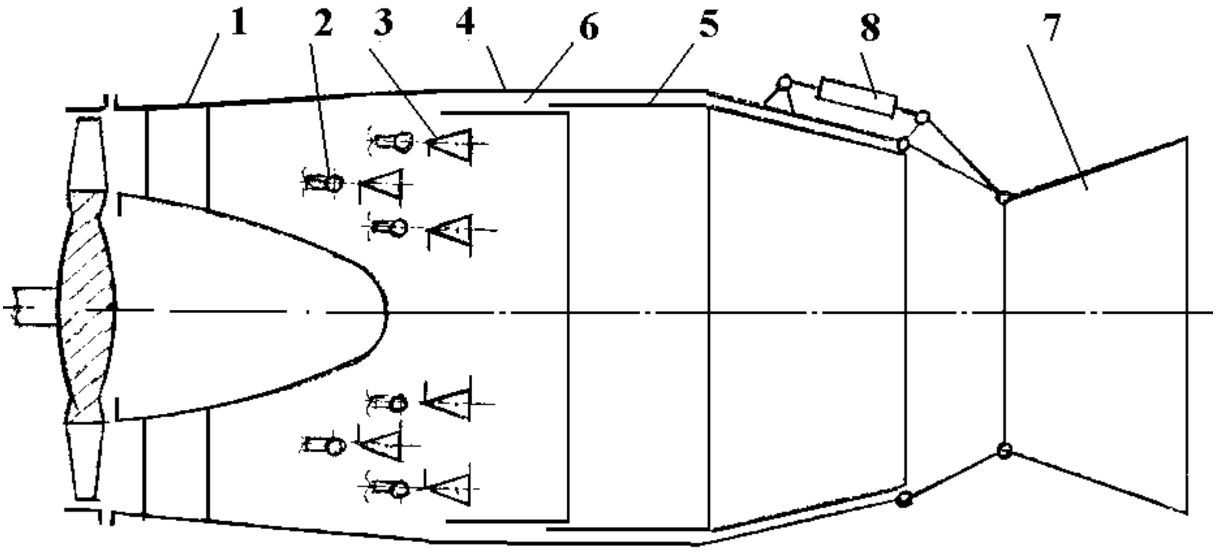

Figure 1.1 – Scheme of ATJE afterburner:
1 – diffuser; 2 – fuel manifolds with nozzles; 3 – flame stabilizers; 4 – flame tube;
5 – heat-protection screen; 6 – acoustic liner; 7 – variable nozzle;
8 – nozzle driving mechanism

Afterburner and jet nozzle of ATJE are shown in Figure 1.2. Figure 1.3 represents diffuser and combustor dome of ATFE afterburner.

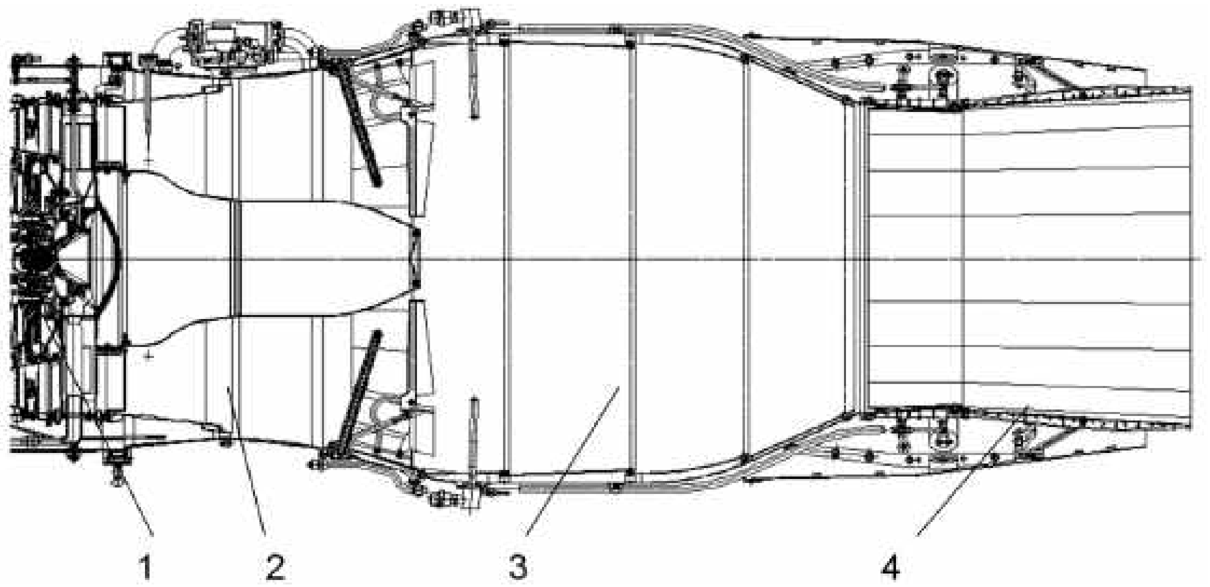

Figure 1.2 – Afterburner and jet nozzle of ATJE:
1 – turbine; 2 – diffuser; 3 – combustor; 4 – jet nozzle

Exercise 1.1

Draw scheme of ATJE afterburner in laboratory notebook, set main constructive elements, note requirements to construction of afterburner.

Diffuser (see Figures 1.2 and 1.3) decreases gas flow velocity to provide stable combustion of afterburning fuel. It is placed directly after turbine. Diameter and length of diffuser are determined from condition of velocity decreasing from 300…400 m/s to 120…200 m/s. Combination of hydraulic losses, size and mass must be optimal. Optimal diffuser angle is 8…12^0, ratio of inlet and discharge areas must be in range $F_1/F_2 = 1.3\ldots2.3$.

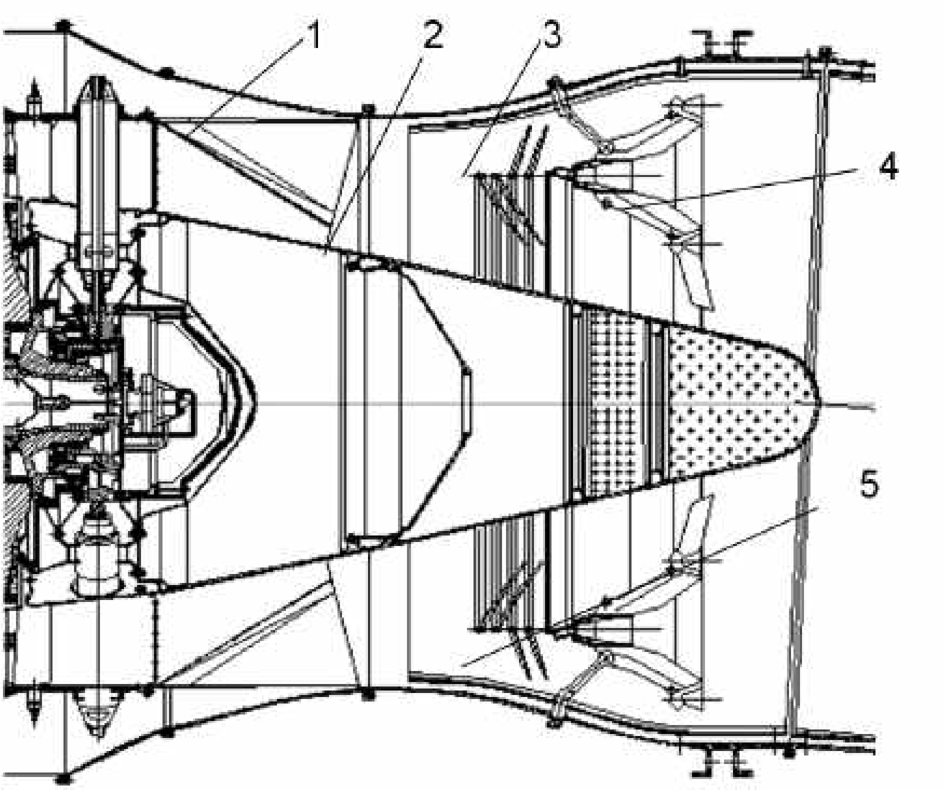

Figure 1.3 – Diffuser and combustor dome of ATFE afterburner:
1 – mixer; 2 – conic cowl of turbine disc; 3 – fuel nozzles; 4 – flame stabilizer; 5 – external case of diffuser

Ring channel of diffuser is created by outer case and conical cowl of turbine disc, which are joined by aerodynamic struts (Figure 1.4). These struts may have non-symmetric profile for strengthening gas flow, going from turbine. Outer case and conical cowl may be also joined by hinged rods (Figure 1.5). The junction must give freedom of thermal deformations. Generating lines of diffuser walls are profiled to provide minimal hydraulic losses at minimum length. Sometimes, with this purpose inner wall is truncated, thus creating dump diffuser with sudden expansion (see Figure 1.5).

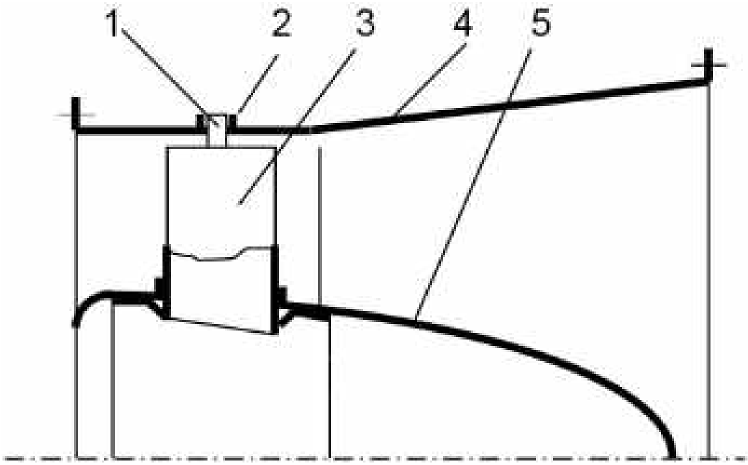

Figure 1.4 – Diffuser with cowl of turbine disc, fixed by struts:
1 – pin; 2 – spherical sleeve; 3 – strut; 4 – outer wall; 5 – cowl of turbine disc

Diffuser of ATFE afterburner is more complex than diffuser of ATJE as the first one contains devices for flows mixing (mixers) that mix cold flow of secondary duct and hot gas with minimum hydraulic losses (see Figure 1.3).

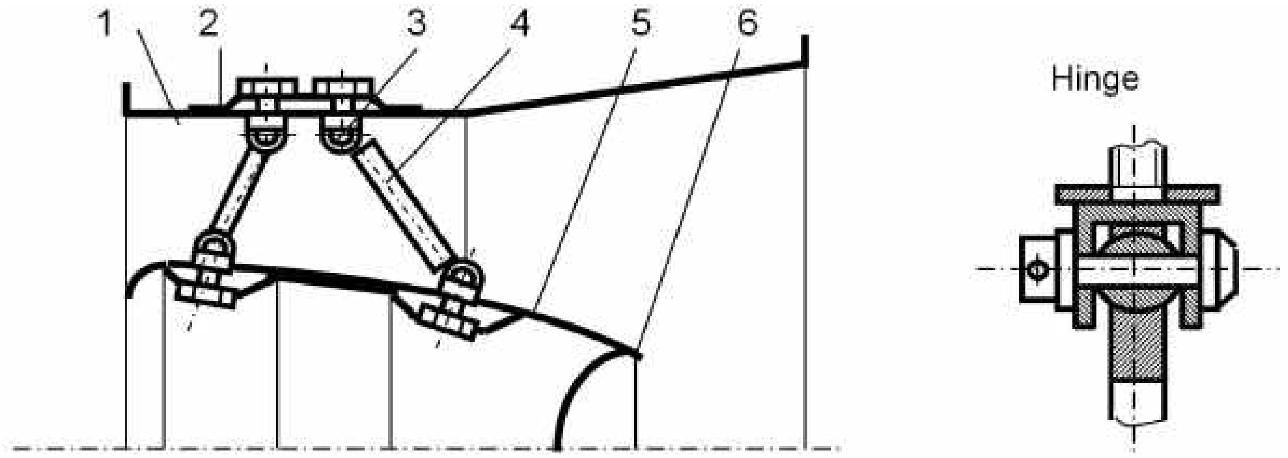

Figure 1.5 – Diffuser with cowl of turbine disc, fixed by rods:
1 – outer wall; 2 – binding band; 3 – rod fixing hinge; 4 – rod; 5 – cowl of turbine disc;
6 – sudden expansion

Exercise 1.2

Consider constructions of diffusers of afterburners using drawings and mockups of engines AL-7F and R11F-300. Draw scheme of one of these diffusers. Explain how the freedom of thermal deformations of constructive elements is provided.

Flame stabilizers save stable position of flame front in combustion chamber and prevent its drifting by gas flow. Turbulent velocity of flame propagation is 10…15 m/s, but gas velocity at diffuser discharge is 150…200 m/s. Therefore stable combustion in afterburner is impossible without special devices, which are named flame stabilizers. The bluff body stabilizers are most widespread. They are made of sheet material and are a bluff body – V-shape profile ring with apex angle 30…60°, which is directed upstream. Zone of reverse flows is formed after a flame stabilizer, in which combustion products with temperature 1800…2200 К circulate. Reverse flow zone, due to high temperature, continuously inflames new portions of fuel-gas mixture, entering afterburner. Wall of stabilizer is cooled from outside by more cold gas flow and by afterburning fuel.

V-shape flame stabilizers may be ring, radial and ring-radial. Ring stabilizers are preferable for ATJE. Ring-radial stabilizers are usually used in ATFE.

Shape of stabilizer is determined not only by specific features of engine and its afterburner, but also by requirement to prevent dangerous oscillatory combustion.

Flame stabilizers jam afterburner cross-section essentially (up to 20…25 % of cross-sectional area). To decrease hydraulic losses, stabilizers are separated by displacing them along flow.

Exercise 1.3

Make sketches of flame stabilizers of afterburners using drawings and mockups of engines. Set methods of their fixation. Sign zones of reverse flows. Add flame stabilizers to previously drawn scheme of diffuser.

System of fuel supplying and mixing serves fuel supplying to afterburner, its spraying and partial vaporizing for inflammable mixture creation, and also distributes fuel between flame stabilizers and in cross-section of afterburner. Mixing system includes feeding pipelines and manifolds, nozzles for fuel spraying (sprayers) and devices for fuel vaporizing (carburetors).

Liquid fuel is sprayed by centrifugal or jet nozzles, which are welded to fuel manifold. Centrifugal nozzles are directed upstream, jet nozzles are directed crosswise or angularly. Fuel jet is fragmented to small droplets due to action of gas flow.

Fuel manifolds are usually placed before stabilizers at a distance 100…150 mm. They are fixed by radial pins or hinges providing freedom of thermal expansions. This position of fuel manifolds and nozzles allows mixing of fuel with maximal amount of gas before fuel reaches trailing edge of stabilizer; substantial amount of liquid droplets is vaporized, thus providing maximum lateral size of flambeau. Non-vaporized fuel droplets create liquid film on surface of stabilizer which cools it. This fuel drains from trailing edges of stabilizer and enriches zone of reverse flows, thus improving combustion stability in afterburner.

Afterburner must operate stably at different altitudes of flight and at varied air/fuel ratio. Therefore there is expedient to place nozzles in some rows at different distance from stabilizers.

Size and positions of stabilizers, number and positions of fuel nozzles are finally chosen experimentally during development of afterburner.

Special devices (carburetors) placed inside stabilizer (Figure 1.6) serve fuel vaporizing. They provide stable operation of afterburner with lean mixtures at $\alpha_{\Sigma} \geq \mathbf{3}$.

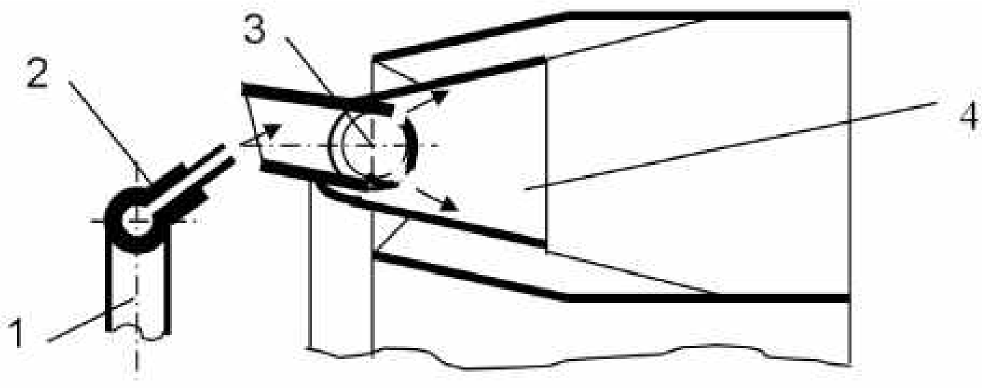

Figure 1.6 – Stabilizer with carburetor:
1 – fuel manifold; 2 – fuel nozzle; 3 – carburetor; 4 – precombustor

Exercise 1.4

Using mockups of engines, study methods of fuel supplying and injection into afterburner. Add fuel manifolds and nozzles to previously drawn scheme of diffuser.

Ignition of mixture in afterburner is done using special device – igniter, placed on axis of combustor dome (Figure 1.7), or using starting igniter, placed on outer casing of combustor dome (Figure 1.8).

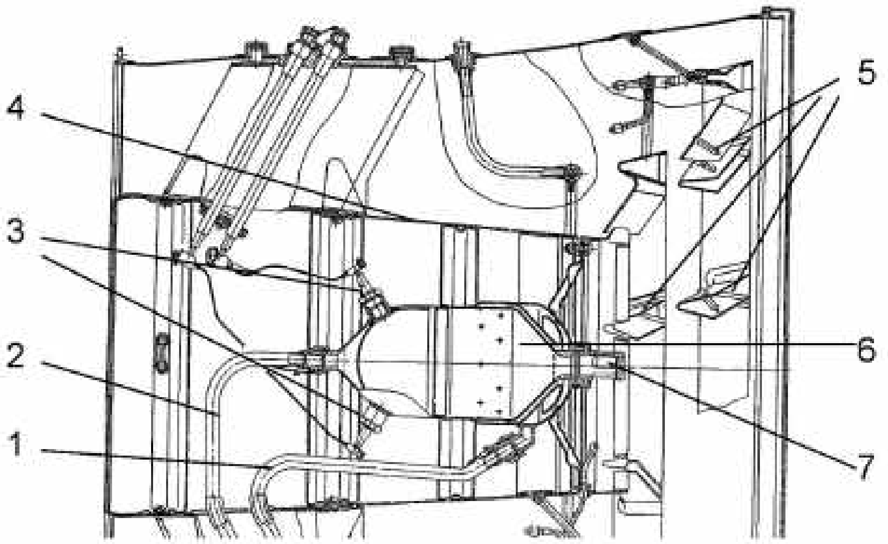

Figure 1.7 – Starting igniter of ATFE afterburner:
1 – air supplying pipeline; 2 – pipeline supplying carbureted fuel/air mixture;
3 – electric sparking plug; 4 – cowl of turbine disc; 5 – flame stabilizers;
6 – combustion chamber of starting igniter; 7 – flame splitter

Starting fuel is ignited into starting igniter by electric sparking plug. Starting ignition is simplified by supplying air to igniter from compressor or oxygen from on-board vessels. Special tube directs starting flambeau from igniter to zone of most intensive flow turbulence, where energy of inflaming is minimal.

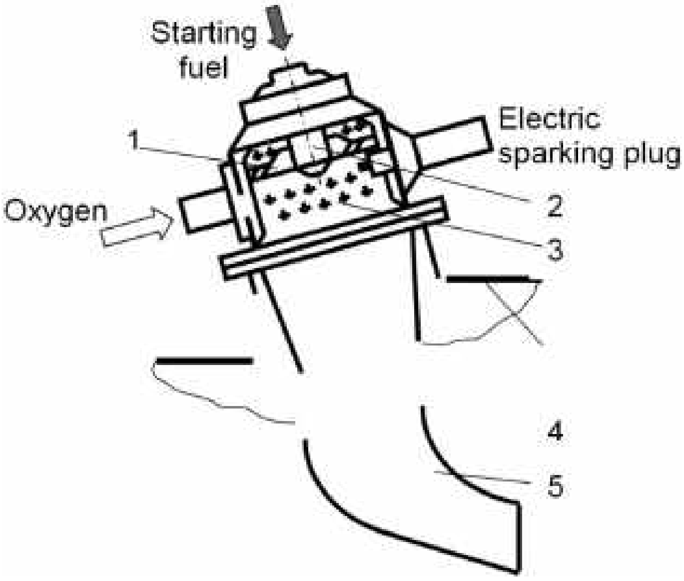

Figure 1.8 – Starting igniter of ATJE afterburner:
1 – vortex generator; 2 – starting fuel nozzle; 3 – holes of oxygen supplying;
4 – case of combustor dome; 5 – flame propagation tube

Modern ATFE are equipped with simple but high thermal power torch system, named as the **‘hot-shot’ ignition system** (Figure 1.9). This system contains jet nozzle, placed at the end of main combustor, directed aside turbine. Starting fuel is injected by this nozzle, goes through turbine, evaporates and inflames due to action of high temperature, thus creating power flambeau after turbine. This device operates at afterburner starting during short time (about 0,2…0,5 s), to prevent intensive heating of turbine blades.

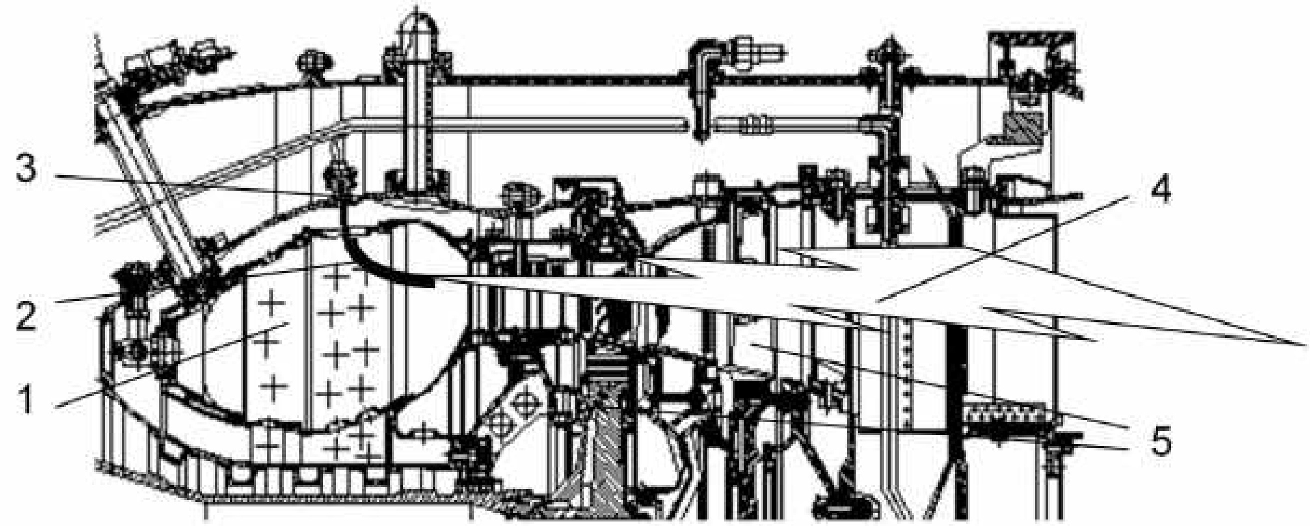

Figure 1.9 – Starting of afterburner by ‘hot shot’:
1 – flame tube of main combustion chamber; 2 – fuel jet;
3 – starting fuel nozzle; 4 – flambeau; 5 – turbine stages

Exercise 1.5

Name methods of afterburners starting. Draw sketch of ATJE starting igniter. Study construction of ‘hot-shot’ system of the engine RD-33 using its drawing.

Combustion chamber is cylindrical or conical shell, welded of a heat resistant sheet material. The combustion chamber begins directly after flame stabilizers and ends by flange, fixing jet nozzle. Geometric sizes of combustion chamber are determined for providing maximum combustion efficiency. Its length is usually 1,2…2,0 m, diameter is 1,2…1,5 m.

Welds of combustion chamber walls are made spiral, for static and vibration strength increasing. Combustion chamber is joined to combustor dome by telescopic or flange-bolt junction allowing freedom of thermal deformations at non-uniform heating. Combustion chamber is blown by air taken from external flow that streamlines aircraft. With this purpose, cowl is mounted outside afterburner, which directs cooling air and simultaneously protects construction of airplane from heating by radiation of hot combustion chamber case. Inner surface of afterburner is cooled by gas going from turbine; in turbofan engine this surface is cooled by air going from secondary duct. Thermal screens improve cooling.

During combustion in afterburner, specific operational mode may appear which is accompanied with gas oscillations with frequency from 50 to 5000 Hz. This mode is named «***oscillatory combustion***». At oscillatory combustion, longitudinal and lateral acoustic oscillations are generated in chamber. Oscillatory combustion is detected by characteristic «squeal» and fast destruction of afterburner elements.

High-frequency oscillations are dumped by acoustic liner, mounted along wall inside chamber (Figure 1.10).

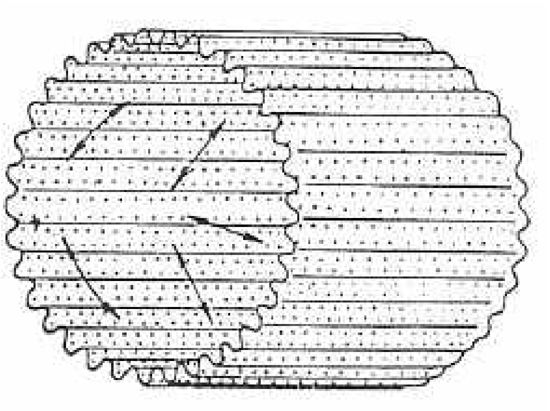

Figure 1.10 – Acoustic liner

Acoustic liner is corrugated perforated construction. It is acoustic resonant absorber, adjusted to suppress oscillations of determined frequencies. Oscillatory combustion is eliminated using next methods:

– acoustic volume changing (for example, choosing shape and size of turbine disc cowl);

– zone of maximal heat generation displacing;

– fuel distribution changing in cross-section of chamber;

– shape and position of stabilizers changing;

– velocity of gas flow changing etc.

Acoustic liner is used also as thermal screen, which decreases radiant heating of wall and controls convex and film cooling.

Position of acoustic liner in case must serve compensation of differences in thermal expansions of elements in relation to case. Radial expansions are compensated by longitudinal goffers, which are deformed at heating; axial displacements are compensated by oval holes in liner for fixing bolts or by telescopic supporting on adjacent section of screen.

Exercise 1.6

1. Study construction of ATJE AL-21F afterburner.
2. Draw fragments of acoustic liner.

1.3 Constructive materials of afterburners

Diffuser is made of sheet heat resistant material, for example XH60B (ЭИ868), using contact welding and fusion welding. Outer rings of diffusers, intensively cooled by air from secondary duct of ATFE, may be made of titanium alloys OT4-1 and BT-20.

Supplying pipelines and manifolds are made of solid-drawn pipes of stainless steel 1X18H9T or of heat resistant alloy XH60B (ЭИ868), joined by welding or soldering. Threaded nipple joints inside afterburner give no satisfactory leak proofness in conditions of variable thermal loads; therefore they are no used.

Case of combustion chamber and acoustic liner of ATJE, which operational temperature is 900…1100^{0}C, are made of heat resistant alloy XH60B (ЭИ868). Outer case of ATFE, which temperature no exceeds 300…400^{0}C due to cooling by air from secondary duct, is made of titanium alloys OT4-1 and BT-20.

Corrosion protection of stabilizers and acoustic liners is provided by high-melting chromium or silicon enamels.

Exercise 1.7

Write in your notebooks main constructive materials used in afterburners. Explain why ATFE afterburner case may be made no of heat resistant alloys but of more light titanium alloys.

1.4 Answer the questions about afterburners

1. What aircrafts need engines with afterburning?
2. Purpose, shape of gas path and construction of afterburner diffuser.
3. How is the burning zone in afterburner stabilized?
4. Name means improving fuel vaporizing and mixing with air and gas flow in afterburner.
5. How does the afterburner start? Name methods of afterburner starting.
6. Describe ‘hot-shot’ ignition system.
7. What is oscillatory combustion and how is it prevented in afterburners?
8. Name cooled parts of afterburner and methods of their cooling.
9. What materials are used in afterburners?

2 EXHAUST SYSTEMS OF GAS TURBINE ENGINES

2.1 Appropriation and composition of exhaust systems

Exhaust system is a part of gas turbine power plant placed after turbine. In general case, gas turbine engine exhaust systems may include:

– exhaust diffuser;

– gas-outlet tube that connects turbine and jet nozzle;

– mixing chamber (it is used in turbofans with mixing flows to provide uniform temperature field at inlet to nozzle, thus decreasing losses of output impulse);

– jet nozzle (fixed or variable);

– reverse device;

– thrust deviator (device for thrust vector control);

– noise suppressors.

Exhaust systems have a lot of appropriations determined by their functions. The main appropriation is effective transformation of available heat (potential energy of gas) into kinetic energy of gas flow. Besides, exhaust systems solve next tasks:

– engine control by varying area of jet nozzle;

– providing minimal aerodynamic drag of power plant tail part;

– thrust vector control;

– noise suppression;

– infrared radiation suppression to decrease aircraft infrared perceptibility.

These multiple functions that are to be realized in wide range of flight altitudes and velocities, transform simple jet nozzle of first generation of engines into complex system which quality determines aircraft performances, especially for supersonic and maneuverable airplanes.

Exhaust systems of turbine engines operate under heavy-load conditions:

– high gas temperature (at non-afterburning conditions, turbine discharge temperature is 1000…1200 К and at afterburning this temperature is 2100…2200 К);

– high velocity of gas flow (nozzle discharge velocity under non-afterburning conditions is 600…750 m/s and under afterburning reaches 1100 m/s);

– high-temperature gas going from turbine is chemically active, as it contains a lot of oxygen, which doesn't take part in burning kerosene in main combustor;

– essential non-uniformity of temperature, velocity and pressure both along duct and in circumferential direction.

Requirements to exhaust systems of turbine engines are as follows:

– minimum loss of effective thrust in all maintenance range of flight altitudes and velocities;

– minimum heat losses through walls and minimum heating of aircraft constructive elements;

– reliable operation in chemically active high-temperature substance;

– low mass and size (no more than 4…10 % of engine mass).

Exercise 2.1

Name functions of turbine engines exhaust systems. What are requirements to construction of exhaust system?

Exercise 2.2

Explain influence of jet nozzle area variation on turbine pressure ratio and turbine inlet temperature.

2.2 Construction of exhaust systems' elements

The simplest exhaust system has a **turbojet engine**; this device consists of turbine disc cowl and fixed conical spout (Figure 2.1). Cowl of turbine disc prevents sudden expansion of flow and vortex creation after turbine, and also protects turbine disc heating by hot gas.

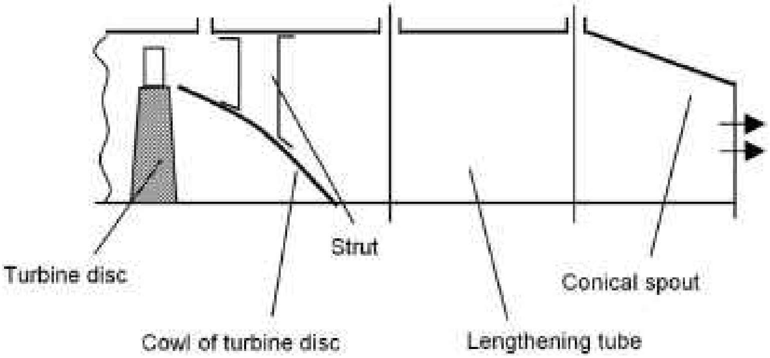

Figure 2.1 – Fixed jet nozzle of turbofan engine

Angle of internal cone is 35…50^0. This cone is joined with outer case by radial struts or rods protected from overheating by cowls. Struts are cooled by air; their construction serves free thermal expansion of joined elements.

If turbine discharge flow has non-axial direction, then cowls of struts are made twisted to strengthen flow, thus decreasing hydraulic losses in other parts of nozzle.

Taking into account conditions of engine mounting in airplane, construction of exhaust system may contain gas-escape lengthening tube made by welding of heat resistant sheet steel. Its diameter must provide velocity of gas to be no more than 150…200 m/s, thus decreasing hydraulic losses. Joint of lengthening tube to gas generator must allow displacement to compensate engine and planer manufacturing and mounting errors, and also to decrease loads caused by deformations of fuselage and engine nacelle.

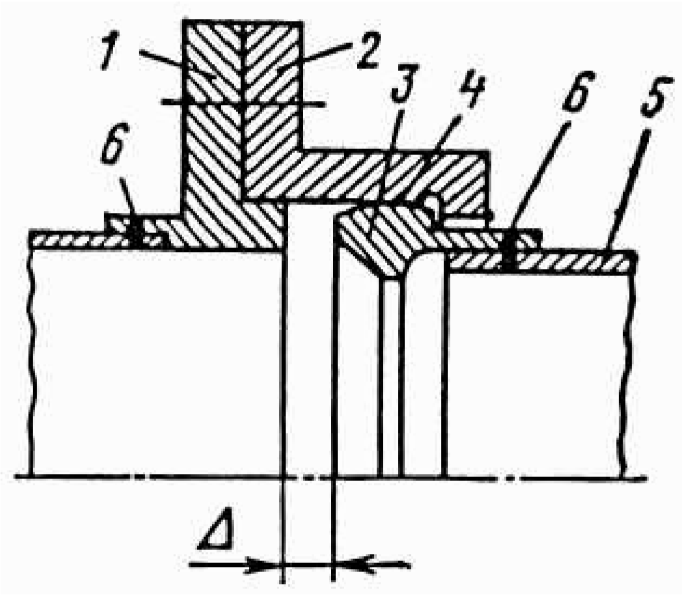

Figure 2.2 – Flange of lengthening tube fixation:
1 – flange of exhaust tube;
2 – flange of lengthening tube;
3 – spherical ring; 4 – spherical surface;
5 – lengthening tube; 6 – weld

Figure 2.2 shows example of lengthening tube mount construction. Spherical ring 3 joined with flange 2, which has long groove for ring, allows ring displacement Δ and simultaneously small turning. Rear side of lengthening tube is joined by rollers with eccentrics, which can move by guiding channel bars in fuselage when tube and engine as a whole take thermal deformations.

To decrease planer elements heating, lengthening tube is covered by heat isolation and screen, under which cooling air is supplied.

Exercise 2.3

Draw in your notebook scheme of exhaust system with lengthening tube and graphics of gas parameters (pressure, temperature and velocity) variation on length of exhaust system.

Exhaust system of turboprop engine (Figure 2.3) no changes gas parameters essentially, as main thrust is generated by propeller, and jet thrust is only 10…15 % of total thrust. Exhaust system of turboprop engine discharges gas without its essential expansion. So exhaust gas velocity is less than in turbojet engine. Low velocity of gas allows gas discharging at a small angle to a flight line (up to 20^0), taking into account engine integration with airplane.

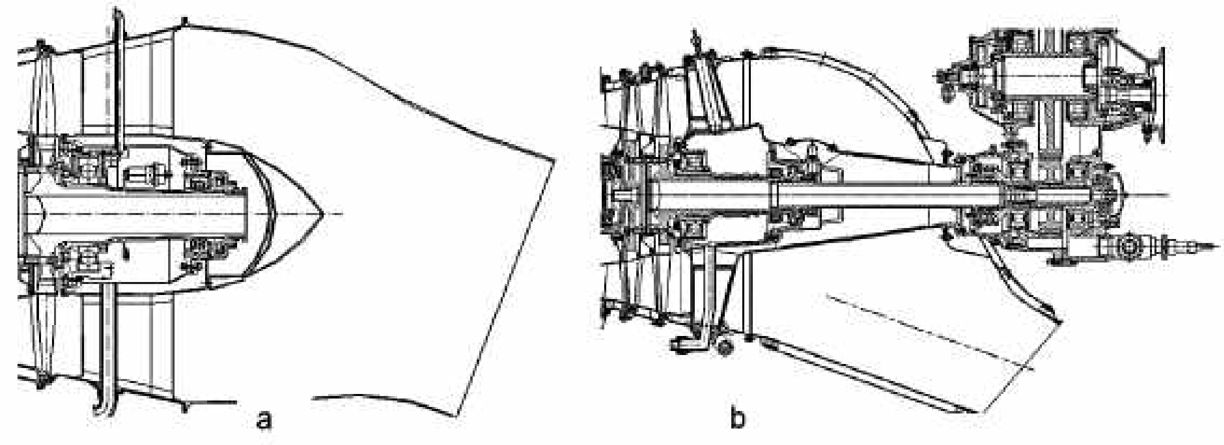

Figure 2.3 – Exhaust systems of turboprop engines:
a – single-shaft turboprop; b – free-turbine turboprop

In **helicopter engines**, gas is discharged sideways (Figure 2.4).

In **turboshaft engines**, available heat energy of gas is transformed into mechanical energy of free turbine. Therefore these engines are designed with maximal free turbine temperature difference, which needs maximal possible pressure difference. So turbine discharge static pressure may be less than atmospheric pressure, and exhaust branch pipe is designed no convergent, but divergent.

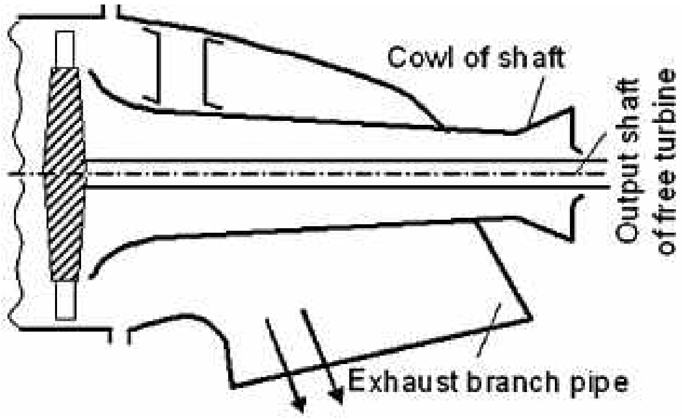

Figure 2.4 – Exhaust system of helicopter turboshaft engine

Mixing chamber is used in TFE for mixing gas going from primary duct, with air going from secondary duct. Mixer placed at the inlet to chamber, separates flows of air and gas onto separate jets of small diameter, thus improving turbulent mixing and shortening length of chamber.

Mixers are axial and radial (Figure 2.5).

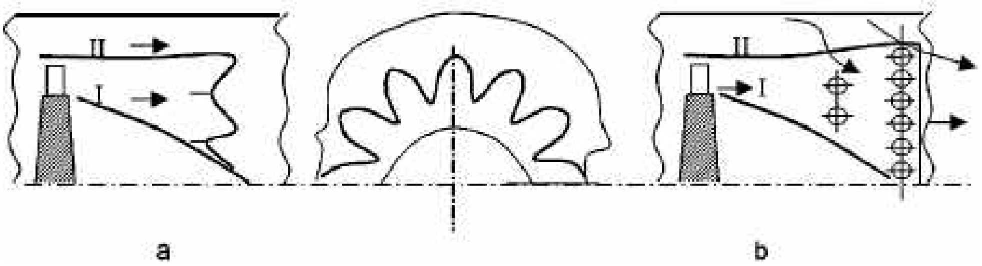

Figure 2.5 – Types of mixers: a – axial (D-30P); b – radial (RD-33)

2.3. Construction of jet nozzles

2.3.1 Parameters and shape of jet nozzle

The main parameter that determines choice of nozzle type, is available pressure ratio – ratio of nozzle inlet stagnation pressure to static atmospheric pressure: $\pi_N = \dfrac{p_T^*}{p_H}$.

This ratio for turbojet engine at $CPR \approx 10 \ldots 15$ and $TIT \approx 1400 \ldots 1500$ K is $\pi_N \approx 6 \ldots 8$ for $M = 1$, and $\pi_N \approx 25 \ldots 35$ for $M = 3$.

Nozzle transforms potential energy of gas (pressure) in kinetic energy (velocity), so gas is expanded. Maximal specific thrust may be obtained at full expansion, which means nozzle discharge static pressure is equal to atmospheric one. Full expansion with minimum hydraulic losses gives appropriate shape (profile) of nozzle (Figure 2.6).

Engines for airplanes which flight Mach number is $M \le 1.5 \ldots 1.7$ are equipped with convergent nozzles (Figure 2.6, a). Engines for supersonic flight with Mach number $M \ge 1.7$ are equipped with convergent-divergent (Laval) nozzles (Figure 2.6, b).

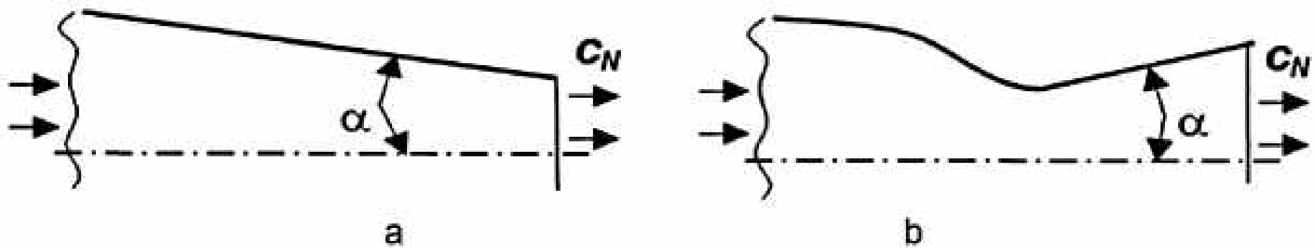

Figure 2.6 – Nozzle profile:
a – convergent nozzle for subcritical and critical flows ($c_N < a$);
b – convergent-divergent nozzle (Laval nozzle) for supercritical nozzles ($c_N > a$)

Output velocity of real nozzle c_N is less than theoretical (adiabatic) velocity $c_{N\ ad}$ because of losses. This decreasing is characterized by velocity factor $\varphi_N = c_N / c_{N\ ad}$ which value is 0,97…0,99.

2.3.2 Nozzle control

Fixed nozzle that operates at off-design conditions worsens engine performances. Effective engine operation at all flight conditions needs controlling of nozzle. Variable nozzle also gives following improvements:

– helps engine starting;

– increases compressor stability;

– provides minimum fuel consumption at cruise modes;

– provides independence of turbocompressor parameters on afterburner operation.

Control of subsonic nozzle is realized by variation of its exhaust cross-section. Control of supersonic nozzle needs variation of two cross-sections: critical and exhaust. Nozzle cross-sectional area may be varied by three methods:

– rotating special plates – nozzle flaps – around hinges fixed to casing; these flaps are placed on circle and create movable crown; this nozzle is named lobe one; variant of lobe nozzle is flat nozzle of rectangular section created by two horizontal and two vertical flat plates;

– moving specially profiled central body in axial direction;

– varying cross-sectional area pneumatically using jet of compressed air, which is supplied to exit section and creates ‘liquid’ duct in nozzle.

2.3.3 Fixed nozzle

Fixed subsonic nozzles have angle β no more than 10-12° and length/diameter ratio $\boldsymbol{L_N / D_N \approx 0{,}15 \ldots 0{,}4}$ (Figure 2.7).

Exhaust section of nozzle is circular, sometimes is elliptic. Construction rigidity is improved by welding profiled rings to trailing edge or by flanging trailing edge.

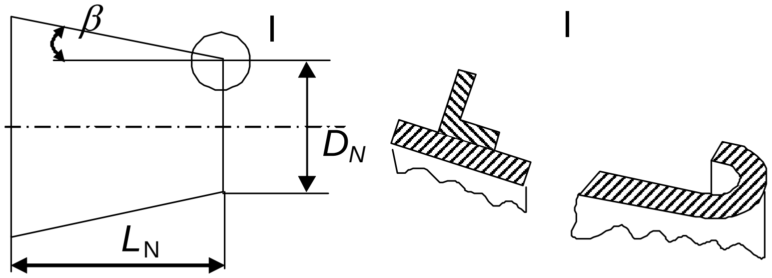

Figure 2.7 – Fixed subsonic nozzle – conical spout

2.3.3 Variable nozzle

Variable subsonic nozzle gives possibility to support optimal operation of turbocompressor, to facilitate engine starting, to improve fuel consumption at off-design operational conditions. The nozzle is made of separate flaps fixed in front section by hinges. Area of exhaust cross-section is changed by power ring with hydraulic cylinder (Figure 2.8).

Figure 2.8 – Scheme of subsonic variable nozzle:
1 – hydraulic cylinder; 2 – power ring; 3 – roller; 4 – profiled cam; 5, 6 – variants of flaps construction in position of minimum area; 5 – seam connection; 6 – peripheral flaps

Law of exhaust area variation determines profile of cam. Leak-proofness is provided by seam connection or by peripheral flaps. Number of flaps in known constructions is ***z*** = ***6…36***. Shape of cross-section becomes more circular when number of flaps increases. Flaps are cooled by air.

Figure 2.9 shows construction of multi-flap convergent nozzle. Flaps 3 are box-type to improve rigidity and air cooling. Flaps are sealed between themselves by shelf 4 which enters forked channel 5 of adjacent flap. All flaps are fixed by hinges to flange of outer tube. Gas pressure actuated their opening and pressing to external ring 6. This ring controls flaps, driven by three hydraulic cylinders 1. When ring goes left (Figure 2.9), flaps close, when ring goes right, flaps open.

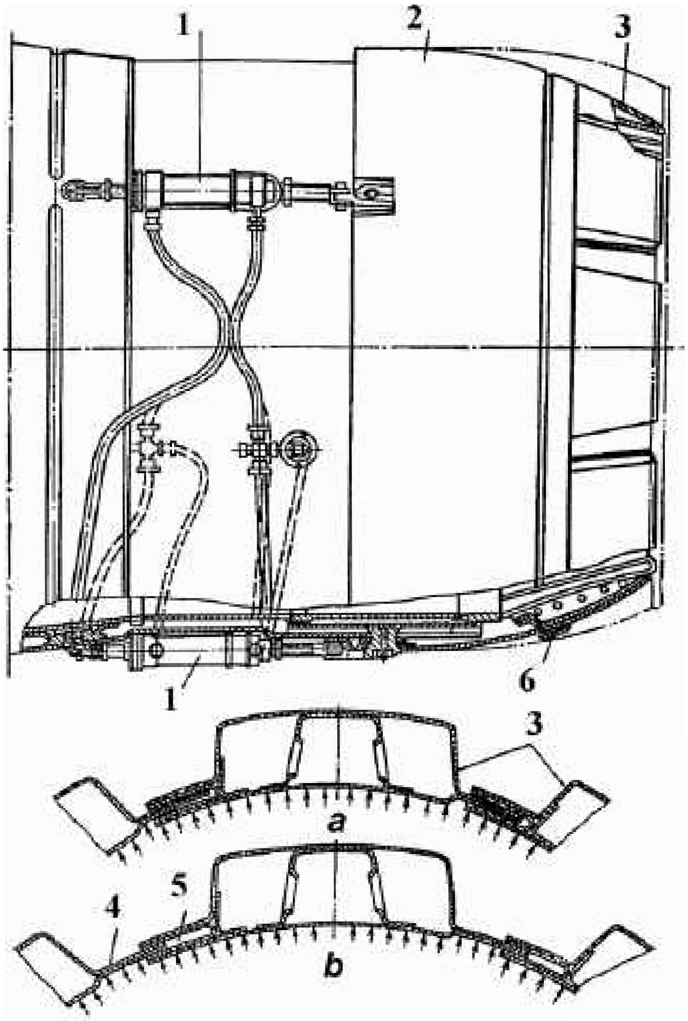

Figure 2.9 – Variable multi-flap convergent nozzle:
1 – hydraulic cylinder; 2 – variable nozzle;
3 – flaps; 4 – shelf; 5 – forked channel;
6 – ring; a –minimum exhaust area flaps position;
б – maximum exhaust area flaps position

Exercise 2.3

1. Draw scheme of subsonic variable nozzle in your notebook.
2. Study construction of flaps, power ring and hydraulic cylinders using mockup of ATJE RD-9B. How is a leak-proofness of nozzle provided?

Lobe double-row nozzle is variable convergent–divergent (Laval) nozzle. It has two rows of flaps – subsonic flaps fixed by hinges in inlet section, and supersonic flaps that are hinged to subsonic flaps (Figure 2.10).

Supersonic flaps may be driven by special rods (ATJE AL-21F of airplanes Su-17 and Su-24) or using their placement in feathering position actuated by pressure difference (ATFE RD33 of MiG-29 airplane).

Ejector nozzle is flapped single-row nozzle equipped with external ejector flaps (Figure 2.11). In this construction, solid wall of nozzle supersonic part is substituted by liquid wall created by jet of secondary air going from ejector flaps.

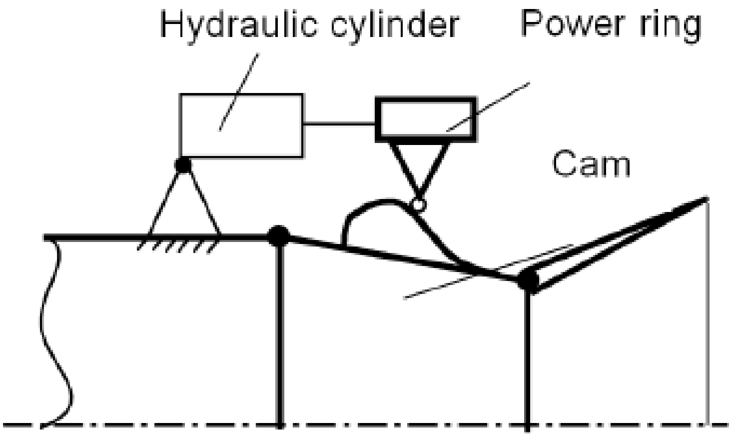

Figure 2.10 – Lobe double-row nozzle

Ejector nozzle operates as follows. At supercritical operational mode, exhaust jet of gas going from convergent part expands in concurrent subsonic flow and takes shape of divergent part of Laval nozzle. This stimulates further acceleration of flow and decreasing of gas temperature and pressure.

Essential thrust increase and simple control are attractive features of this nozzle. So it is widely used in afterburning engines (for example ATJE R15B of MiG-25 airplane). Ejector flaps may be feathering (without mechanical drive), then they fix themselves in flow actuated by pressure difference p_N and p_H (for example ATJE R29-F-300 of MiG-23 airplane).

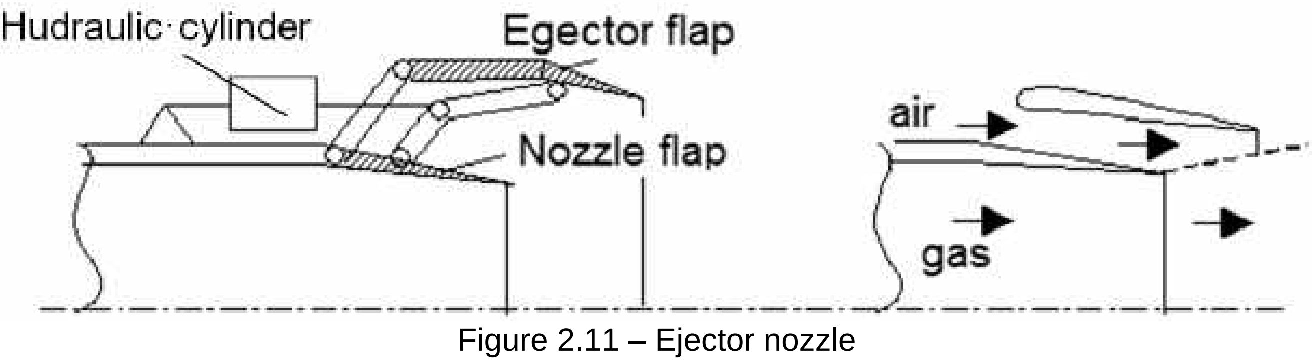

Figure 2.11 – Ejector nozzle

Supersonic nozzle with central body is aerodynamically controlled. There are differed nozzles with external expansion and combined nozzles having partial internal and partial external expansion. They are controlled due to axial displacement of central body (Figure 2.12). Nozzles with central body have simple construction, but are not widely used because it is difficult to cool central body and its driving mechanism.

Figure 2.12 – Nozzle with central body:
a – with external expansion; b – combined

Driving mechanism of variable nozzle consists of some hydraulic cylinders and flaps. Hydraulic cylinders are two-position, three-position or multimode. Mounting units of cylinders are placed as close to hinges of flaps as it is possible to exclude influence of axial thermal deformations on nozzle area.

Working fluid of hydraulic cylinders is kerosene with pressure 15…20 MPa. To prevent heating of kerosene cylinders have circulating construction, they are heat-isolated by asbestos and protected by heat-reflecting screen.

Pistons of power cylinders are synchronized to exclude skewing of power ring in relation to nozzle axis. Hydraulic, electrohydraulic or mechanical synchronizing may be used. Hydraulic synchronizing system contains constant flow valve in drain line of cylinder. In electrohydraulic system, this valve is electrically driven. At mechanical synchronizing, rods of cylinders are connected by flexible shafts and warm-and-warm pair or semirevolving mechanisms.

Driving mechanism transmits forces from hydraulic cylinders to flaps through power ring, transforming linear motion of piston rods into angular motion of flaps. Power ring drives flaps through cam mechanisms or hinged polyarticular mechanisms.

Exercise 2.4

Using drawing and mockup of ATJE AL-21F nozzle, study its construction. How is nozzle leak-proofness provided? How are pistons of power cylinders synchronized? How are flaps and external flaps driven?

Flat nozzles. General direction of nozzles development is integration with airplane. Now different types of flat nozzles for multimode maneuverable planes are known. Scheme of flat nozzle is analogous to scheme of axisymmetric nozzle (Figure 2.13).

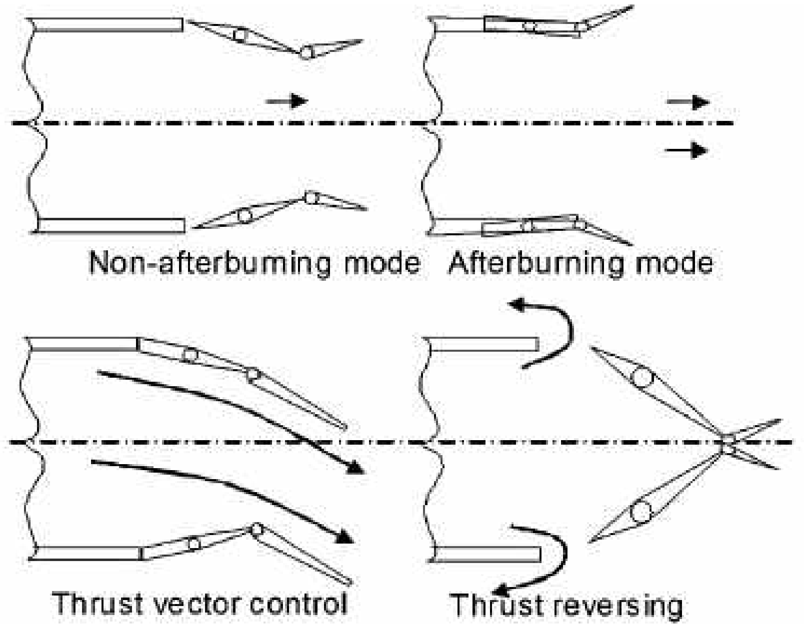

Figure 2.13 – Operation of flat universal exhaust auxiliary

Advantages of flat nozzles are simple constructive realization of different functions (thrust vector controlling, reversing), good aerodynamic coordination of exhaust jet stream with streamlining of airplane tail part, improvement of airplane lift-and-landing performances due to vertical thrust generation.

Main disadvantages of flat nozzle are increased mass comparing to axisymmetric nozzle and difficult cooling of big flat panels.

2.4 Thrust reversers and deviators

Thrust reversing is used during airplane landing for breaking and during taxing. Some military airplanes use thrust reversing for inflight maneuvers. Thrust reverser functions by obstructing exhaust by blocker doors which can be turned into the flow. This diverts the jet radially outwards making forward velocity component. Turning exhaust flow to a forward direction results in a forward thrust component which acts as a brake.

Main parameter of reverse device is reversing factor. It is a ratio of reverse (negative) thrust to maximal direct thrust

$$K_r = \frac{P_r}{P}.$$

Experimental reversers reach values of reverse factor ***– 0,85…– 0,9***. Commonly used reversers with gas turn 120…140° have $K_r \approx -0{,}5 \ldots -0{,}6$.

Requirements to construction of reverser:

– no influence of reverser on operation of turbocompressor;

– minimum loss of positive thrust when reverser doesn't operate;

– no hot gas entering engine inlet when reverser operates;

– fast (in 1–2 s) changing thrust direction from positive to negative;

– synchronizing of reversers in multi-engine power plant.

There a lot of schemes of reversers exist, but today two of them are widely used:

– with turning flow before exhaust nozzle (pre-exit clamshell reverser, Figure 2.14, a, b);

– with turning flow after exhaust nozzle (post-exit bucket target reverser, Figure 2.14, c, d).

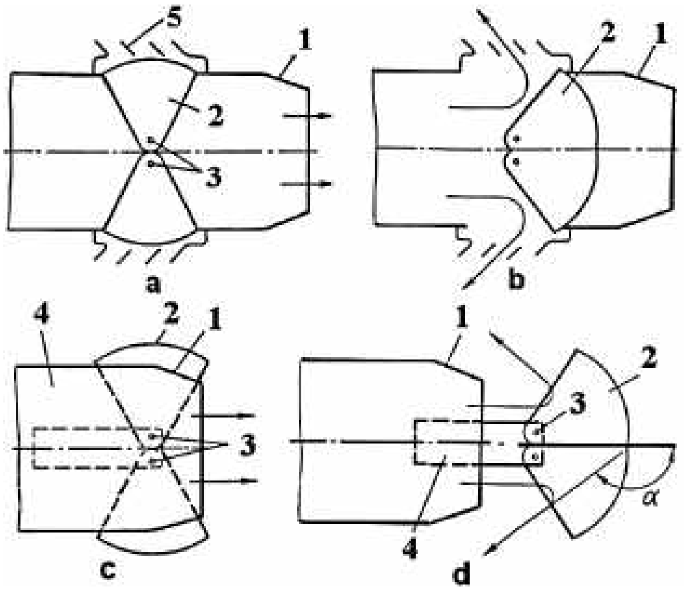

Figure 2.14 – Thrust reversers:
a, b – pre-exit clamshell reverser; c, d – post-exit bucket target reverser;
a, c – normal position; b, d – reverse position; 1 – common jet nozzle;
2 – blocking doors; 3 – hinges of doors; 4 – sliding doors keeper; 5 – cascade

First scheme is more complex and needs special cascades for flow turning and needs sealing between clams and gas-escape tube. But this scheme needs less driving force, so pneumatic cylinders may be used.

In second scheme, bucket doors that turn flow are elements of cowl. This scheme has increased losses because turns high-velocity flow; bucket doors must have high strength and rigidity, as take more loads than in previous scheme.

Exercise 2.5

1. Using poster «Thrust reverser of D-30P turbofan» and engine mockup, study operational principle of thrust reverser, construction of components,

sealing between clams and casing at direct thrust mode. Draw a scheme of this thrust reverser in your notebook.

2. Consider thrust reversers of NK-8-2 and D-30KP turbofans.

Turbofan engines which bypass ratio is high are designed without mixing of primary and secondary flows. Therefore thrust reverser is placed in secondary duct. This duct is accomplished by vanned cascades arranged as single elements around the engine circumference. In their retracted position they are shrouded on both sides in order not to disturb the interior and exterior flows (Figure 2.15, a). The shroud, together with rear nacelle, forms convergent nozzle for fan jet. When extended into reverse position, the cascade shroud slides backwards, then individual blocker doors swing into the secondary nozzle duct and direct the secondary flow through the fixed cascades. The shape of the grid turns the flow in forward direction, thus providing reverse thrust (Figure 2.15, b). The value of reversing factor is 0,22…0,25. Examples are thrust reversers of turbofans D-18T, D-436T, CF6.

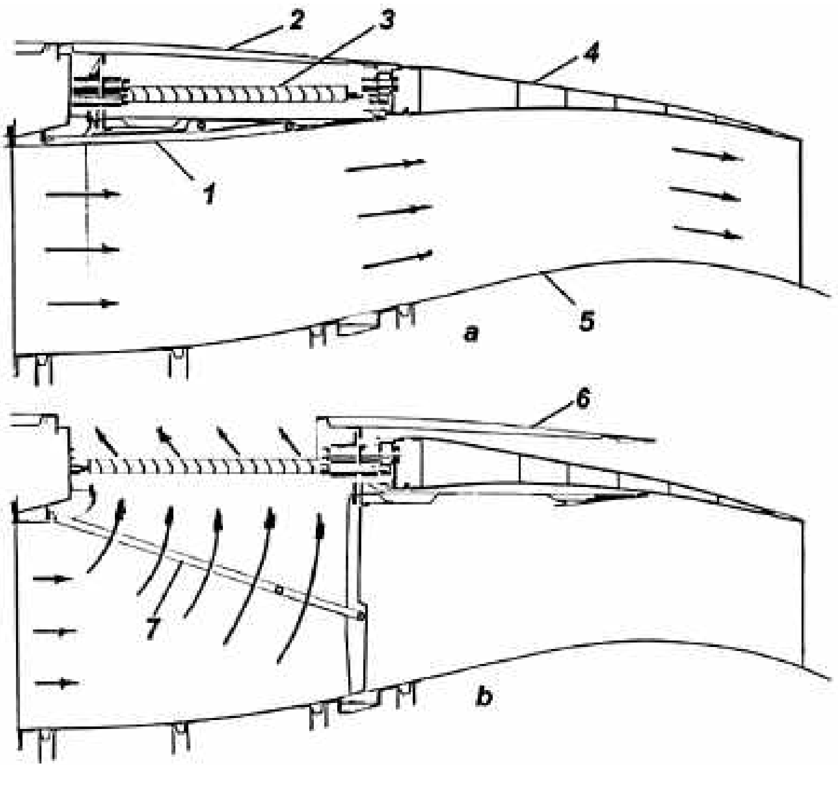

Figure 2.15 – Turbofan thrust reversing in secondary duct:
a – normal position; b – reverse position; 1 – blocker door in normal position;
2– cowl in normal position; 3 – cascade; 4 – cowl; 5 – cowl of engine core;
6 – cowl in rearward position; 7 – blocker door extended

Thrust deviators are used for vertical or short takeoff and landing (VSTOL) and maneuverable airplanes. They create vertical component of thrust and control thrust at airplane maneuvers.

There are differed deviators which construction is independent on main nozzle and deviators combined with main nozzle (Figure 2.16). First scheme contains deviator nozzles and shuttles; second scheme contains vectorable nozzles.

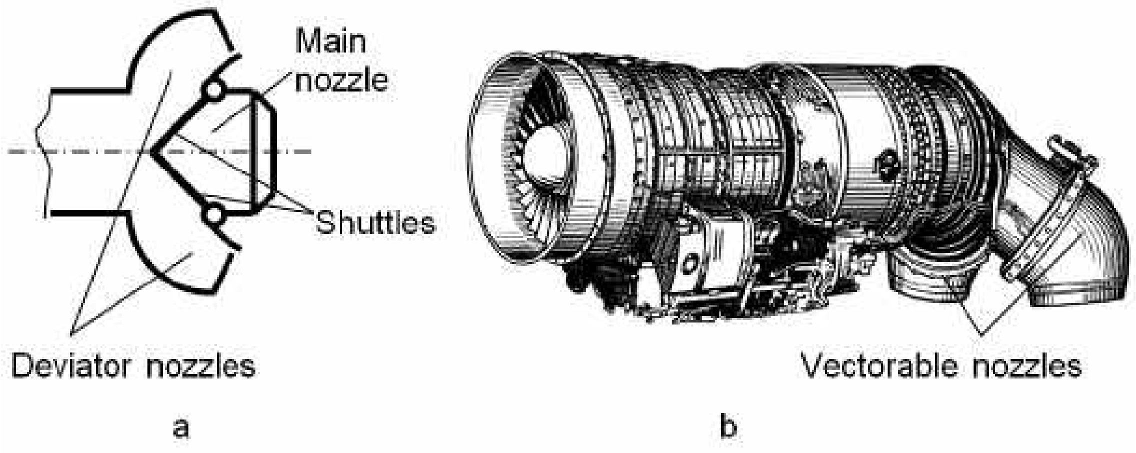

Figure 2.16 – Thrust deviators:
a – with deviator nozzles and shuttles; b – with vectorable nozzles

Position of thrust reversers is such that the thrust vector of engine with activated deviator goes through gravity center of airplane.

2.5 Noise suppressors of jet nozzles

The major source of noise in the pure jet engine and low bypass ratio turbofan is high-velocity jet stream of gas that mixes with atmospheric air. Power of noise is proportional to a nozzle exhaust area and to velocity in eights power. Therefore reduction in noise level occurs if the mixing rate is accelerated or if the velocity of the exhaust jet relative to the atmosphere is reduced.

It is achieved by increasing the contact area of the atmosphere with the exhaust gas stream. With this purpose a propelling nozzle is fitted by a corrugated or lobe-type noise suppressor.

In the corrugated nozzle, freestream atmospheric air flows down the outside corrugations and into the exhaust jet to promote rapid mixing. Principle of noise suppression in high-bypass ratio turbofans with separate flows is the same as for pure or low-bypass engine. Both nozzles of these engines are equipped with chevron-shape trailing edges that improve mixing (Figure 2.17).

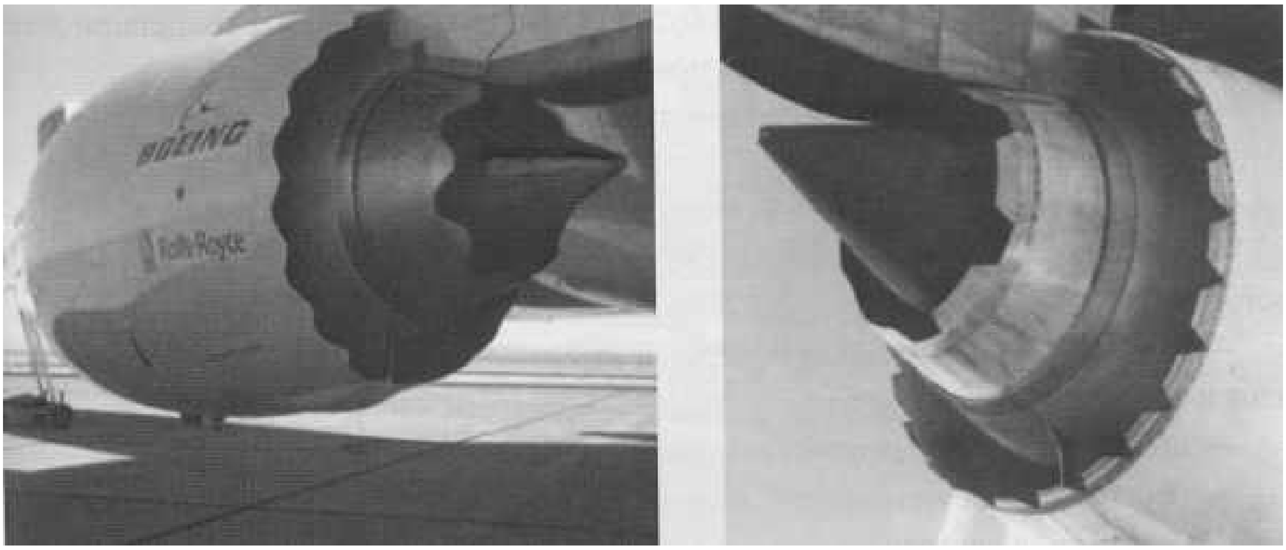

Figure 2.17 – Corrugated (chevron-type) nozzles of high-bypass turbofan

In the lobe-type nozzle (Figure 2.18), the exhaust gases are divided to flow through the lobes and a small central nozzle. This forms a number of separate exhaust jets that rapidly mix with the air entrained by suppressor lobes. This principle can be extended by use of a series of tubes to give same overall area as the basic circular nozzle.

Otherwise, noise suppressors used in nozzles increase engine mass on 2…3 %. Besides, internal and external hydraulic losses are increased, so thrust decreases and specific fuel consumption increases on 1…2%. Therefore nozzle noise suppressors have no wide application now.

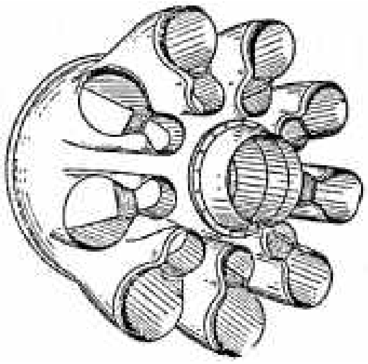

Figure 2.18 – Lobe-type nozzle

2.6 Infrared radiation suppressors

Modern tools for air targets detection use infrared radiation of engines as a signal to identify aircraft, that makes aircraft attackable by rockets equipped with self-direction heat heads.

Major elements determining intensity of engine heat radiation are:

– blades of last turbine stage;

– internal surfaces and constructive elements of afterburner and jet nozzle;

– high-temperature jet of nozzle exhaust gas.

Methods of infrared perceptibility decreasing are:

– shielding of direct IR-radiation of hot engine elements (turbine blades, struts of exhaust duct etc.) by cooled central body with curved exhaust duct;

– curving exhaust duct without central body (Figure 2.19);

– mixing exhaust gas flow with cold atmospheric air (for ATFE at non-afterburning modes) or with air of secondary duct (for ATFE);

– cooling hot surfaces of engine gas path to temperature that is close to temperature of aircraft surface, using air film cooling;

– covering hot internal and external surfaces of inlet device by materials with low radiating capacity.

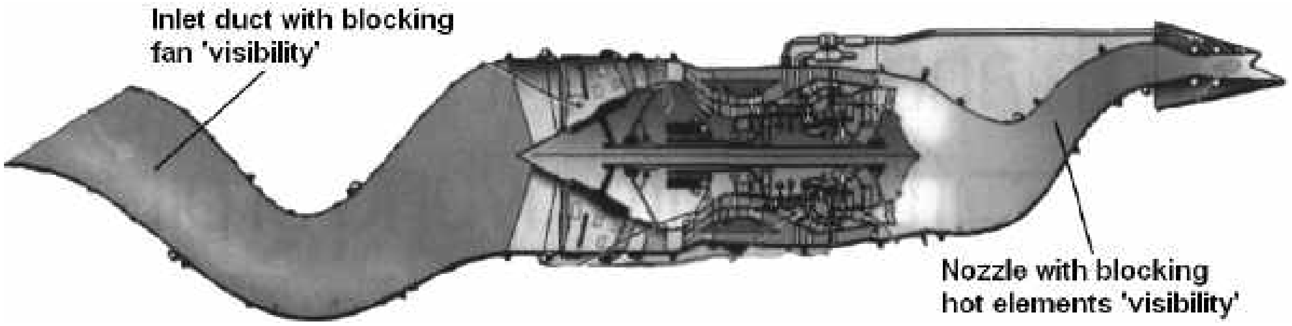

Figure 2.19 – Engine gas path curving for IR-perceptibility decreasing

Figure 2.20 represents scheme of exhaust device with IR-radiation suppression system.

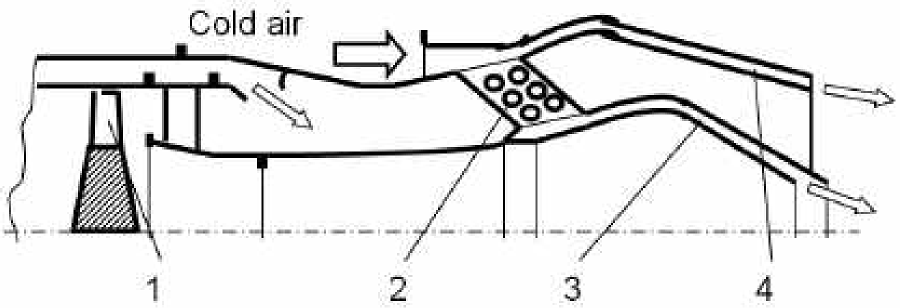

Figure 2.20 – Exhaust system with low IR-radiation capacity:
1 – turbine blade; 2 – cooled struts; 3 – cooled central body; 4 – cooled external shell

Efficient IR-radiation decreasing is given by flat nozzles with screening hot components of gas path and intensive mixing of flat exhaust stream with atmospheric air.

Original construction of exhaust system is used in unobtrusive fighter Lockheed F-117A. In this system traditional circular jet transforms into flat jet of rectangular shape and goes away with high velocity through a slot in tail part of fuselage, i. e. directly through construction of planer (Figure 2.21). This decreases noise and IR-perceptibility.

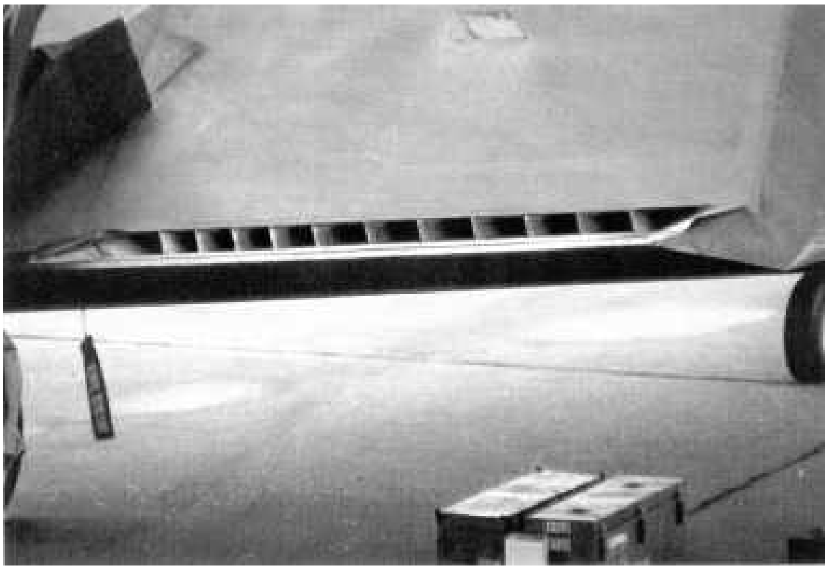

Figure 2.21 – Slots in tail part of fuselage for jet stream exhaust

Some nozzle components are honeycomb panels made of nickel alloy. This material has high strength and resistance for acoustic and heat loads.

2.7 Constructive materials

Materials for components of exhaust systems operate at temperatures 650…900^{0}C. Therefore components for operational temperature 650…750^{0}C are made of heat resistant steel 12Х18Н9Т or of heat resistant steel casted by niobium Х18Н11Б (ЭИ-402); for more operational temperature nickel heat-resistant alloys ХН78Т (ЭИ-435), ХН75МБТЮ (ЭИ-602), ХН60БТ (ЭИ-868, ВЖ-98) are used. External screens are made of titanium alloys, for example ОТ4-1.

2.8 Answer the questions about exhaust systems

1. Types of exhaust systems, their functions and requirements to them.
2. Elements of exhaust systems.
3. Specifics of exhaust systems for turboprop engines.
4. Specifics of exhaust systems for turboshaft engines.
5. What is a function of mixer? What types of mixers do you know?
6. What is a difference between convergent and Laval nozzle? Name areas of their application?
7. Which methods are used for nozzle area variation in variable nozzles?
8. What is a principle of ejector nozzle operation? Name advantages of these nozzles.
9. How are the nozzles driving mechanisms synchronized?

10. What is the reverse factor?
11. Describe types of thrust reversers.
12. How the thrust reverser of high bypass ratio turbofan operates?
13. Functions and types of thrust deviators.
14. Name main principles of engine noise suppression.
15. Types of noise suppressors and their operation.
16. Name main principles of engine infrared perceptibility improvement.
17. Name cooled elements of exhaust systems and methods of their cooling.
18. What materials are used in exhaust systems?

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