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MAJOR UNITS
OF AIRCRAFT GAS TURBINE ENGINES

Tutorial

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Розглянуто основні питання конструювання вузлів газотурбінних двигунів − компресорів, турбін, камер згоряння і трансмісій. Наведено вимоги до цих вузлів, класифікацію та відомості про конструктивні рішення, які можуть використовуватися для реалізації зазначених вимог. 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, які 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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Yepifanov, S.
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This tutorial copes with main problems of designing gas turbine engines and their major units. They are compressors, turbines, combustion chambers and transmissions. Studying this tutorial, students will learn requirements, which are made for major units, their classification and information about constructive decisions to meet these requirements. 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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CONTENTS

INTRODUCTION

For driving the aircraft needs thrust force or mechanical power which is transmitted to propulsion or lifting propeller.

The engine is to supply required take-off and landing performance and maneuvering data of aircraft, required flight range, rate of climb. Economic fuel consumption is to be provided in wide range of flight altitude and velocity. Thus, the engine must operate reliably and stably, being safe of fire and having enough total life and overhaul period. All of these complex and inconsistent requirements result in designing and using of different types of engines.

In modern aviation the ***gas turbine engines*** are most widely used. The gas turbine engine (GTE) is a heat machine which transmits energy of fuel burning into kinetic energy of jet stream and (or) mechanical energy on output shaft. The GTE's characteristic feature is a presence of the ***gas generator*** which consists of ***compressor***, ***combustion chamber*** and ***turbine*** which drives compressor. The engine rotating parts with supports and links form the ***shafting*** (***transmission)***.

This manual is intended for studying of these major units of GTE. It contains four parts: Compressors, Turbines, Combustion Chambers and Shaftings. It is recommended to study these units in the GTE Construction classroom because a lot of references to the engine design examples representing at this classroom are used in the manual. For practical hardening of a 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 COMPRESSORS

1.1 General information about compressors

1.1.1 Compressor qualifying standards

Compressor of gas turbine engine is a blade machine, in which energy is transmitted to the air to increase its absolute pressure. A role of compressor is to supply a maximum of high-pressure air that can be heated in combustion chamber and then expanded in a turbine. The energy, stored in fuel that can be released in combustion chamber, is proportional to the mass of air consumed. The more compressor pressure ratio the higher engine thermodynamic efficiency. Therefore compressor is one of the most important components of gas turbine engine since its efficient operation (maximum compression with minimum temperature rise) is a key to high performances of engine as a whole.

Compressor must provide a necessary value of compressor pressure ratio π_C^* and air consumption $\boldsymbol{G_{air}}$. Main requirements to its construction are:

- **minimum overall size and weight;**
- **high efficiency;**
- **enough gas-dynamic stability at all operational modes;**
- **high reliability and safety at maintenance conditions during operation period;**
- **manufacturability and possibility of modernization;**
- **fire safety;**
- **convenience of availability index control.**

All the list of requirements must be satisfied, but getting the minimum sizes and weight is the demand for any aircraft system and the engine as a whole. Choice of compressor construction arrangement, its gas-dynamic and construction parameters, durability of its parts and the most suitable materials are determined by the purpose of the gas turbine engine application (to be used in aircraft or in a ground power plant).

1.1.2 Classification of gas turbine engine compressors

To tag of the air flow direction through a gas path there are differed:

- **axial flow compressors, in which air flow is directed through a meridional plane approximately parallel to the engine axis;**
- **centrifugal (radial flow) compressors, in which the output flow is radial;**
- **diagonal flow compressors, in which the flow direction is kept in intermediate position between the direction of air movement in axial and centrifugal compressors;**
- **combined flow compressors, which are consecutive arrangement of axial and centrifugal or axial and diagonal (diagonal-axial) compressors (Fig 1.1).**

Besides depending on the relation of airflow velocity to the sonic velocity through the gas path, there are differed **supersonic** and **subsonic** compressors.

In modern gas turbine engines the most commonly used compressors are the axial flow compressors because they provide an acceptable answer for all mentioned above requirements. The axial compressors compared to other types of compressors present more advantages such as higher possible compressor pressure ratio π^*_c and bigger air mass flow G_{air}; their efficiency is higher and diametric overall size (frontal area) and mass are smaller. Since the air flow is an important factor in determining the thrust, this means the engine with axial compressor also gives more thrust at the same frontal area. However, centrifugal compressor is still favored for smaller engines where its simplicity and ruggedness outweigh any other disadvantages.

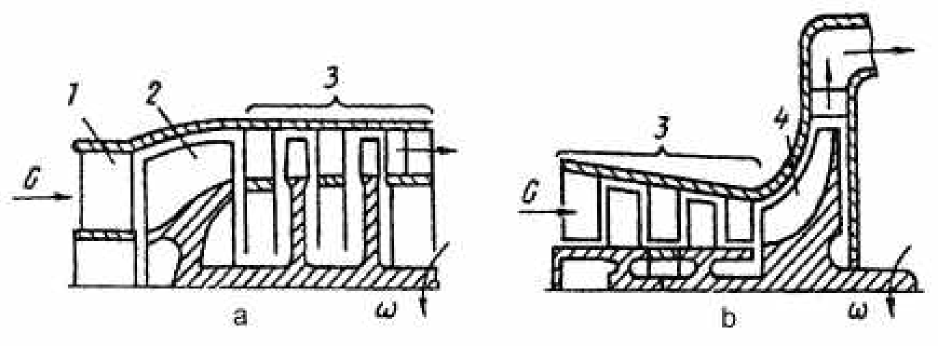


Figure 1.1 – Schemes of combined compressors:
a – diagonal-axial; b – axial-centrifugal;
1 – inlet guide vane; 2 – diagonal impeller; 3 – axial compressor;
4 – centrifugal impeller; ω – angular velocity

Exercise 1.1

Go to the laboratory room and write examples of different kinds of compressors of the gas turbine engines that are located there.

1.2 Centrifugal flow compressors

Centrifugal compressor basically consists of **impeller** and **diffuser manifold**. Other components such as a **compressor manifold** may be added to direct the compressed air into the combustion chamber. The impeller is rotated at high speed by the turbine and air is continuously induced into the center of the impeller. Centrifugal action causes the air to flow radially outwards along the blades to the impeller tip, thus accelerating the air and increasing its kinetic energy. After leaving impeller, the air passes into diffuser section where vanes form divergent ducts, converting most of kinetic energy into pressure energy. Total compression is shared between the rotor and the diffuser.

The centrifugal compressors have some advantages that distinguish them form axial compressors, such as:

- simple construction;

- small number of components;
- not so big axial size;
- relatively small production work and cost;
- big maintenance reliability;
- wide range of stable operation.

The centrifugal compressors have some fewer similar characteristics comparing with axial flow compressors, like air pressure ratio, productivity and efficiency. The diametrical size of the centrifugal compressor is larger than the diametrical size of an axial compressor with the same air consumption.

Taking into account the previous list of centrifugal compressor's characteristics, they are used in small engines and in auxiliary gas turbine powerplants (gas turbine starters, generators of compressed air, etc.).

On the other hand, the main direction of the gas turbine engine development is closely related with increasing the compressor pressure ratio. Its value for 4-th generation engines reached 20-35 and for 5-th generation 25-50. If axial compressors are used, with the increasing of the pressure ratio the last stages become too short, the relative radial clearance, which determines the compressor stage efficiency, becomes too big and the efficiency of last stages drops. Thus, is more effective to use centrifugal last stages of high pressure ratio compressors even at mean values of air flow (engines GTD-3F, D-27).

Centrifugal flow compressors can be classified by the following characteristics:

1. ***By construction of inlet duct and impeller***:

– compressors with one-way inlet and single-sided impeller, which are used at small air consumption;

– double-entry compressors with double-sided impellers, which are used at big air consumption (Fig. 1.2).

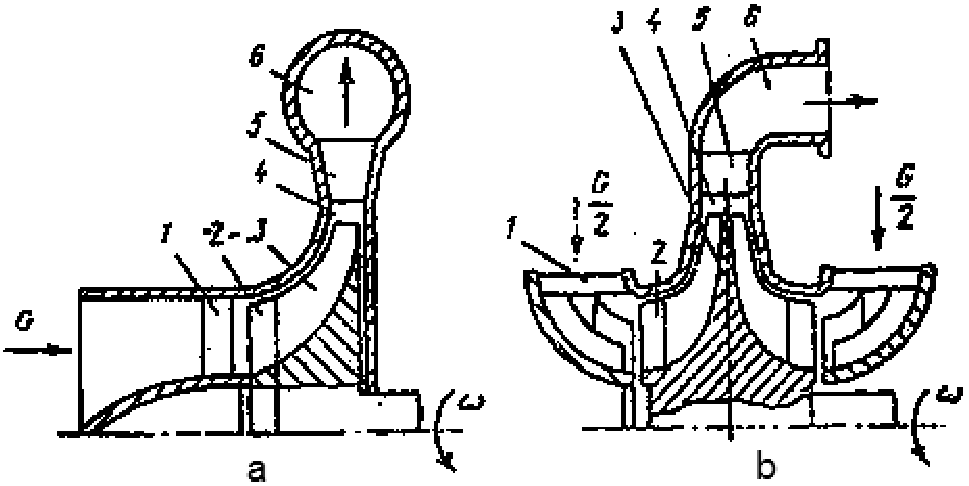


Figure 1.2 - Scheme of centrifugal flow compressors:
a – one-entry; b – double-entry;
1 – guide vane; 2 – inlet part of the blade; 3 – Impeller; 4 – vaneless diffuser;
5 – vaned diffuser; 6 – exhaust auxiliary (snail assembly); ω – angular velocity

2. ***By construction of rotor blades***:

- compressors with radial blades;
- compressors with blades located under the angle towards the radius, against the rotation (so-called active blades), allow increasing the compressor head without increasing the rotation speed and diametric size;
- compressors with blades located under the angle towards the radius, aside the rotation, allow to provide a high efficiency.

3. ***By type of impeller***:

- compressors with opened impeller;
- compressors with semi-opened impeller;
- compressors with closed impeller.

4. ***By number of compression stages***:

- single-stage compressors;
- two-stage compressors; the construction of engines with two-stage centrifugal compressor is more complicated;
- multistage compressors.

At maximum admissible circumferential velocity (which depends on impeller durability), about 450…500 m/s, the pressure ratio in centrifugal compressor usually is 4…4.5. If supersonic diffuser and active impeller are used the air pressure ratio can reach 6…8.

Dimension of centrifugal compressor depends on necessary air consumption and axial speed of the air at inlet to impeller.

Maximal speed at the inlet to impeller shouldn’t exceed 120…150 m/s, otherwise, subsequence increasing axial velocity will promote increasing losses at the inlet to impeller. Under this condition in centrifugal compressors with single-sided impeller the value of specific air consumption (relation between mass consumption and frontal area of compressor) should be 15…30 kg/(s m^2). Use of two-sided impeller allows to reach air consumption of 80…85% more than a single-sided impeller.

Compressor efficiency is relation of the energy used to compress the air and the energy that is extracted from turbine. Efficiency of centrifugal flow compressor is 0.76…0.80 at a pressure ratio 4…7. Above this ratio, efficiency drops off at a rapid rate because of excessively high impeller-tip speeds and due to shock wave formation.

As consequence of compression process the air temperature is increased, the air temperature at the exhaust of centrifugal compressor may reach 200…300 ^{o}C.

Exercise 1.2

Use the prepared mockup of the VK-1 turbojet and draw the centrifugal flow compressor of this engine, study the construction of the VK-1 compressor and answer the following questions:

1) What is the purpose to install the fixed inlet guide vanes at the inlet of the compressor for swirling the incoming airflow?

2) What is the function of the attached curved inlet part of the impeller?

3) What is the function of the metallic net (screen) installed at the inlet of the centrifugal compressor?

4) What reason the semi-opened impeller is used for?

5) What is the function of the vaneless and the vane diffusers? What is the explanation for their design?

6) What is designed in the rotor construction for its balancing?

7) Write in your notebook the materials used in the construction of the parts of the centrifugal compressor VK-1.

8) Write in your notebook the main parameters of the VK- 1 turbojet:
   - take-off thrust **P** = 2700 kg (≈26.5 kN);
   - rotor rotational speed n = 11560 rpm;
   - air flow G_{air} = 48.2 kg/s at air inlet temperature 15^{o}C;
   - compressor pressure ratio at take-off mode π^*_c = 4.22…4.36.

1.3 Axial flow compressors

Axial compressor consists of series of rotary airfoils called **rotor blades** and a stationary set of airfoils called **stator vanes**. As its name implies, the air is being compressed in a direction parallel to engine axis. Entire compressor is made up from stages. Each stage contains rotor blades and stator vanes which are shaped to provide the most lift for the least drag.

During operation rotor rotates at high speed under a turbine torque action, continuously inducing air into compressor. Air is accelerated by rotating blades and swept downstream to adjacent row of stator vanes. Energy, imparted to air in a rotary stage, increases air velocity. Air decelerates (diffuses) in a following stator passage and kinetic energy is transformed into pressure. Stator vanes also serve to correct deflection, given to the air by rotor blades and to supply the air at correct angle to the rotor blades of next stage. The last row of stator vanes usually operates as air straighteners to remove swirl from the air prior to entry into combustion chamber at axial velocity.

Main parameters of axial flow compressors, used in aircraft gas turbine engines, have the following values:

- compressor pressure ratio π^*_c, related to the ground atmospheric conditions, is in limits 6…40; to get the necessary value of π^*_c it is necessary to use a multistage axial compressor with number of stages 6…19;
- compressor efficiency η^*_c = 0,85…0,88.

1.3.1 Classification of axial flow compressors. Short information concerning compressor rotor construction

Axial flow compressors can be classified by the following main features:

1. *By the number of rotor assemblies (cascades)* they can be divided into:
   - single-spool (one-cascade) compressors;
   - twin-spool (two-cascade) compressors;

- triple-spool (three-cascade) compressors.

Twin-spool compressor consists of two spools located in series; **triple-spool compressor** consists of three spools located in series.

The first compressor spool of twin-spool and triple-spool gas turbine engine is named the **low pressure compressor** (LPC), the middle spool of triple-spool gas turbine engine is called the **intermediate pressure compressor** (IPC); the last spool of twin and triple-spool gas-turbine engine is called the **high pressure compressor** (HPC).

Low pressure compressor of turbofan engine is named as **fan**. Compressor stages mounted after fan on the same shaft with fan and supplying air only to gas generator, are named as **booster stages** (see the fan of the engine NK-8).

Booster stages have lower circumferential rim velocities comparing with rim velocity of first stage of fan, supplying air to both primary and secondary flows. So booster stages have low efficiency. But total effect of their usage is positive.

Twin- and triple-spool compressors have some advantages compared to single-spool ones, such as:

- *good operating stability;*
- *high efficiency in wide range of operational modes,*
- *simplified compressor control;*
- *engine easy starting.*

However, construction of engines with multi-spool compressors is more complex.

2. *By the air speed along a gas* path compressors can be divided into:

- subsonic;
- supersonic.

The compressor pressure ratio of supersonic stages is considerably higher (reaches π_{st}=1,9) than of subsonic stages (π_{st}=1,15…1,35).

Using supersonic stages allows considerable increasing total pressure ratio at invariable number of stages or decreasing the number of stages at invariable total pressure ratio in each stage.

However, using supersonic stages is limited because of some disadvantages, such as: efficiency of supersonic stages is lower than efficiency of subsonic stages and a range of compressor stable operation (absence of stall) in supersonic stages is lower.

3. *By the shape of gas path* compressors can be differed as:

- constant external diameter (Fig. 1.3,a);
- constant internal diameter (Fig. 1.3,b);
- constant mean diameter (Fig. 1.3,c);
- shapes combination, for example with constant external diameter at the beginning of the gas path and constant internal diameter at the rest of it.

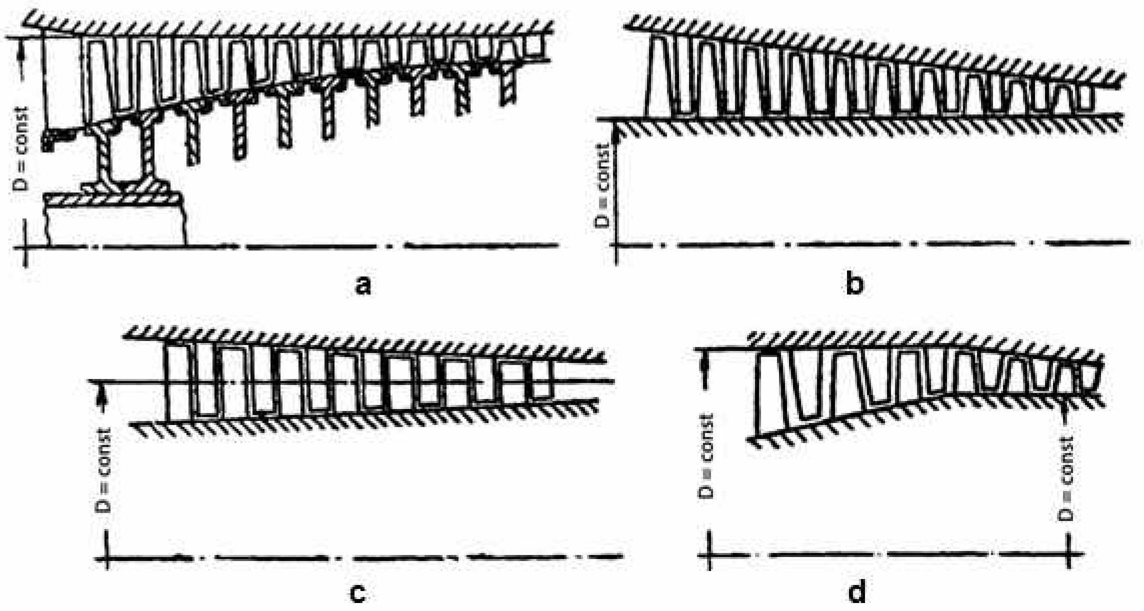


Figure 1.3 - Schemes of different gas path shapes:
a - constant external diameter; b - constant internal diameter; c - constant meaning diameter; d - variable external, meaning and internal diameters

Exercise 1.3

Write in your notebook examples of engines with different gas path shape of compressor.

4. *By the rotor construction* compressors can be divided into compressors with:

- drum-type rotor;
- disk-type rotor;
- drum-and-disk-type rotor.

Drum-type rotors have a big bending rigidity, however strength of this kind of rotors is lower (they have small admissible circumferential speed in a rotor periphery, reaching less than 180…200 m\s).

A drum can be manufactured from single bar (TR-1) or by welding. If a rotor is manufactured by welding, its coefficient of using material is higher.

Disk-type rotors are considerably stronger; this allows them having higher circumferential speeds. The disadvantage of this kind of rotors is small bending rigidity.

Exercise 1.4

Using the drawings and engines located in the laboratory class room, find compressors with the following type of rotors:

- drum design;
- disk;
- drum and disk.

Write examples of engines with different rotor types.

1.3.2 Rotors of axial compressors

Rotor of axial compressor serves rotation of rotor blades. Power for this rotation is transmitted from a turbine. Main components of rotor are: shaft, disks, drum elements and blades.

1.3.2.1 Rotor elements mounting

Junction of disk with shaft can be realized in the following ways:

- tighten mounting of disk on a shaft (unsafe transmission of torsion-torque) (the compressor used in the engine RD-20);
- splines (high pressure compressors of the engines D-20P, D-30);
- flanges (the fan of the engines D-36, D-18T).

Drum-and-disk-type rotors are the most commonly used in gas-turbine engines. In this case separate sections which consist of disks and drum parts are joined together. Such drum-and-disk construction has a big bending rigidity and strength. The disadvantages of this rotor type are manufacturing complexity and big mass.

Junction of a drum-and-disk rotor elements can be done in the following ways:

1. Assembling with radial pins (AI-20, AI-24, AM-3, RD-9B, R11F-300). The radial pins provide alignment, transfer a torsion torque and an axial force. The lack of this kind of junction is complexity of dismantling the rotor.
2. Assembling with central coupling bolt, located along a compressor axis. The bolt must be tightened in the way which provides contact between parts and ensures absence of any displacement between connections of components at any combinations of loads that could appear during operation.
3. In low power engines and support powerplants with low torsion torque transmitted (GTD-3F, APP-10 et al.) a joint can be realized using a flat surface, transmitting torsion from turbine to compressor rotor by a friction force in the joint (the friction force must be bigger than the torsion torque).
4. Engines with high thrust (AL-7F, AL-21F, LPC of engines D-30 and D-20P) have triangular slots in drums backs. They transmit torsion torque (thus originating axial forces) and provide components centering.
5. To decrease the force of the coupling bolt tightening an elastic element is inserted into a tightened package that looks like a back plate spring (AL-7F), or elastic spacers (RD-10), packed under the nut and head of the bolt.
6. For last stages of HPC, where axial distance between disks is smaller, to connect several stages the long precise coupling bolts with the distance bushes are used (AI-25, RD-33). The bolts are located in parallel to a compressor axis at equal distance form each other (this is called the peripheral coupling bolts). They work under action of bearing deformation, transmitting torsion torque.
7. Assembling with the flange bolts. To connect two adjacent sections the short precise bolts are used which provide alignment and transmit a torsion torque (NK-12, NK-8).

8. Assembling with the electron-laser welding (TV3-117, D-36, D-136).

9. Assembling with the friction welding (GE-90, F-404, Trent and some other engines of the 5-th generation).

The last two ways represent the modern kind of junction, which provides a small mass and don’t need another mechanical operation. Their disadvantage is complex mounting and rotor repairing.

Exercise 1.5

Look at the design of the two-cascade compressor of R11F-300 afterburning turbojet and AI-25 turbofan. What method is used to transmit the torsion torque from one compressor stage to another?

Exercise 1.6

Look at the engines AI-20, RD-9B, AL-7F, NK-12, TV3-117, D-36 and write the methods that are used to connect the disks in the drum and disk rotor. Show their advantages and disadvantages.

1.3.2.2 Compressor blades mounting

When looking at the blade, it is possible to identify two parts, the body of the blade and its root (locking part).

Securing blades to a disk or to a drum (in case of a drum type rotor) is done by locks. The **lock** is a profiled root of the blade and the slot of corresponding conFiguration in the disk rim. The slots in the disk rim can be **longitudinal** for every blade, or situated along a ring (**transversal**). The last slot is common for all airfoil blades (TR-1, TV3-117).

The “dovetail” (trapezoidal) lock is the most widely propagated securing blades to a disk. The slots in the disk are manufactured by broaching, and the blade root is manufactured by milling. The angle at the top of the trapezoidal profile is set in the limits of 40…60^{o}. The slots of the “dovetail” type provide enough strength of fastening, accommodation of the necessary blades number at the least disk weakening.

The blade must be fixed to prevent any displacement along its slot when gas (pressure difference), centrifugal and no-determinate forces act on it. Fixing in ensured in the following ways:

- individual plate;
- radial and axial pins;
- spring split ring (RD-9B).

Exercise 1.7

Look at the mockup and find all considered above blade roots and the methods of their fixing to prevent displacement along the slot. Draw a sketch of the “dovetail” lock and two or three sketches that describe methods of blade fixing to prevent its displacement along the slots.

How to mount blades in the ring (transversal) slot (TR-1, TV3-117)?

Besides a hard junction between blade and disk, hinged fastening is also used (LPC of AI-25, LPC of D-30). This kind of fastening allows blade self positioning during operation when it is under gas-dynamic and centrifugal forces action. That is why the bending stresses in the blade root are two times lower.

Exercise 1.8

Draw in your notebook a sketch of the hinge junction of the blade and disk. Show the tendency of the gas-dynamic and centrifugal moments that act the blade.

In TFE with high bypass ratio there is necessary to mount a mid-span support shroud (‘snubber’ or ‘clapper’) in the fan blades, which is located on the radius, approximately equal to two thirds of blade length. The main purpose of this snubber is to eliminate the threat of the blade bending and torsion vibration; that is why it has also a name of anti-vibration shroud.

The disadvantage of this design concept is high pressure losses as the snubber is situated in supersonic flow. This disadvantage has been overcome with introduction of wide chord fan blade; stability is provided by increasing the blade chord, thus avoiding a need in snubbers.

1.3.2.3 Compressor rotor balancing

Compressor rotor or impeller balancing is extremely important operation in manufacture. In view of high rotational speed and mass of material any unbalance affects a rotating assembly operation. Balancing of these parts is provided using a special balancing machine.

The compressor rotor balancing means making the sum of inertia forces and the sum of the inertia forces moments, concerning the axis of rotation, to be equal zero.

The goal of ***static balancing*** is to place the rotor gravity center on axis of rotation (in this case eccentricity is zero). This operation no needs rotor fast rotation.

The goal of ***dynamic balancing*** is decreasing of total moment of inertia acting on meridional plane. This balancing is done in special balancing machine which allows finding the magnitude and direction of the counterbalance moment which must be applied to rotor for balance provision.

To make rotor balancing is necessary removing material in some places, installing balancing weights or selecting washers under the screw-nuts (AL-7F).

The complete rotor balancing is practically impossible. The magnitude of residual unbalancing force depends on admissible balancing.

The unbalance is a reason of rotor oscillations and becomes especially dangerous when rotor rotational speed is near the critical value.

Exercise 1.9

Find the balancing weights used in compressor rotors of the engines AI-25, D-36, R11F-300; remember that the unbalanced moment can be counterbalanced only by the moment.

1.3.2.4 Compressor rotor unloading from axial forces

Axial gas forces and air pressure forces act on rotor blades and face walls of a rotor. Axial force originated, which is resultant of all gas and pressure forces action. It is directed against the air flow.

Usually compressor and turbine rotors are joined together in axial direction. This is done to transmit axial force from turbine rotor to rotor of compressor, as a turbine rotor usually is not equipped with thrust support and is placed in roller bearing.

Axial forces acting compressor and turbine rotors are directed oppositely. Therefore they compensate one other. As the axial force acting a turbine rotor, is less than the force acting a compressor rotor, the unbalanced axial force remains. This force is directed oppositely to air flow. Its value can exceed the admissible value of thrust (ball) bearing. In this case unloading a compressor rotor from axial force is organized. To provide unloading there is possible to separate the frontal trim cavity "A" (Fig. 1.4) and the rear trim cavity "B" from the compressor gas path by seal labyrinths 1 and 5. Pressures in these cavities are designed to decrease the axial force acting the compressor rotor. Obviously, the unloading force is directed downstream, so the pressure in the front cavity must be higher than the pressure in the rear cavity.

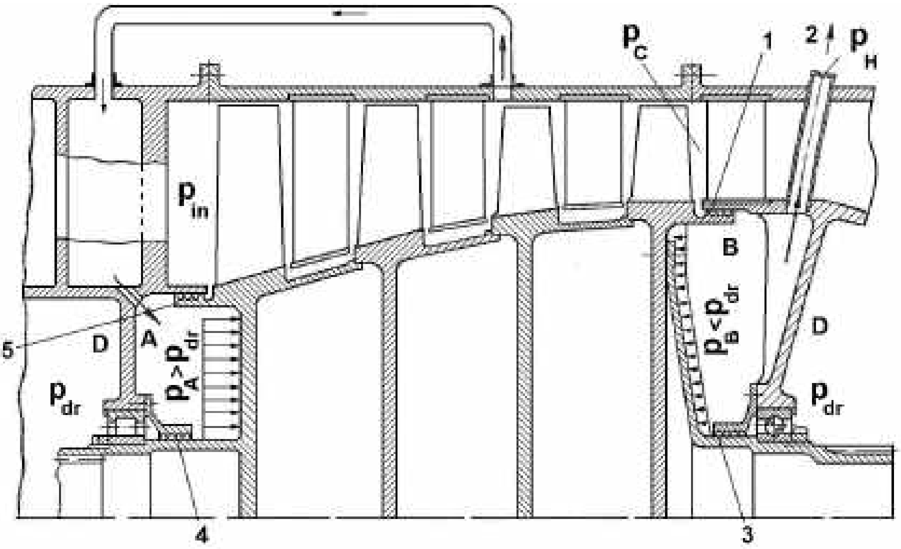


Figure 1.4 – Unloading compressor rotor form axial forces:
1, 3, 4 and 5 – seal labyrinths; 2 – bleed, A – front unloading cavity; B – rear unloading cavity; D – drain cavities; p_{air} (p_{in}) - air inlet pressure; p_H – atmospheric pressure; p_A – air pressure in the cavity A; p_B – air pressure in the cavity B; p_{dr} – drain pressure

Air is supplied to the front cavity from the compressor discharge or from its intermediate stage. The rear cavity is connected to the atmosphere by the fixed restrictor 2, and the area of restrictor is chosen to provide the pressure in this cavity more than atmospheric on 0,5…0,7 atm (0,05…0,07 MPa). This pressure is necessary to prevent oil from the cavity "C" getting to the cavity "B". So the air enters the rear cavity B through the rear labyrinth sealing 1 of the compressor and bleeds to the atmosphere through the restrictor 2. Analogically air enters the front cavity A from the compressor discharge or intermediate stage through the connecting tube and bleeds to the compressor gas path through the front labyrinth sealing 5.

Exercise 1.10

1. Look at scheme of compressor unloading from axial force of the AM-3 and RD-9B turbojets.
2. Find the unloading cavities in compressor of the TV3-117 turboshaft, HPC of the AI-25 turbofan, and in IPC of the D-36 turbofan.

1.3.3 Stators of axial compressors

The main elements of compressor stators (fixed parts of compressors) are cases, inlet guide vanes and guide vanes of stages.

The case of compressor is the major part of a stator, thus it is one of main power elements of the engine. Inside the case rotor is mounted and the guide vanes are fastened. Outside the case units are located which are used for engine on an airplane mounting, and aggregates are attached which provide “habitability” of the engine (fuel and oil pumps, control units and so on).

On side walls of the case it is possible to have channels to: supply oil to the bearings and take it off, and also supply and take off air with the aim to heat the inlet device and decrease the axial force that acts on the rotor. The construction of these channels can be provided by casting process of the case or fastening pipes on the ends of the case.

The following factors act the case:

- rotor weight and inertia forces;
- air pressure in inner cavity of the case;
- axial force of guide vanes;
- torsion torque transmitted from guide vanes;
- axial forces and bending moments transmitted to the case through connections of parts.

The main requirements that must satisfy the compressor case are the following:

- sufficient durability and rigidity with the minimum mass;
- convenient mounting of guide vanes;
- simple manufacturing;
- leakproofability;
- parts of the gas path, bearings and gears must be mounted in a convenient position to make inspections.

1.3.3.1 Construction of compressor case

Cases of axial compressors used in TJE, TPE and TShE usually consist of three parts:

- front frame;
- case of guide vanes;
- rear frame.

The **front frame** is a ring-shaped single-piece light-weight structure made of aluminium alloy or steel, usually cast and then machined. Characteristic of this component is outer ring and inner hub joined by streamlined supporting struts (or inlet guide vanes), which transmit strain from the front support to the engine case.

In the front frame the bearing is mounted on the compressor's rotor front support.

The supporting struts are hollow to accommodate pipelines to lubricate and ventilate the front bearing, and to provide space for electric cables. Power is usually extracted from the compressor shaft to drive accessories. This is done by means of inner gearbox and radial shaft which runs through one of the radial struts.

Inside the streamlined struts there are located aggregate drive shafts, holes for oil and hot air supply and takeoff. This oil is used for bearings cooling, and this air is used to heat the inlet device which is attached to the front case. The case also supports the cowl of the bush of the compressor rotor (engines RD-9B, TV3-117, AM-3).

The **case of guide vanes** (GV) is a tubelike construction which provides power connection between the front and the rear frames. The inner surfaces of this case are machined with circumferential T-section groves to retain the guide vanes. Case of guide vanes and rotor simultaneously constitute the gas path of the compressor.

The use of one or other case design depends on a rotor type and general construction of compressor. The most profitable is casing which is **splitted longwise**. This facilitates engine assembling and maintenance. After the rotor has been installed in the casing, both halves are bolted together through longitudinal flanges (AI-20, RD-9B, NK-12, HPC of R11F-300).

The case **splitted crosswise** is of uniform circular rigidity. Therefore, it is possible to decrease radial clearance between the tip of the blade and the internal surface of the case, comparing with the compressor case splitted longwise. However the case splitted crosswise can be used only with split rotors (AL-7F, LPC of D-30).

Depending on the general structure, compressor conFiguration and the way of assembling, cases with both methods of splitting can be used. (R11F-300). Crosswise splitted case allows its blocks manufacturing from different materials or with different wall thickness (RD-9B).

By the manufacturing method case can be casted or welded. Aluminum and magnesium cases are casted. Taking into account the pressure increasing downstream a compressor, it is necessary to increase thickness of walls from first stage to the last. To provide equal-strength construction of the case, its walls must be casted with variable thickness of 6…10 mm.

If the manufacturing process is welding, the case is produced from sheets of steel or titanium alloys. Enough strength is provided with correct choosing of the case wall thickness and introduction of external flanges. Wall thickness of steel case is within range 1,5…3 mm.

To ensure the engine maintenance by technical state, guide vanes state is to be checked in maintenance. To meet this requirement special accesses are foreseen in the case. They have different structure and are closed by threaded plugs. It is also necessary to provide the special apertures in the case for air bleeding to atmosphere and, in this way, preventing a compressor gas-dynamic instability.

The rear frame of compressor is used to join the engine hot part with compressor. Usually the centre of the compressor rear frame is designed to house the rearward rotor bearing, the ball bearing which absorbs the axial force of the rotor. The rear frame consists of power rings (external and internal), radial connections, rigidly joining power rings, and power diaphragm, connecting the internal ring with the bearing housing (RD-9B). This diaphragm transmits strains from the bearing to the case.

Compressor guide vanes (RD-9B) or aerodynamic struts are used as radial power connections.

In the rear case of TJE the engine front mounting is located, transmitting thrust to the airplane.

In TFE there is an intermediate casing between the fan and compressor of the gas generator. It separates the airflow on primary and secondary flows. This case plays a role of a load-bearing element joining rotor and stator (AI-25, D-30).

The **intermediate case** (main case of high bypass ratio TFE) consists of three concentric rings, joined together by aerodynamic struts (D-36). Inside are pipelines to supply and take off oil, to supply fuel, and drives of lubrication system pumps and starter units. In the intermediate case there are fan rotor support and HPC rotor support (in two-spool TFE), or intermediate pressure compressor support (in three-spool TFE).

The intermediate case on the engines AI-25 and D-30 is cast from the magnesium alloy ML-5; of the engine D-36 from magnesium alloy ML-10 (more heat resistant). In most cases devices that are used to mount the TFE on the airplane are in this case.

1.3.3.2 Guide vanes and flow straightening vanes

The guide vanes and flow straightening vanes are seemed as ring sets of fixed or rotary profiled blades which create divergent channels and are a part of the engine stator.

The guide vanes and flow straightening vanes are subjected to a bending and torsion gas forces. As it has been shown, usually the straightening vanes are used as radial connections to transmit a strain from compressor bearing to compressor case. In this case they are loaded with high extra strain.

Guide vanes and straightening vanes are locked in the compressor casing, either directly through T-groves or by retaining rings or semi-rings.

Depending on a way that blades are attached it's possible to distinguish cantilever (HPC D-36, TV3-117) or two-side (AI-20, AI-25, D-36, D-136, NK-12) attachment.

In the **cantilever attachment**, the blades are rigidly fixed to the case or to the intermediate external ring using their ending parts. For such purpose the blades are supplied with root supports (locks) of rectangular or trapezoidal "dovetail" type (HPC D-36, TV3-117).

The **two-side attachment** is used when it is necessary to have inflexible guide vanes. In this case the blade is attached between the external and internal rings (AI-20, AI-25, D-36, D-136, NK-12). The rings are mounted in the case using screws or pins.

Depending on compressor rotor and case construction, the guide vanes can be constructed with diametrical disconnects (AI-20, AI-25, D-36, NK-12, HPC of D-30) and single piece (AL-7F, LPC of D-30).

The flow straightening grid can be twin (TV3-117, AI-25, D-30) i.e. consists of two ring airfoils with equal pitch. This construction is necessary at a high air flow twisting in impeller. Thus the air flows through the slot between the first and second airfoils improving the airflow conditions of the second airfoil.

The inlet guide vanes (IGV) are in front of a rotor, providing preliminary air twisting aside a rotor rotation.

To ensure gas dynamic stability of the engine it is necessary to use variable inlet guide vanes and guide vanes of some first and last stages. They turn automatically depending on the reduced rotational speed of the rotor (TV3-117, D-30, AL-21F). In some designs only IGV trailing part turns, which economies weight (F119).

In some engines (AM-3, AI-25, D-36, D-136) the rotational inlet guide vanes (IGV) are used only on test benches for rigging of the engines.

Exercise 1.11

Look at the construction of the case and guide vanes of the compressors of the engines AI-20, NK-12 and AL-7F.

Exercise 1.12

Look at TFE AI-25, D-30, D-36 and make their sketches, familiarize with the construction of the intermediate casing.

Exercise 1.13

Look at the engine TV3-117 and its drawing; study the construction of its fixed and rotary guide vanes.

Exercise 1.14

Look at the construction of the inlet guide vanes of the engines AI-25 and D-36.

Exercise 1.15

Using the D-36 turbofan (three cascades, with high bypass ratio) and its sketch, look for the details of the compressor stator construction. Write the design features that are used to decrease the noise produced by the fan in your notebook.

Exercise 1.16

Familiarize with the construction of the mixed flow compressor of the engine GTD-3F.

1.3.4 Gas path sealing

To reduce air leakages a radial clearance between compressor casing and blade tips must be minimized. To protect blades touching the case, which results in blade destruction, the surface of case is coated with an abradable material. Powders of talc, graphite, aluminum and other materials blinded by varnish or glue are used. Abradable coatings of HPC last stages are manufactured by baking heat-resistant graphite-nickel or copper-graphite.

1.4 Means for providing compressor stable operation

Designing a **high-pressure axial compressor** which operates stably in a wide range of operation conditions is one of the most difficult problems. To expand the range of compressor stable operation, the following means can be applied:

- choosing of gas-dynamically connected two- or three-spool scheme instead of single-spool scheme of compressor with a gas dynamic connection between cascades;
- modulating compressor airflow by variable IGV and guide vanes which turn according to some program (e.g. corrected rotational speed) which forms commands basing on received information from sensors;
- use air bleeding to atmosphere (in TFE – to bypass) from mid-compressor stages during starting and low operating modes through ports in compressor casing and air bleed valves (AI-20, AI-25, D36, D-136) or through air bleed tapes (AM-3, RD-9B, AL-7F).

Heavily loaded single spool compressors need airflow control introduction to provide the required gas dynamic stability margin in the whole range of operational modes. The control may be ensured by variable inlet guide vanes and guide vanes of some other succeeding stages. As compressor decelerates from its design value these variable guide vanes are progressively closed in order to keep an acceptable attack angle on the adjacent rotor blades.

Additionally or alternatively an interstage air bleeding may be provided through air bleed valves or air bleed strips (which are known as the anti-surge devices). Air bleeding is done through ports, uniformly located in circumferential direction on the casing`s external wall. So air from gas path enters through these ports to the ring collector, isolated from atmosphere (or bypass duct) by bypass structural elements which may be valves, tapes or throttle flaps. These elements are automatically controlled by pneumatic (AI-25, D-36) or hydraulic (AI-20, D-30, NK-12) systems, which receive information about rotor rotational speed from sensors. The working fluid, used in hydraulic systems, usually is kerosene or oil.

The other means which increase compressor stability are applied to separate (namely first) stages. They are named as **devices behind a rotor**. The main part of these devices is a ring hole – receiver, made in the case behind inlet tip of rotor blade. This hole creates a local torus-shape vortex in peripheral area of the rotor inlet section, so local air velocity increases. At low operational modes this corrects velocity triangle aside decrease of attack angle; therefore unstable operation of this stage (surge) is prevented. In addition at changing of flow mode in compressor, cross-section of this vortex is changed. So this anti-surge device is self-controlled.

An above mentioned torus-shape hole may be equipped with the blade lattice to decrease additional hydraulic losses caused by circumferential motion of the air in this hole. In some designs (for example HPC D-30) this hole is separated from the gas path by cylindrical diaphragm equipped with drilled apertures which provide effective dumping pressure oscillations when pre-surge operation happens.

Exercise 1.17

Find and write names of engines with two- and three-cascade compressors in your notebook.

Exercise 1.18

Find and write names of engines with variable guide vanes in your notebook. Draw a sketch of variable guide vane.

Exercise 1.19

Find and write names of engines where bypass valves, strips and throttle flaps are used in your notebook. Draw a sketch illustrating the way of air bleeding from the gas path throw holes to the ring cavity and throw the bypass elements to atmosphere.

1.5 Icing protection

Engine intake duct elements icing can occur during operation at temperatures close to $0^{o}C$ at high humidity conditions, for example, at flight through clouds containing supercooled water drops or during ground operating in freezing fog. Protection from ice formation is required since icing of these regions can considerably restrict the airflow through engine resulting in a loss of performance and possible malfunction of compressor. Additionally, damage may result from ice breaking away and being injected into engine or hitting acoustic material lining intake duct.

Analyses are carried out to determine whether ice protection is requested, thus the heat input required to limit ice build up to acceptable levels. The areas of gas turbine engine typically considered for ice protection are:

- nose cowl or nose cone;
- intake aerodynamic struts of compressor front frame;
- inlet guide vanes of compressor.

Protection of rotor blades is rarely necessary because any ice accretions are dispersed by centrifugal force action.

If IGV or struts are fitted upstream rotating blades of the first compressor stage, they may require protection. If a nose cone (spinner) rotates it may not need anti-icing if its shape, construction and rotational characteristics are such that likely icing is acceptable. For example, in engines PW-4000 and Trent the spinner has a sharpened rubber tip, which flexibility provides breaking off ice even if thickness of its coating is very low, and other part of spinner is made of hydrophobic composite material.

There are three basic systems of ice protection, distinguished by heat sources:

- hot air;
- hot oil;
- electrical power.

The **most widely used is hot air system.** It provides surface heating when ice is likely to form. The hot air is usually taken from high pressure compressor stages. It is ducted throw pressure regulating valves to the parts requiring anti-icing. The used air from a nose cowl anti-icing system may be exhausted into compressor intake or vented overboard.

If a nose cone is anti-iced its hot air supply may be independent or integral with that of a nose cowl and compressor stators. For an independent system a nose cone is usually anti-iced by a permanent uncontrolled supply of hot air via internal ducting from compressor.

Exercise 1.20

Familiarize with air heated inlet guide vanes and the intake of the engines AI-25 and TV3-117.

Exercise 1.21

Using the drawing and the mockup, study the air heating of the D-36 turbofan spinner.

Exercise 1.22

Using the drawing and the mockup, study the hot oil system of the GTD-3F turboshaft.

Exercise 1.23

Study the electrical elements of the engine NK-12 propeller blades ice protection.

1.6 Compressor materials

Materials are chosen to achieve the most cost effective design for components in question. In practice of aero engine design this need is usually best satisfied by the lightest design that technology allows for the given loads and temperatures prevailing.

When choosing material to produce compressor blade and rotor disk is necessary to account the following thermal conditions: for temperatures to 250°C - aluminum alloys are used, to 450°C – titanium alloys, to 500°C – steel, at higher temperatures to 550…600°C – heat resistant nickel-chromium alloys.

For **cased structures** require to be light but rigid enabling radial clearances to be accurately maintained ensuring the highest possible efficiency. These requirements are met by using aluminium or magnesium at the front of compressor followed by titanium alloys and steel at the rear part of compressor. Temperature of air flow, reached last compressor stages may exceed acceptable level for best steels, which results in necessity for nickel based alloys application. The titanium using in preference to aluminium and steel is now more common, especially in engines for military aircrafts, where its high rigidity and low weight are of high importance. New manufacturing methods allow acceptable component cost despite high stock cost. There are known modern low pressure compressor cases made of composite materials as single-piece structures, which need no further machining (F119).

Stator vanes are normally manufactured from steel or nickel-chromium alloys; prime requirements being the high fatigue strength when ‘notched’ by ingestion damage. Earlier designs specified aluminum alloys but because of their interior ability to withstand damage their use has declined. Titanium may be used for stator vanes in a low pressure area but it is unsuitable for smaller stator vanes further rearwards in compressor because of the higher pressures and temperatures encountered. Any excessive rub which may occur between rotating and static components as a result of other mechanical failures can generate sufficient heat from friction to ignite the titanium. This can lead to expensive repair costs and a possible airworthiness hazard.

Guide and straightening vanes can be manufactured from the same material as rotor blades. Besides aluminium alloy D-1, steel 20, X17H2 and some others are used. Operational temperature is the major criterion to choose material for guide vanes.

Centrifugal forces are dominative forces for **rotor disks, drums and blades**, so metal with the highest ratio of strength to density is required. The lighter rotor is, the lower centrifugal forces act the rotor. For this reason titanium, even with its high stock cost, is the preferred material and has replaced the steel alloys that were favored in earlier designs. The higher temperatures new titanium alloys can stand the bigger number of parts are manufactured from it (discs and blades of compressor last stages).

Material used for **fan blades** is titanium (D-36, D-18T, CFM56). Some companies use the hollow wide-chord swept fan blades of titanium alloy made by the super-plastic extrusion attached to the titanium disc by diffusion welding (Trent 500) or friction welding (F119). Some other constructions contain a fan made as the **blisk** (**bl**ade&d**isk**) with solid blades of titanium alloy (PW6000). The weight of wide-chord fan blades is maintained at a low level by fabricating the blade from skins of titanium incorporating a honeycomb core. If a construction material of a fan blade is composition of fibrous material (high-fill, boor-fill) which has big damping behavior, it won't be necessary to use anti-vibration snubber.

1.7 Answer the questions about compressors

1. Compressors functions in gas turbine engines and requirements to their construction.
2. Compressors of gas turbine engines classification.
3. Centrifugal compressors advantages, disadvantages and fields of application.
4. Centrifugal compressors classification.
5. Does the axial force acts on a centrifugal compressor rotor? If yes, what side it is directed?
6. What loads act on a centrifugal compressor stator?
7. How is connection between impeller and shaft of a centrifugal compressor provided: torsion torque and axial force transmission, centering, axial clearance providing.
8. Advantages, disadvantages and fields of centrifugal compressors application.
9. Axial compressors classification.
10. The axial compressor main elements and their functions.
11. Compressor rotor blade construction and its main elements.
12. Requirements to mounting units of rotor blades.
13. Kinds of blade locks, their advantages and disadvantages. Blades fixing from axial displacement.
14. What loads act axial compressor blades?
15. What loads act axial compressor rotor?
16. What loads act axial compressor stator?
17. Methods of a drum-disc rotor elements joining. How the torsion torque and the axial force are transmitted from one stage to other?
18. Methods of rotor blades fixation in radial and axial directions.
19. Purpose and methods of compressor rotors balancing.
20. Compressor rotors axial unloading.
21. Cases of axial compressors and their main functions. Types of cases, their advantages and disadvantages.
22. Methods of compressors detachable cases main parts joining.

23. Assignment of inlet guide vanes, guide vanes and strengthening vanes of axial compressor.

24. What is the reason of inlet guide vanes application? Describe their construction.

25. What is the reason of variable inlet guide vanes application?

26. What is the reason of inlet guide vanes heating? How is it done?

27. Methods of axial compressor stator vanes mounting.

28. Compressor radial and axial clearances, their influence on compressor performances. Methods of radial clearances decreasing.

29. Labyrinth sealing: functions, construction and operation.

30. Means to expand a range of compressor stable operation modes.

31. Compressor air bleeding systems purpose, construction and operation.

32. Requirements to materials used in construction of blades, discs and other elements of compressor's rotors. Give examples.

33. Requirements to materials used in construction of compressor's stators elements. Give examples.

2 GAS TURBINES

2.1 Gas turbines classification and composition

2.1.1 General information, classification

Turbine of GTE is a blade machine in which gas stream energy is transformed into mechanical energy to rotate the rotor. This energy is distributed to drive the compressor, aircraft units and power plant units which insure its operation and also to drive propeller in turbo-prop, lift and tail rotors in turbo-shaft engines.

Gas turbine is one of the most crucial GTE units. Profitability, fuel consumption, reliability and life time of the engine appreciably depend on the turbine perfection. The turbine should provide necessary power, being small and light, efficient and reliable in whole operation range.

Turbine consists of rotating part – “rotor” and fixed part – “stator”.

Turbine rotor consists of rotating parts, such as rotor blades, disks, shaft with bearings, etc. (Fig. 2.1).

Turbine stator consists of no rotating parts joined together, such as nozzle vanes, shroud rings, turbine case, etc.

The turbine disk with blades is called driving wheel or **impeller**. The nozzle vanes joined to a ring constitute the **nozzle box**. Combination of the nozzle box and impeller constitute one turbine stage.

GTE turbines can be classified as follows:

1. By the *direction of the moving gas*:
   - axial;
   - centrifugal (radial);
   - diagonal.
2. By the *number of stages*:
   - single-stage;
   - multistage.
3. By the *number of rotors*:
   - single-spool;
   - twin-spool;
   - triple-spool.
4. By the *support location*:
   - with disks mounted in cantilever;
   - with disks mounted between supports.
5. By the direction of rotors rotation:
   - conventional;
   - contra-rotating.

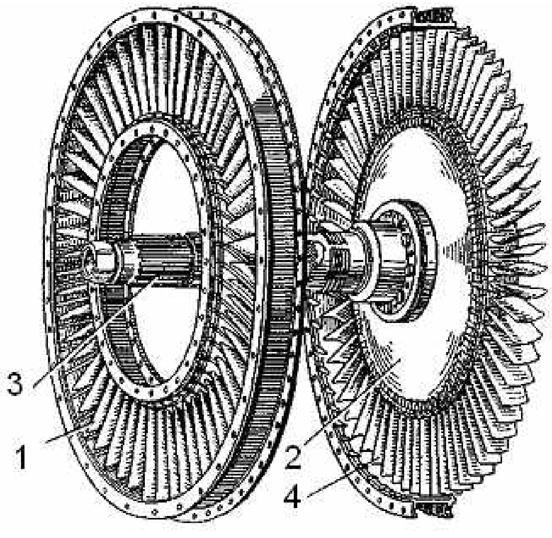


Figure 2.1 – Nozzle box and rotor of the gas turbine:
1 – nozzle vanes; 2 – disk;
3 – shaft; 4 – rotor blade

In **axial turbines** gas moves along the axis both at turbine inlet and at its discharge. In modern and perspective designs of GTE for planes and helicopters the axial gas turbine is the most commonly used.

In multi-stage single-spool turbines, all the impellers are mounted in just one shaft (Fig. 2.2 and 2.3). Multi-stage twin-spool turbines have some impellers mounted in one shaft, and the rest − in other; there is no junction between these parts which rotate with different rotational speeds. Such scheme of gas turbine is used in two-shaft ATJE (R11F-300), TFE (AI-25, D-20P, D-30, NK-8) and ATFE (AL-31, RD-33).

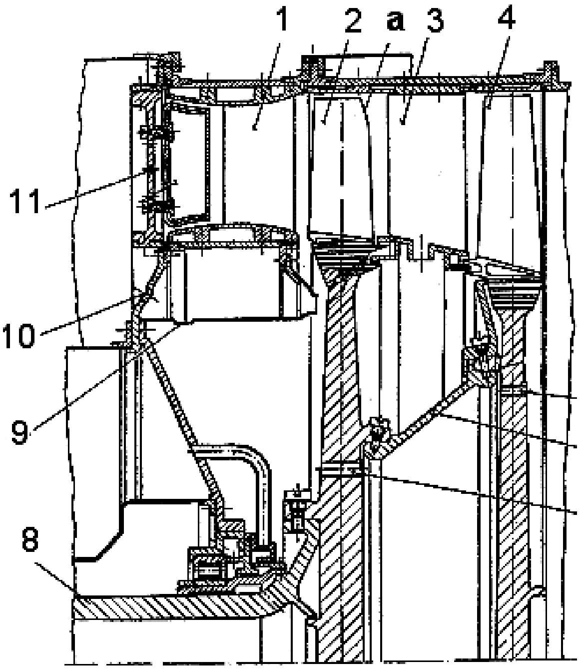


Figure 2.2 - Two-stage, single-spool gas turbine: 1 - nozzle vane of the first stage; 2 - impeller of the first stage (blades have cutouts “a”); 3 - nozzle vane of the second stage; 4 - impeller of the second stage; 5, 7, 9, 10 - apertures to pass cooling air; 6 - power ring to attach the disk of the second stage; 8 – shaft; 11 - power racks or power struts; 12 – support

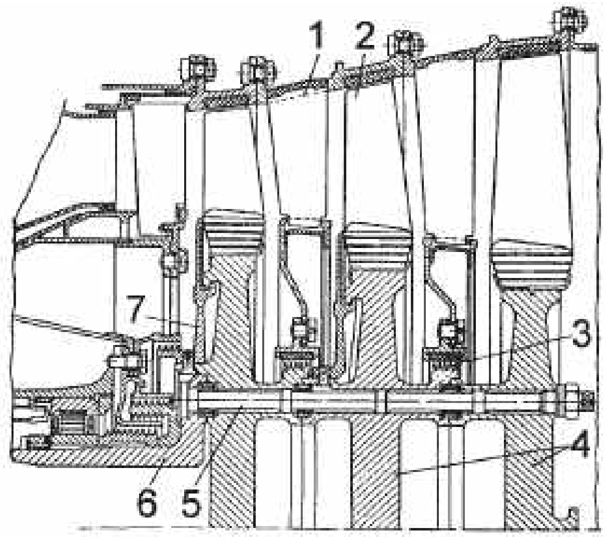


Figure 2.3 - Three-stage single-shaft turbine: 1 - nozzle vane; 2 – rotor blade; 3 - labyrinth sealing; 4 – discs; 5 – precise coupling bolt; 6 – shaft; 7 – shield disc; 8 - support

Multiple-stage three-shaft turbines are used in three-spool GTE (TFE D-36, D-18T, TShE D-136).

Turbine of two and three-spool GTE consists of the following cascades:

- **Low-pressure turbine** (LPT) is mechanically joined with low pressure compressor or fan (drives LPC or fan);
- **High-pressure turbine** (HPT) is mechanically joined with high pressure compressor (drives HPC);
- **Intermediate pressure turbine** (IPT) in three-spool GTE is mechanically joined with intermediate pressure compressor;
- **Free turbine** – is not mechanically joined with compressor, its power is

used to drive a separate unit, for example propeller through transmission in TPE or TShE.

Turbine constructive perfection is indirectly characterized by ***specific mass*****.** Turbine mass constitutes 25...35 % of engine total mass and more than half of this mass is mass of rotor.

Exercise 2.1

Write in your laboratory notebook the classification of turbines according to different criteria and examples of GTEs available in the laboratory room with single-, two-, three-, four- and five-stage turbines.

2.1.2 Design schemes of turbines

Some design schemes of turbines are known; these designs differ by supports number and their arrangement. It is desirable to have minimal number of supports, because design becomes simpler and the turbine mass decreases. However, increasing the distance between rotor supports can increase rotor and stator bending at critical rotational speeds or when the airplane carries out maneuvers. The increasing bending causes increasing of radial clearances, thus turbine efficiency decreases.

Number and arrangement of turbine supports depend on number of engine rotors.

Turbine of **single-spool** TJE, ATJE, TPE and TShE is usually mounted in cantilever to its support (AI-20, AI-24, AL-7F, AM-3, RD-9B, VK-1) (Fig. 2.2, 2.3). On one hand this results in minimal distance between supports; but on another hand turbine radial support (roll bearing) operates in high temperature zone. It causes difficulties to provide necessary thermal conditions of operation. The turbine radial-thrust support often is also back compressor support.

Forces from turbine radial support to turbine case are transmitted:

- through compressor last guide vane (straightening vane) (AI-20, AI-24, NK-12);
- through the support (racks) of combustion chamber diffuser;
- through the first nozzle box (AL-7F, AM-3, RD-9B).

The last method of force transmission is the worst because the power elements are located in the hot gas stream coming from the combustion chamber.

Another alternative is to locate the support after turbine (GTD-3F, TV3-117). In this case the support operating temperature is lower than in previous alternative, but the distance between supports is bigger. Mass of multi-stage turbine rotors is very high, what results in necessity to use two supports: front and rear (NK-12).

In **two-spool** GTE the following alternatives supports arrangement is possible:

- high pressure turbine (HPT) is mounted in cantilever relative to its support, and low pressure turbine (LPT) has a rear support (AI-25, D-30);
- high pressure turbine support is after a turbine, and the low pressure turbine support − in front of LPT; both supports are integrated in one housing

(D-136); such integration facilitates oil supplying and removing;

- HPT rotor is supported by LPT rotor through the inter-shaft bearing, and both rotors are supported by the rear LPT support which transmits loads to turbine case (NК-8, RD-33);
- as well as in the previous alternative, there is the inter-shaft bearing between HPT and LPT rotors, but load from both rotors is transmitted to the case through HPT front support (R11F-300). It allows reducing a distance between supports and therefore increasing the rotor bending rigidity. This HPT support is in high temperature zone, what results in difficulties to supply and remove lubricant from inter-shaft support.

Turbines of **three-spool** GTE have the following specific features:

- intermediate pressure turbine (IPT) is in cantilever to its support, which is mounted in common housing with HPT rear support, and fan turbine has a rear support (D-36, D-136, D-18T);
- HPT rotor is supported by IPT rotor through inter-shaft bearing, both of these rotors transmit a load to IPT rear support which is mounted in common housing with fan turbine which is mounted in cantilever (D-27).

Contra-rotating turbine

The two-shaft or three-shaft turbine can be designed on contra-rotated scheme. This design has only one row of static nozzle guide vanes. The remaining nozzle guide vanes are, in effect, turbine blades. Since all but one airfoil extracts energy from the gas stream, contra-rotating turbines are capable of operating at much higher stage loadings comparing to conventional turbines, making them attractive for direct drive applications (CFM-56, program TECH56; Trent 500, F119-PW-100; EJ-200, M-88).

Exercise 2.2

Consider constructive schemes of turbines of the engines AI-20, NК-12, RD-9B, R11F-300, AI-25, D-36. Give their short description.

2.2 Rotors of gas turbines

The basic elements of rotor are: rotor blades, disks and shafts. High-pressure turbine rotor of the TFE D-36 is shown in Fig. 2.4.

2.2.1 Turbine rotor blades

Rotor blades transform gas flow energy into mechanical work of the turbine. Originated forces are transmitted to the shaft through the disk.

Rotor blades operate at high temperatures. They are streamlined by hot gases moving at high velocity, what results in corrosion and erosion. Blades are also exposed high static, vibration and thermal stresses. Taking into account heavy operating conditions of rotor blades and their role in the engine (reliability and life-time of blades determine reliability and life-time of engine); the following factors present strict requirements to the constructive form of blades, method of their attachment to disk, materials and manufacturing techniques.

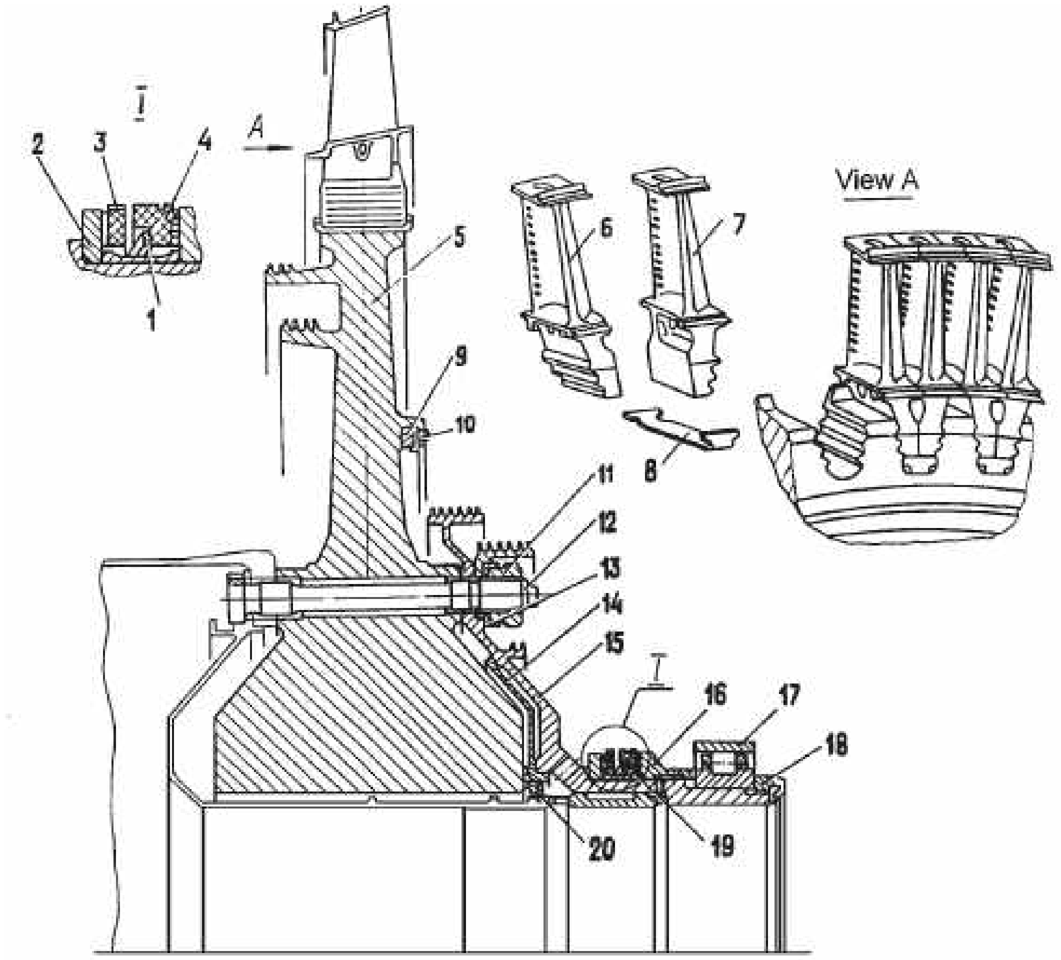


Figure 2.4 – Rotor of TFE D-36: 1 - spring; 2,16 – thrust rings; 3 – ring; 4 – seal ring; 5 – disk; 6 – rotor blade (right); 7 – rotor blade (left); 8 – locktab; 9 – counterbalancing weight; 10 – locking; 11, 18 – nuts; 12 – coupling bolt; 13 – locking spacer; 14 – shield; 15 – rear shaft; 17 – roller bearing; 19 – bush; 20 – sealing ring

Looking at the rotor blades is possible to identify two parts, the blade **body** and its **locking part** (root part). Between the body and locking part are **shelves** which form the gas path of the impeller. The shelves improve cooling of the root and reduce a heat flow to the disk.

There is a **shroud plate** at the end of blade. After impeller assembling shroud plates are joined together forming a shroud ring, thus eliminating gas overflow in circumferential direction through the radial clearance. As a rule, on the shroud ring outside surface a comb labyrinth is installed to reduce the gas overflow through the radial clearance in axial direction. This results in turbine efficiency increasing. Besides, shroud increases rigidity of group of blades; therefore natural blade oscillation frequencies move to zone of high frequencies and small amplitudes. Friction on contact surfaces of the shroud plates cause damping of vibrations, thus decreasing vibration stresses.

In some cases, when it’s difficult to mount the needed number of blades in the disk slots, two blades can be mounted in one slot. This design concept is known as **dual blades**. Such design allows decreasing vibration stresses because energy of blade oscillation dissipates by friction between contact surfaces of each blade. Thus, dual blades vibration amplitude is two times less (HPT of D-25, D-36, see Fig. 2.4).

In some designs a shroud bush (or wire connection) is used which is located through holes in a blade body (R11F-300, second stage) to decrease vibrations. Sometimes to improve the blade vibration properties a corner of its body in the periphery of its trailing edge is cut-off (see Fig. 2.3).

Exercise 2.3

Draw a sketch and make a brief description of the rotor blades design of any stage of the fan turbine D-36 or the free turbine of TV3-117 (or other turbine set by the teacher).

2.2.1.1 Attachment of the turbine rotor blades

Rotor blades are attached to disk by a profiled blade root and a slot of corresponding shape in the disk rim part.

The most abundant blade root is **"fir-tree" lock**. The wedge-shaped blade root allows attaching a great number of blades. The number of teeth pairs may vary from two to six. The more teeth pairs lock has, the lower-loaded each pair is, but as the same time stress concentration at the teeth bottom increases. Aimed stress concentration reducing, thus turbine reliability increasing, only a few (2-3) teeth pairs locks are applied (AI-25, TV3-117, D-36, see Fig. 2.4).

If two blades are mounted in one slot it is necessary to make the blade root with single-side teeth (see Fig. 2.4).

Usually blades are attached to disk using **easy or free fit** (with small clearance); this facilitates assembling, replacement or repairing. Besides, the blade can self-position acted by centrifugal forces and bending moments of centrifugal and gas forces, resulting ***stresses reducing in the root part of the blade***. The easy or free fitting also ***reduces tangential temperature stress,*** originated in the rim as result of different temperatures and thermal expansion factors of materials used to manufacture blades and disks and non-uniform temperature distribution along the disk radius.

During engine operation gas forces try to move the turbine blades along slots. To avoid this movement it is necessary to have enough friction force in the lock which arises under action of centrifugal forces. It allows applying simple **methods of blades fixing from axial displacement**:

- bended flat plates (AI-20, D-36);
- protuberances (out-shots) in the root of the blades (AI-25, TV3-117);
- by the disk deflector (TV3-117);
- expanding spring snap rings;
- by combination of these methods.

Exercise 2.4

Look at the design of the rotor blades using drawings and engines in the laboratory room. Draw the "fir-tree" root and two-three methods of blades axial fixing.

2.2.1.2 Design features of cooled blades

The turbine inlet temperature rise is the main feature of the gas-turbine engines improvement. Owing to this feature is necessary to provide continuous perfection of the cooling intensity of blades, nozzle vanes and disks.

In high-temperature GTE the most widely spread method of cooling is the **blades internal convective air cooling** with radial (longitudinal), lateral or combined (radial-lateral) motion of air and also combination of convective and film cooling.

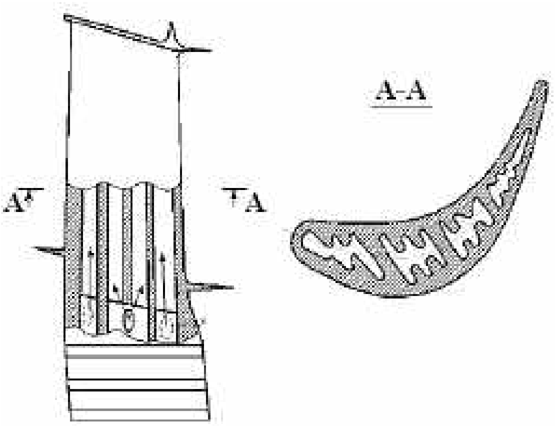


Figure 2.5 –The engine D-36 HPT rotor blade cooling

The HPT rotor blade of the engine D-36 is shown in Fig. 2.5. The air, taken from the compressor, goes through a channel system which is inside blades (radial motion); then air is pushed out to a gas path. The main advantage of longitudinal cooling system is a simpler manufacturing techniques required to produce blades. Otherwise significant temperature non-uniformity along a length and cross-sections of a blade exists, because front and rear edges are hotter than a rest of the blade.

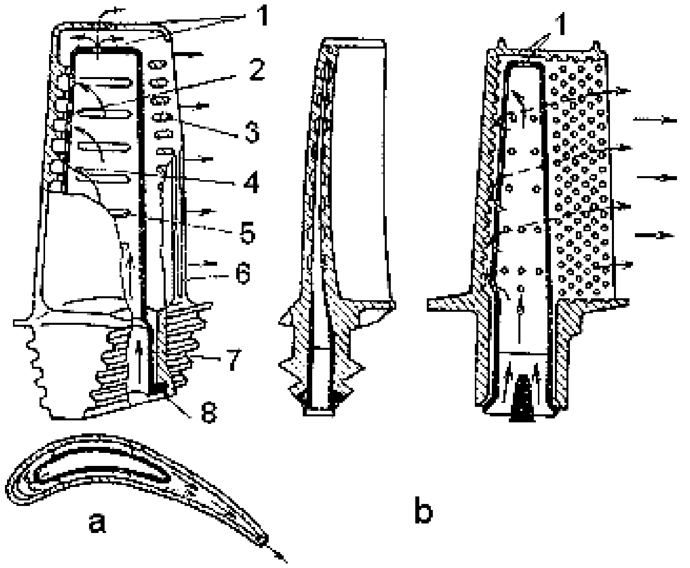


Figure 2.6 – Cooled cast rotor blades with deflector:
a - design concept of “Soyuz” design bureau;
b - blades of TFE JT9D-7 first turbine stage

To increase efficiency of blades convective cooling there is necessary to intensify the heat exchange provided by cooling air. With this purpose various designs of turbine cooled blades are proposed.

The most widespread concept is hollow blade with deflector inside. Cooling air passes inside a **thin-wall metallic deflector** (splash plate) which is inserted into a hollow blade (Fig. 2.6). Deflector 7 is manufactured from thin sheet of heat resistant material. It is inserted into internal cavity of the cast blade through a rectangular slot and is fixed from radial displacing by shroud (overhang) 8. Limiters 5 (forging stamp), made in deflector, prevent it from lateral displacing and separate oscillations.

Air moves from deflector to blade internal surface near leading edge through system of apertures 4. Ribs 2 intensify heat exchange by increasing heat exchange surface area and increasing turbulence of cooling air near leading edge. Then air moves between the deflector and the blade wall (through a clearance) with high velocity, thus heat exchange is intensive.

From blade inner cavity air partially flows out to radial clearance through the aperture 1, and partially passes throw narrow longitudinal gap 6 with ribs 3.

Blade with deflector is heavier, that results higher stresses in disk rim, caused by centrifugal action. Such scheme of cooling is widely used for nozzle vanes.

As it was already above mentioned, ***additional cooling air turbulence*** produced by pins, vortex generators, wavy channels, etc. plays essential role in ***heat exchange intensification*** (Fig. 2.6, b).

In high-temperature turbines used in engines of fourth-fifth generations, the improved cooling method is combination of ***intensive internal convective cooling with film (shield) cooling*** of rotor blades.

For example, Fig. 2.7 shows the scheme of the HPT first stage rotor blades cooling (TFE CF6-6, General Electric). The blades are manufactured by precise casting from nickel-chromium alloy. Their cooling is combined convective-film with radial and transversal motion of air. Small apertures that are necessary for film cooling of blade leading and trailing edges (see Fig. 2.7, pos. 2, 5) are manufactured by electro-erosive methods.

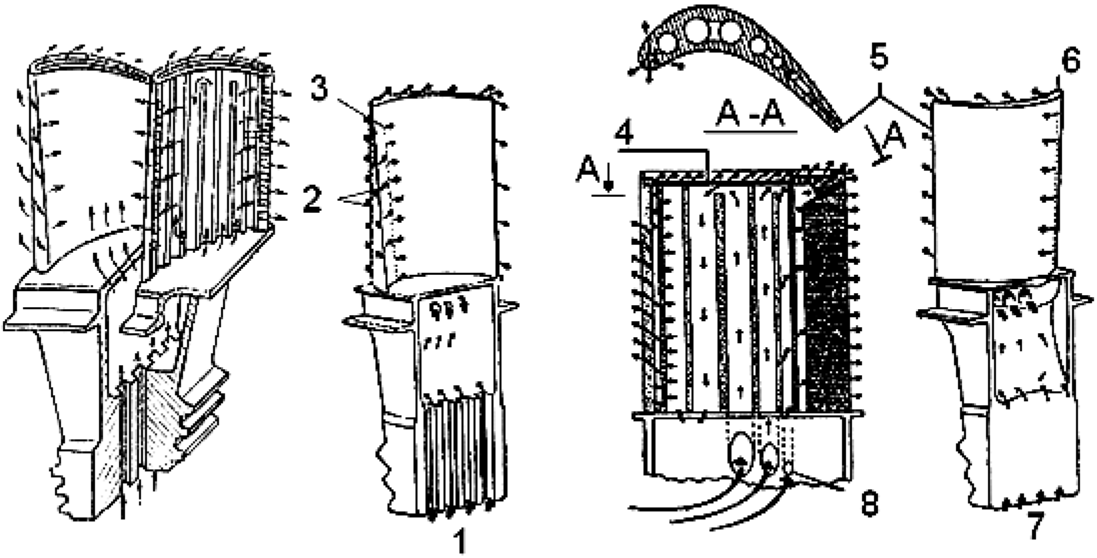


Figure 2.7 – Pair of rotor blades of the HPT first stage of CF6-6: 1 - front side of the blade; 2 - apertures in the leading edge; 3 - tangential apertures; 4 - blade cover; 5 – longitudinal gaps in the trailing edge; 6 – tip of the blade; 7 - rear side of the blade; 8 - holes for the cooling air supplying

HPT rotor blade of the TFE RB.211-524 (Rolls-Royce) is shown in Fig. 2.8. The shrouded blade is casted with direct crystallization. The blade with convective cooling has a set of internal tangential channels, both with radial and recirculation (loop) scheme of air motion. Blades are perforated to exhaust the air outside and to create a film (shield) cooling. Thus a more uniform distribution of temperature along the blade is provided. The cooling air enters the blade through two channels.

HPT blades of turbofan D-18T and propfan D-27 (Zaporozhje "Ivchenko-Progress" design bureau) are casted from nickel-chromium alloys in special vacuum facilities. Method is known as **high-speed guided solidification**. Blades have an advanced convective-film cooling system. Special ceramic rod forms internal cavity in the blade during casting.

A further advance of this technique is to grow blade out of a single crystal. It extends a useful creep life of the blade and operating temperature can be substantially increased.

The greatest cooling effect gives using **porous or transpiration cooling** when the blade (Fig. 2.9) is made, for example, from a load-bearing (power) rod 4 and a porous shell 2 (shell blade). The power rod connects the blade to the disk. Initially air gets to internal cavity 5, from which, throw proportional apertures 3, it passes to longitudinal channels 1. The porous shell is made of transpired (permeable) material with numerous micro-apertures. Air passes through them removing heat from material as a result of convective heat exchange and creates isolating layer which prevents hot gases contact with blade surface.

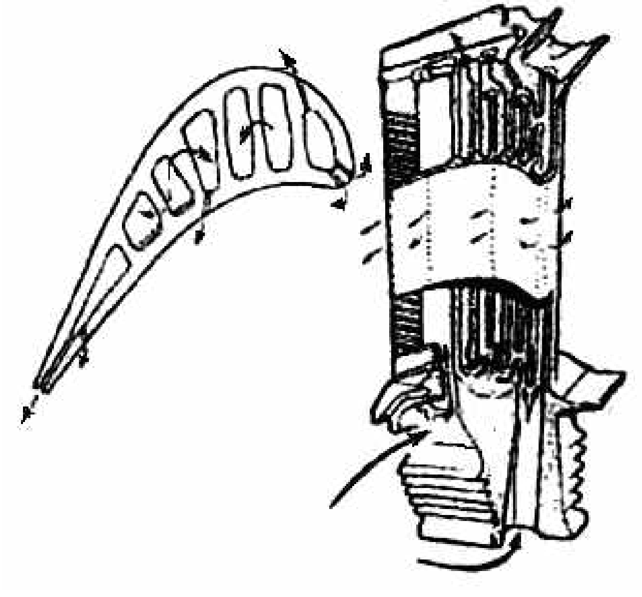


Figure 2.8 – Modified rotor blade of the TFE RB.211-524D4 high pressure turbine

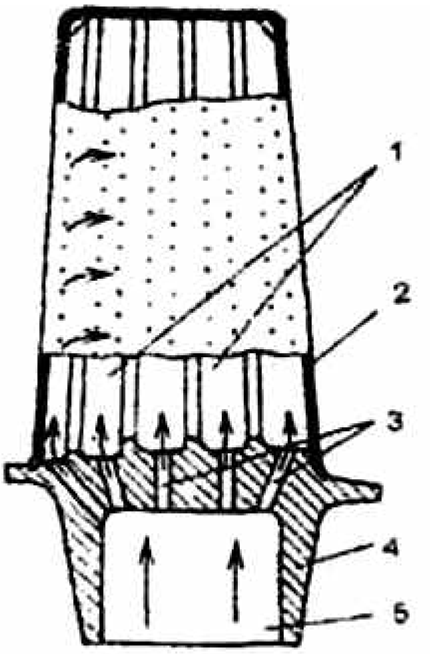


Figure 2.9 – Design scheme of a blade with porous (transpiration) cooling

Practical implementation of porous cooling is now related with significant construction and technological difficulties.

Exercise 2.5

Consider posters and prepared blades with different schemes of cooling. Describe designs of cooled blades of the D-30 and D-36 turbofans first turbine stages.

2.2.2 Disks and shafts of turbines. Coupling disks and shafts together

Turbine disk consists of rim, web, bush, ring ledges (lug, projection) and flanges (see Fig. 2.4).

The **disc rim** is used to attach the blades to the disk.

The shape of the **disk web** is complex, aimed providing a full-strength. Disk web may have eccentric apertures to pass cooling air (see Fig. 2.2, pos. 7).

In case of multi-stage turbine HPT disks have **central hole in the disk bush** to place the LPT shaft inside, or to place other internal shaftings and communications. This hole essentially increases stresses in the disk. To overcome this problem the bush is made of increased width with smooth transition from the bush to the web (see Fig. 2.4).

During engine operation a **turbine shaft** is loaded with torque, axial and radial forces. Shafts are hollow to be full-strength. If to increase a shaft external diameter, its bending rigidity grows and its weight reduces.

The shaft is designed to transmit mechanical shaft power to the compressor by a splined end that mates with the rear compressor shaft. A special connecting bolt locks the components together. At the opposite side of the shaft there is a flange (rib, shoulder) to join a shaft with turbine impeller, the seats for bearing and sealing elements.

Disk joining together and disks joining to the shaft may be performed in different ways, but all of them must provide transition of torque, axial and radial forces.

The junction construction should be rigid enough and provide reliable mutual alignment of both compressor and turbine rotors and fixing of all rotor components in cold and hot conditions, minimal heat transfer from disk to shaft in contact places and prevent joints opening under axial forces and bending moments action.

Joining disks together can be split or one-piece.

Split junction simplifies manufacturing, assembling and disassembling, and also replacement of damaged parts.

One-piece rotors are structurally simpler and lighter, however it complicates the turbine assembling and disassembling.

Split junctions are:

- **Flange bolt junction*.*** The torque transition from one disk to another and to the shaft is made by the contact places in the precise (fit) coupling bolts (AI-25, D-36, D-18T, RD-33) or precise (fit) sleeves (AI-20, AI-24, NK-12, NK-8, GTD-3F). Torque may be also transmitted by friction initiated by axial force-coupling of the tie bolts (pins, double-end bolts, studs). The parts are aligned in a contact area of the coupling bolts or fit sleeves.

- **Spline junction** (using face splines of triangular shape). Face splines transmit a torque with high reliability, provide alignment of parts (TV3-117), the rotor disks have bosses (lugs) in which apertures are drilled for coupling bolts. To reduce bending stresses acting coupling bolts, caused by centrifugal forces, cylindrical collars are used which are supported on corresponding shoulders (ribs) of the turbine disks.

Exercise 2.6

Using the prepared engines and drawings of junctions used to couple disks together and to the shaft in the engines RD-9B, NK-12, AI-25, D-36, TV3-117, indicate the elements of junctions to transmit the axial force and torque (orally). Draw the tie (through, fit) bolt of the engine AI-25 HPT.

2.3 Stators of gas turbines

The stator of the gas turbine consists of nozzle boxes, case and other no-rotational parts.

2.3.1 Nozzle boxes

2.3.1.1 Specific features of nozzle vanes

The nozzle vanes are assembled in a ring airfoil forming the **nozzle box** (NB). Passing NB, gas is deflected at greater angles than in impeller (rotor blades). Therefore NB blades (vanes) are wider. The elongation of nozzle vanes lies in limits 1,2 ... 3.

In manufacturing and assembling substantial attention is paid to NB ***discharge area `value to be equal to its design value***. The adjustment of the cross-sectional area is carried out on a test-cell by: turning the vanes (R11F-300), cutting a part of material at the trailing edges or replacing them.

The number of nozzle vanes should not equate or be multiple to the number of rotor blades to reduce probability of dangerous resonant oscillations.

Nozzle vanes are milled from forged pieces, press stamped, welded from deformable sheet material, cast on melted models (“investment pattern”). The precision casting of blades provides high accuracy and cleanliness of the blade surface without application of complex and expensive machining; therefore it is the most widely used method of manufacturing. To increase heat resistance, the nozzle vanes are exposed to nitride hardening or covering with a heat resistant enamels.

Nozzle vanes are designed with **shelves** at their ends. The shelves form the gas path and serve to attach the blades to the case.

Nozzle vanes can be **hollow** or **solid**. Cooled nozzle vanes are hollow. To intensify a cooling process the splash plate (deflector) is mounted inside the cooled blade. The air comes inside the deflector and through apertures in its leading edge goes first to leading edge of the blade and then in lateral direction. The air goes out to the gas path through slots or punching in the trailing edge (R11F-300, AI-25, D-30, D-36).

In a high-temperature turbines the **convective-film cooling of nozzle vanes** is used (D-18T, HPT). As an example in Fig. 2.10 the design scheme of the cooling used for HPT first stage vanes of CF-6-6 turbofan is shown.

Nozzle vanes are produced couple (are individually cast and then welded). The cooling air moves through the splash plates (deflector) 5, 7 and through a system of small apertures 6 and goes out by a clearances between the deflector and blade inner wall and is expulsed to the gas path through the punching system 2, 9. The convective-film cooling of the trailing edge is provided by the slots 1 located in the blade profile.

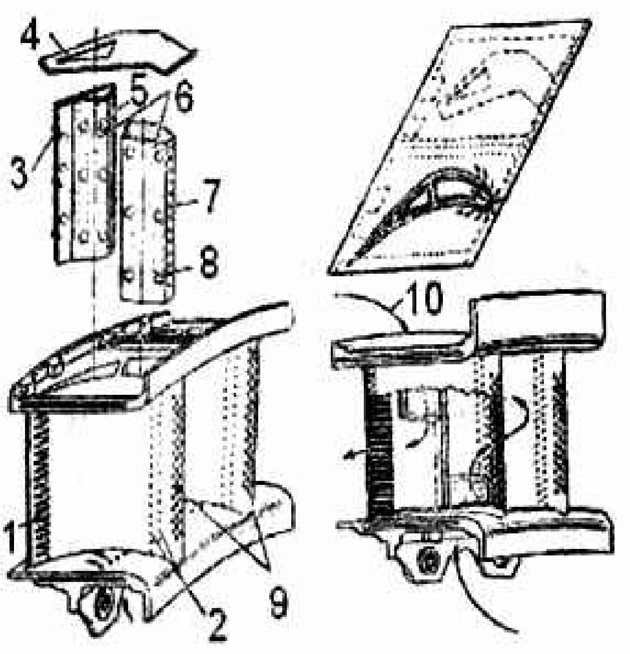


Figure 2.10 – The first stage nozzle vanes pair of the engine CF6 HPT:
1 – slots at trailing edges;
2 – gill holes; 3 – dimples on output to an edge, 4 – cover; 5 – rear deflector; 6 – holes for cooling air; 7 – front deflector; 8 – dimples; 9 – holes in the front edge; 10 – cooling air supplying

2.3.1.2 Attachment of nozzle vanes

The attachment must provide the blades fixing in axial and circumferential directions, transmit the load to the turbine case. The attachment must also provide an opportunity of free thermal expanding of blades relative to the connected parts during operation.

Taking into account the mentioned requirements, ***the nozzle vanes, as a rule, are not engaged to the load-bearing system of the turbine case***, because the load-bearing elements clamp the body.

Nozzle vanes are located and fixed between internal and external shrouds which are attached to the nozzle box housings.

Attachment of the nozzle vanes can be double-supported or in cantilever.

Double-support attachment of nozzle vanes is mainly used in nozzle boxes of first turbine stages to provide significant bending rigidity and strength. The vane can be free fixed in both shrouds (AL-7F, AI-20, NK-12) or only in the internal shroud (R11F-300, D-30).

Force is transmitted from bearing support to turbine external case through power bolts which are located in hollow vanes.

Cantilever attachment of blades is used in second and subsequent turbine stages. The most used constructive solution is the rigid attachment to the outer case and loose attachment disposed end-to-end of the internal blade shroud with an internal ring (R11F-300, AI-25, D-30). So at the second and third turbine stages of the engine AI-25 the external shrouds of the nozzle vanes are rigidly retained to the turbine case. The side surfaces of internal shrouds of nozzle vanes are loosely mounted on box-shape disks of labyrinth seals which allow vanes radial elongating.

Nozzle vanes can be screwed (R11F-300), ***riveted or welded*** (AI-20, NK-12) ***to the case or to the external shroud***. Vane inner edge loosely enters shroud ring, ensuring free thermal expansion.

The cast process of the nozzle vanes can be made in blocks of two, three or four blades. Blocks are assembled to form ring of nozzle boxes. So the nozzle box of the D-36 high-pressure turbine includes seven blocks (sectors) on four vanes and one vane between them (totally 29 nozzle vanes). All sectors have possibility of thermal expansion. The assembling method is known as **frame mounting**.

Exercise 2.7

Look at drawings and prepared engines AI-20, AI-25, D-36 and study the construction of the nozzle boxes and methods of their attachment.

2.3.2 Casings of gas turbines

The gas turbine casing is a constitutive part of the engine power case that typically consists of nozzle vanes case, rotor support frame and turbine shaft frame.

The turbine case design must be rigid and provide reliable alignment of parts in places of their connection, high operation and repair manufacturability.

The **nozzle vanes case** is a thin-walled shell with flanges and rigid edges used to place and attach the turbine nozzle vanes. Depending on profiling a turbine gas path the case can be cylindrical or conical.

The **nozzle vanes case** has a row of lateral connectors.

Alignment of turbine case parts is made using cylindrical shoulders or precise (fit) bolts.

The **turbine rotor support case** is rigid; it includes bearing housing, internal and external rings formed by shrouds of nozzle box of the first turbine stage which are rigidly joined together by power rods or diaphragms. The load-bearing elements pass through hollow blades of a nozzle box of the first stage (RD-9B, R11F-300), or are placed in spaces between a flame tube in combustion chamber (D-25V, D-30).

In case of annular combustion chamber, power connection between bearing housing and power frame can be arranged not through nozzle vanes of the first turbine stage, but through cantilever turbine shaft case (AI-20, NK-12).

If the bearing is located after the turbine (TV3-117, D-36) the case of rear rotor support is a frame, formed by external and internal power rings, connected by radial struts (racks), rods and other load-bearing elements.

The **turbine shaft case** limits a volume of combustion chamber from inside and joins the bearing cases of compressor rear support and the turbine rotor support (RD-9B, R11F-300). There is an opportunity to mount pipelines for oil supplying inside casings. Thermal shields are used to protect the case from heating (D-30).

Exercise 2.8

Study the power links between the turbine bearing housing with the external case in the engines RD-9B and D-30. Draw sketches in your notebook.

2.3.3 Clearances and seals of turbine gas path

There are axial and radial clearances between rotor and stator. The value of clearance, especially radial (clearance between blade and casing) influences the turbine efficiency. The clearance value varies on the engine operational mode.

To set initial radial clearance value, the following demands must be met. During rotor switch-off deceleration casings cool quicker than rotor, which results in clearance diminution. Therefore it may result in inadmissible blades grazing the casing.

To reduce radial clearance variation from mode to mode, it is controlled by **active and passive systems of radial clearance control**.

To prevent rotor jamming when rotor blades graze the case, the **metal-ceramic (cermet) seals** in the turbine case (see Fig. 2.4) or **honeycomb seals** (D-36) are used.

The metal-ceramic seals are baked from powders of iron, nickel and graphite. The honeycomb has the form of hexahedral cells produced by high-temperature welding of corrugate strips with thickness 0,08...0,15 mm of nickel-chromium alloy. Such inserts sharply decrease the gas leakage and increase the turbine efficiency.

The value of axial clearance also changes during engine operational mode changing.

The labyrinths located in radial or axial directions can operate as seals, decreasing the gas overflow in axial clearance between turbine stages. Because the clearances significantly vary at different engine operating modes, there is more preferable to use labyrinths, which allow axial displacement of their mobile elements without decreasing sealing efficiency (RD-9B, TV3-117). The metal-ceramic or honeycomb insertions are used to reduce the clearances in the labyrinths seals.

The **active clearance control (ACC)** is more effective method to keep minimum tip clearance throughout the flight. The air taken from compressor cools the turbine casing and in combination with shroudless turbine blades enables higher temperatures and rotor rotational speeds (D-27).

Exercise 2.9

Consider the sealing used in the turbine gas path of the engines RD-9B and D-36. Draw a sketch of honeycomb seal.

2.4. Cooling systems of the gas turbines

Turbine cooling systems are necessary for providing set values of the engine components temperature, thus providing required strength, reliability and life time.

Perfect cooling system allows increasing turbine inlet temperature (TIT), decreasing variation of radial and axial clearances from mode to mode, reducing weight of some components and using less heat resisting materials.

In GTE the open air cooling system is used. It means that after removing heat from the cooled elements the air goes to the turbine gas path, i.e. it is used for cooling only once.

The engine elements which need cooling are turbine disks, rotor blades, nozzle vanes, cases of nozzle boxes and rotor supports.

Pipelines of lubrication system and load-bearing elements of other systems are isolated from heat.

The internal cooling system of turbine components consists of:

- inlets of cooling air,
- ducts to guide air to the turbine,
- seals in places of air transition from fixed parts to rotating,
- deflectors of turbine disks to provide the air motion along the disk radius for increasing their cooling efficiency.

The air before entering the cooled rotor blades can be preliminary twisted, providing a shock-free inlet to cooling channels in the rotating disk or in the roots of the blades. Thus the heat exchange is improved or the required consumption of cooling air (TFE D-36) is reduced.

In Fig. 2.11 the cooling system of the five-stage gas turbine of the engine D-36 is shown. Thermal-stressed components of the turbine (disks, rotor blades of the first stage, nozzle boxes of first and second stages and casings of support) are cooled by air, taken from fourth IPC stage, third HPC stage and seventh HPC stage.

Cooling of high pressure turbine is shown in Fig. 2.12. Nozzle vanes of the first turbine stage are cooled by air taken from the HPC. The cooling air enters the top side of the blade and then inside the deflector. Then this air through apertures in the deflector gets to the clearance between the deflector and the blade internal wall and leaves to the gas path through the trailing edge slots of the blade.

The rotor blades and disk of the first stage are cooled by air taken from the HPC seventh stage.

Air, bleed from third HPC stage, cools IPT nozzle vanes and, passing through internal cavity of NB case, cools disks of IPT and LPT.

Cavities of the rotor bearings of the first and second turbine stages are cooled by air coming from fourth stage of IPC through internal cavities of nozzle vanes of the second stage. This air decreases a heat transfer from disk to bearings of the first and second turbine stages and provides the necessary heat over-drop in labyrinths and non-flow oil seals. Same air is used to cool the fan turbine bearing.

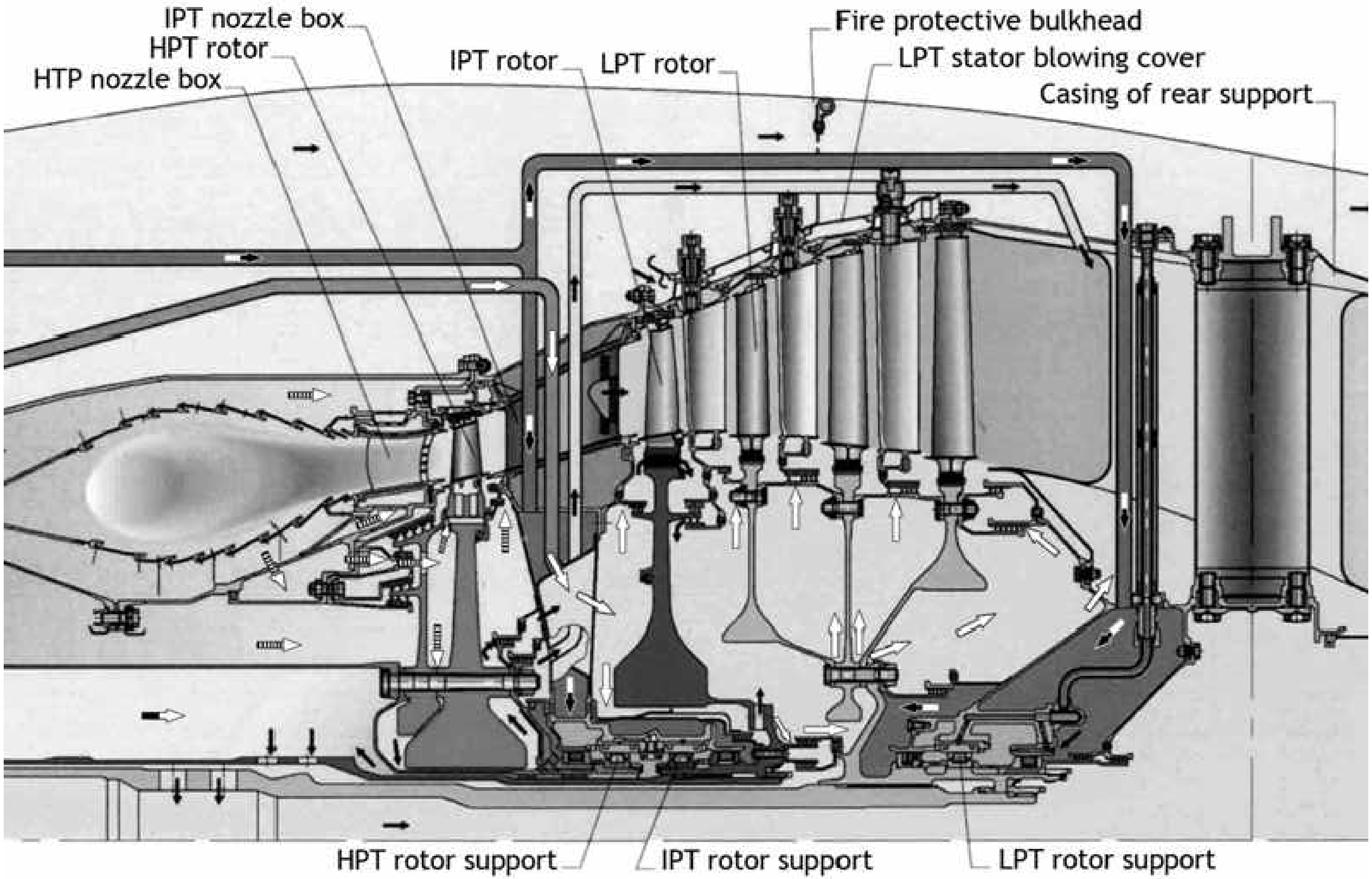


Figure 2.11 – Scheme of the D-36 turbine cooling:

– bleed from IPC 4-th stage;

– bleed from IPC discharge;

– bleed from HPC 3-rd stage;

– bleed from HPC dascharge.

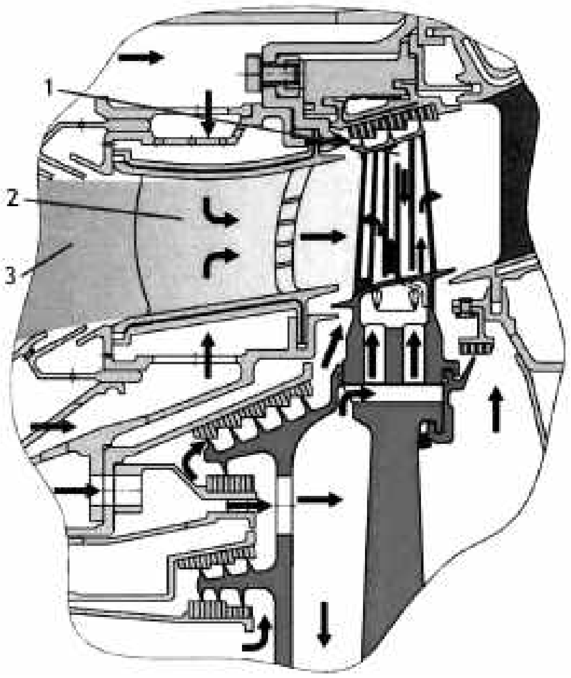


Figure 2.12 – Scheme of the D-36 turbine cooling:
1 – rotor blade; 2 – nozzle vanes; 3 – gas path

Exercise 2.10

Using posters, drawings and prepared engines consider cooling the engine D-36 turbine.

2.5 Materials for gas turbines

Following requirements are applied to materials used to manufacture the turbine components:

- high thermal resistance;
- high creep resistance with necessary plasticity;
- resistance to corrosion and erosion caused by the gas;
- high heat conductivity, etc.

These requirements are satisfied using heat-resistant alloys based on nickel, chromium and in some cases on cobalt.

The rotor blades are made of nickel-chromium alloys ЖС6-К, ЖС6-КП, ХН70ВМТЮ (ЭИ617), ЖС3, ЖС32, and others.

Modern blade materials are alloys N5 (nickel-cobalt), CMSX-4. A non-metallic turbine blade can be manufactured from reinforced ceramics.

The nozzle vanes are also made of nickel-chromium alloys ЖС6-У, ЖС6-К, ЖС3, ЖС16-ВИ, much less often of alloys based on cobalt ЛК-4.

Disks are made of nickel-chromium alloys ЭИ698-ВД (ХН73МБТЮ-ВД), ЭП742-ИД (ХН62БМКТЮ-ИД), ЭП741, ВЖ-122 (ХН60КМВБЮТФ), ЭИ437Б (ХН77ТЮР), and also Ni-Cr-Mg steel ЭИ481 (37Х12Н8Г8МФБ).

Modern disk material is alloy ME3 (nickel powder).

For shafts steels ЭИ736 (13Х14Н3В2ФР), 40ХН2М and nickel-chromium alloy ЭИ698-ВД are used.

Components of the case are made of steel ЭИ961 (13Х11Н2В2МФ), ВЖ102, 12Х18Н9Т and others.

Exercise 2.11

Using the poster “Materials for gas turbines blades” write in your notebook a chemical composition of the heat resisting alloy ЖС6-К.

2.6 Answer the questions about turbines

1. Functions of GTE turbines and requirements to their construction.
2. Major turbine components.
3. Classification of GTE turbines.
4. Design schemes of turbines.

5. Construction and main elements of the turbine rotor blade.
6. Advantages of the dual rotor blades.
7. Requirements to the lock of the rotor blade.
8. Kinds of the blade locks, their advantages and disadvantages. Fixing of the blades from axial displacement.
9. What loads act the turbine blades?
10. Advantages and disadvantages of the film cooling.
11. What loads act the turbine rotor?
12. Construction of the turbine disk.
13. Construction of the turbine shaft. What loads act on the shaft?
14. How are the turbine disks joined among themselves and attached to the shaft?
15. What loads act on the turbine stator?
16. Specifics of the nozzle boxes construction and manufacturing.
17. Why the nozzle vanes are not engaged to the load-bearing system of the turbine case? How are they attached to the case?
18. Cases of the turbines: requirements and main functions. Case of the nozzle vanes, support case of the turbine rotor, turbine shaft case.
19. Methods of the main parts of the turbine cases junction.
20. Radial and axial clearances in the turbine, their influence on the turbine performances. Methods of decreasing the radial clearances. Active and passive clearance control.
21. The turbine labyrinth sealing: functions, construction and operation.
22. Why the cooling air before entering the cooled rotor blades is preliminary twisted? What constructive elements provide this?
23. What factors are to be taken into account when a place for cooling air bleed from compressor is chosen?
24. Requirements to materials used for blades, disks and other elements of the turbine rotors. Give examples.
25. Requirements to materials used for the turbine stator elements. Give examples.

3 COMBUSTION CHAMBERS

3.1 Basic requirements to combustion chambers

Combustion chamber is a basic unit of an engine, responsible to burn the fuel at the highest level of efficiency, delivering a stream of hot gases to the turbine. Combustion chamber is the most thermo-stressed unit, that is why its reliable operation at start-up and at all operating modes, its efficiency and life time determine similar parameters of an engine as a whole.

Combustion chamber (CC) must provide:

1. Fast reliable start-up and stabile operation CC at all operating modes.
2. Efficient fuel combusting. The degree of actual fuel usage is characterized by a combustion efficiency factor giving the amount of heat realized by combustion in relation to the heat theoretically available in the fuel:

$$\eta_{CC}=Q_1 \backslash Q_2,$$

where Q_1 is realized heat;
Q_2 is the theoretically available heat.

Modern combustion chambers achieve efficiencies η_{CC} = 0,98...0,99.

3. Minimal hydraulic losses of stagnation pressure in the chamber. The total pressure loss is characterized by the ratio of stagnation pressures at CC discharge p^*_g and CC inlet p^*_{IN} :

$$\sigma^*_g = p^*_g \backslash p^*_{IN}.$$

Typical values of σ^*_g are 0,95 … 0,97, but in some unfortunate conditions may drop to 0,90. The pressure losses in combustion chamber consist of hydraulic and heat pressure losses. Hydraulic losses appear when airflow contacts with walls of combustion chamber (friction losses) and when airflow drastically expands (turbulent losses). Hydraulic efficiency is measured experimentally by blowing atmospheric air through CC. Heat losses appear during fuel combustion process, because temperature rise results in gas expansion, airflow increasing and redistributing.

4. High thermal density of working volume $H = Q_1/(V_{HP}\ p_{IN})$, where V_{HP} is the internal volume of a flame tube. For GTE of aircraft H = 4000–5000 kJ\(м^{3}sPa).

Maximum temperature field uniformity at CC discharge. Optimum engine performance will be achieved if the average temperature of hot gas is as close as possible to temperature tolerable to turbine blades. If the temperature distribution is non-uniform such as hot spot exists in the gas, the turbine inlet temperature must be reduced to prevent blades damage. this will inevitably reduce engine performance, life time of blades and other engine components.

5. Big life time, convenient and safe maintenance.
6. Operation without CC walls carbonization, smoke and toxic substances emitting.

Rig and in-flight testing is usually needed for experimental validation of combustion chamber meeting considered requirements.

Further development of CCs relates with operating cycle parameters increasing, that are limited by thermal stresses, aerodynamics improving and harmful emissions reducing. Designing new CC is impossible without perfect knowledge about its operation.

3.2 Combustion process and composition of combustion chamber

3.2.1 Combustion process

Air mass flow when discharged from compressor enters the CC at velocity of around 150 m\s − far too high to sustain a flame for combustion. What is required in the first place is a slowing down of the airflow. This is achieved in the forward section of the CC which is formed as a diffuser. Air flow at diffuser discharge is 40 m/s which is too high to ignite the air/fuel mixture, because for orderly kerosene/air mixture burning flow velocity must be diminished down to a few meters per second. So special arrangements must be done in CC to form the zone with low airflow velocities. This will provide reliable combustion at all engine operating modes.

Entering CC, the airflow is split by the **combustor dome** into two flows. "Primary air" (25...40% from total airflow) enters the flame tube and is mixed with fuel to form burning appropriate fuel-air mixture (**α=**0,95 ... 1,05). By far the largest part is ducted around the internal flame tube, from where gradual admixing within the flame tube is made by mean of various-size holes arranged behind the primacy combustion zone to continue combusting big drops that need some time to evaporate. Besides, add-mixed air intensifies mixture formation and burning. Optimum distribution of primary air and places to dilute the air are experimentally assigned in special test-cells.

Swirl vanes (punched plate) of combustor dome jointly with longwise arranged holes streamlining air radially, form necessary turbulent flow inside the combustion zone. Primary air leaving the swirl vanes is mixed with the secondary air from holes to create a zone of low velocity flow circulation. Formed vortexes are torus-shaped (similar to smoke ring). They apply stabilizing effect and anchor the flame. The recirculating gases intensify burning of freshly injected fuel droplets by rapidly bringing them to ignition temperature.

Fuel nozzle sprays kerosene in a form of cone in the way to intersect the reverse flow vortex at its center. This jointly with general turbulence in primary zone serves to assist in fuel atomizing and its intensive mixing with incoming air.

Mentioned above constructive elements (swirl vanes) and design solutions (radial injection of secondary air) increase the flame stability in the combustion zone.

Being combusted fuel heats the newly formed gases to the temperature 2300–2400 K. "**Secondary air**" streamlines the flame tube at high speed (**v** = 120...150 m\s), cools it and enters into the **dilution zone** through special apertures and slots in the flame tube. There it is mixed with the combustion products, decreasing their temperature and forming uniform gas stream of the set temperature at the turbine inlet. Combustion should be completed before the dilution air enters the flame tube, otherwise boundary between combustion and dilution zones will move. This results in incomplete combustion due dilution air overcools the flame.

3.2.2 Composition of combustion chamber

Generic scheme of combustion chamber is presented in Fig 3.1. There is a **flame tube** 5 inside combustion chamber **case** 9. Flame tube limits the volume of flame and helps with arranging air supplying to combustion and dilution zones. Leaving compressor the air gets to combustion chamber, where it splits into two flows. “Primary air” enters **diffuser** 1 and decelerates. Then, primary air gets to **combustor dome** 10 formed by **swirl vanes** 3 and **fuel nozzles** 2. The “secondary air” bypasses the combustor dome and gets to the annular duct 4. From this duct air passes to the flame tube through holes in flame tube (6 − holes to deliver air to intermediate zone, 7 − holes to deliver air to dilution zone) to cool combustion products and to form uniform temperature at turbine inlet.

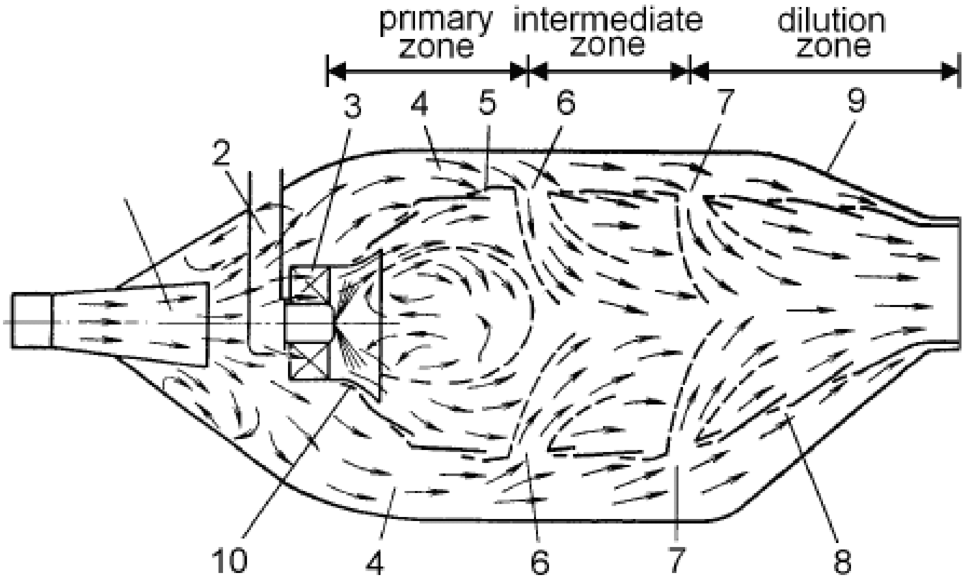


Figure 3.1 – Diagram of the combustion chamber:
1 – diffuser; 2 – fuel nozzle; 3 – swirl vanes; 4 – annular duct; 5 – flame tube;
6 – holes to feed the CC with the secondary air; 7 – holes to feed the CC with the mixing air; 8 – slot for cooling curtain; 9 – case; 10 – combustor dome

There are two ways to ***start of the combustion chamber.*** In the first case starting happens in **firing igniter** that represents a very small CC with **pilot burner** and **electrical sparking plug**; in the other case − directly by electrical sparking plug.

When CC fails to start, the fuel from inside the combustion chamber needs to be removed through the **drain valve** at the bottom of CC. This valve is opened when engine does not operate and is closed during second attempt of CC starting.

There are three zones in flame tube of CC, named for the processes that take place in each particular zone. They are primary combustion zone, intermediate zone and dilution zone.

Primary combustion zone begins at the combustor dome discharge and is applied to prepare and partially burn the air/fuel mixture. After injecting fuel the mixing process starts. Being atomized up to shallow drops, the fuel evaporates and is mixed with primary air. Then the mixture (part of mixture that is in a vapor state) is combusted in the way to stabilize the flame.

Unburnt air/fuel mixture continues burning in the **intermediate zone,** which begins downstream the primary combustion zone. Continuous secondary air admixing allows increasing of time at which gases are highly heated thus preventing of chemical reactions "freezing". These arrangements ensure maximum combustion efficiency.

Final admixing of air that does not participate in combustion process and cooling happens in **dilution zone**. Passing through series of holes or slots and being mixed with combustion products the secondary air forms the gas flow temperature at CC discharge. This flow has two basic parameters for characterizing − gas mean-mass temperature and flow non-uniformity.

Highly heated gases from CC discharge get to the first stage of the turbine. Nozzle vanes and rotor blades are cooled. Air for cooling is bleed from annular channel of combustion chamber. The value of air bleed for turbine cooling makes about 10 % from the total airflow through combustion chamber. Cooling air flow depends on gas temperature (the higher the temperature the higher air flow for cooling). Air, fuel and air/fuel mixture distribution by combustion chamber volume depends on set operating mode, size and shape of CC elements and the CC as a whole. This determines the level of CC perfectness.

Exercise 3.1

Draw in your laboratory notebook a diagram of combustion chamber; mark the combustion and dilution zones and path of the "primary" and "secondary" air.

3.3 Combustion chambers construction

CC has a very specific structure caused by necessity to meet the requirements to operating process.

3.3.1 Design schemes of the combustion chambers

Combustion chamber locates between compressor and turbine around shaft of turbocompressor (***built-in*** combustion chamber) or outside engine casing (***offset*** combustors). The last type is mostly applied for stationary GTEs. Combustor is usually designed to have an external diameter equal or a bit more than external diameter of compressor and turbine.

Classification of combustion chamber types is made according to:

- geometrical characteristics;
- direction of the gas flow;
- method of air/fuel mixture preparation;
- number of combustion zones.

3.3.1.1 By the geometric characteristics combustion chambers can be tubular (can), tube-annular (can-annular) and annular (Fig. 3.2).

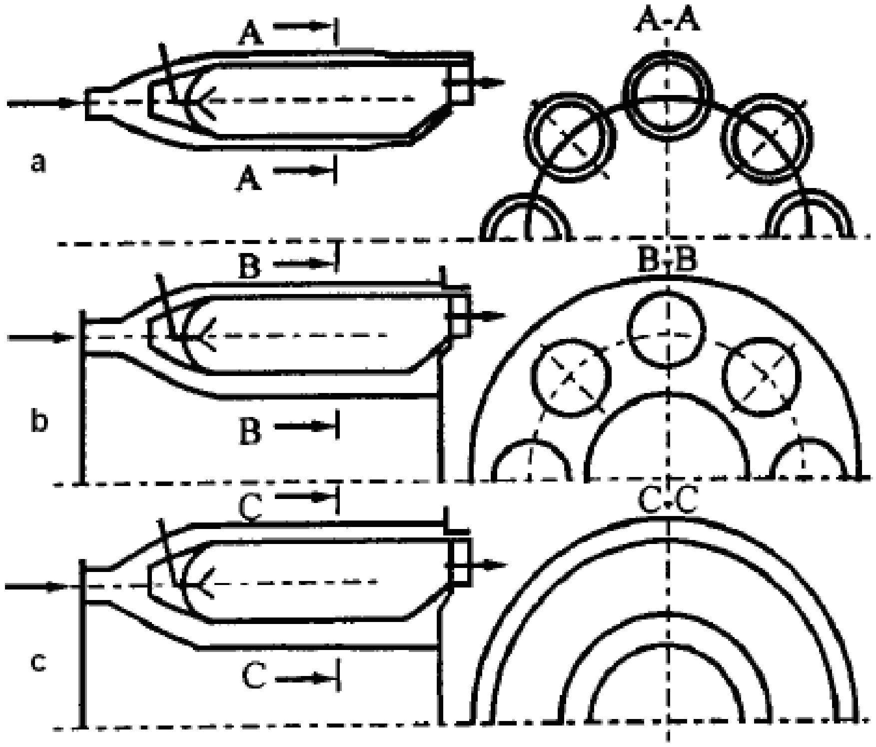


Figure 3.2 – Geometrical schemes of combustion chambers:
a – tubular; b – tube-annular; c – annular

The **tubular-type combustion chamber** (see Fig. 3.2, a) consists of single burners arranged in parallel circumferentially around the engine axis. Individual chamber in its turn has its own casing and flame tube. Burners are linked by interconnectors that enable the flame to spread to neighboring combustion chambers. The tubular combustion chambers are not included into a power (load-bearing) scheme of the engine. This chamber type is very handy in maintenance, because individual combustion chambers can be dismounted for diagnosing and overhaul and mounted back without engine disassembling. This type is found in early jet engines and did constitute a necessary step in more perfect chambers developing (annular and tube-annular). Now they are used only in land engines due to their ability for easy development in the field of emission reduction.

The **tube-annular-type combustion chamber** (see Fig. 3.2, b) consists of some flame tubes, mounted to a circular rim-like arrangement inside common case, which is one of engine load-bearing elements. Rear parts of flame tubes are linked to form a short annular duct (nozzle box). This combustion chamber type is handy for manufacturing and testing, but some parameters are worse than of annular-type chamber.

The **annular-type combustion chamber** (see Fig. 3.2, c) represents annular case which is one of the engine load-bearing elements. It has concentric flame tube inside. Fuel nozzles are arranged in concentric row (or some rows) in the CC head part.

Annular-type combustors have some significant advantages in comparison with a tube-annular. They provide more uniform temperature field at turbine inlet and more reliable engine starting. Annular-type combustor is more light (6…8 % of the engine weight), has less hydraulic resistance and requires less air for cooling purposes as at the same volume it has the least surface. The absolute majority of modern combustion chambers are annular-type.

3.3.1.2 By the gas flow direction combustion chambers can be through-flow and reverse-flow.

Leaving compressor, air enters **through-flow-type** combustion chamber (see Fig. 3.1) in parallel to engine axis and making no turnings leaves the chamber also in parallel to the axis. This chamber type has minimum hydraulic losses, which made it the most abundant for high-power engines.

Reverse-flow-type combustion chambers are components of low-power engines with last centrifugal stage of compressor. Gas flow enters the chamber at some angle to engine axis, and making two turnings leaves in parallel to engine axis (Fig. 3.3).

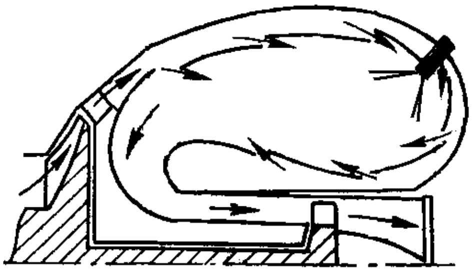


Figure 3.3 – Diagram of reverse-flow combustion chamber

Applying this chamber type allows engine shortening by compressor shortening and placing the chamber above the turbine. A beneficial feature of the reverse-flow-type chamber is significant decreasing of a flame acting the turbine nozzle box. Besides, this chamber type provides free thermal expansion of the flame tube without a special slip joint. However such chamber type is applicable only for engines without radial limitations. Significant disadvantage of the reverse-flow combustors is a high level of hydraulic losses. They are used in auxiliary powerplants and low-power GTEs (to power small aircrafts, helicopters, UAVs and land transport).

3.3.1.3 By the method of the fuel/air mixture preparation combustion chambers may use internal and external mixing.

Chambers with **internal mixing** are equipped with fuel nozzles that inject the fuel in liquid state. This is a conventional scheme used in majority of aircraft turbine engines.

External mixing happens in carburetor with further air/fuel mixture supplying to combustion chamber in vapor state. Prior to be combusted fuel is heated up to vaporizing. This combustion chamber type is perspective for radical lowering of harmful emission. But contradictory limitations for combustion chamber operating at starting and other modes, danger of flame propagation to carburetor and its cocking made this chamber type to be restricted for aircraft.

3.3.1.4 By the number of combustion zones combustion chambers can be: one-zonal (conventional) and two-zonal. There are two combustion zones arranged in parallel (double deck CC) or one by one in combustion chambers. One zone operates optimally at idle mode, another one − at other modes. These schemes are perspective for reducing emissions (engine GE-90-94B, airplane Boeing 777-200ER).

3.3.2 Power links in combustion chambers

At turbine engine operation the forces and moments of forces are affixed on its separate units and components. Some forces acting a component, originate internal forces that equilibrate them (for example, flame tubes of combustion chambers). But most of forces cannot be equilibrated inside the engine component; that results in their propagation on other components causing the corresponding stresses. Resultant force that represents the sum of all unequilibrated forces travels to the air frame in a form of thrust.

Loads acting combustion chamber differ by their nature:

- **gas-dynamic** which appear because of gas pressure acting structure elements and flow velocity changing in a gas path;
- **thermal**, stipulated by temperature gradients inside;
- **inertia**, originating during airplane maneuvers, and also during takeoff and landing.

Half much as engine thrust axial force acts combustion chamber in compressor side. Each engine requires power links to transfer all unbalanced forces and moments of forces from inside the engine to airframe of aircraft during operation. A totality of power links forms the engine power structure.

The outer casing of annular and tube-annular combustion chamber always is a power link of power structure of engine casing. Gauge pressure of air results in the tensile stresses in outer casing. Internal casing is usually loaded with air gauge pressure, present in a cavity of the combustion chamber. This load results in compression strains. Therefore in order to increase the hardness and prevent blocking, combustion chamber walls are strengthened by stiffening ribs (frames) welded to their external surfaces.

All possible power links in combustion chamber may be arranged in three groups (Fig. 3.4):

- power structure with external and internal casings linked in a zone of turbine nozzle box and in a front part, at compressor discharge;

– power structure with external and internal casings not linked in a zone of turbine nozzle box;

– power structure with external case is the only power link used.

3.3.2.1 Power structure with outer and internal combustor cases, linked together in a zone of a nozzle box of the turbine and in a forward part, at the compressor discharge

This power scheme (see Fig. 3.4, a) mostly suits to engines with rear bearing arranged upstream first stage of a turbine. Due to radial links of outer and internal casings the power system represents a rigid and light construction. The axial force transfers from rotor to outer casing through flow-straightening vanes 1. Gas forces acting nozzle vanes of the first stage are taken in equal share by inner 2 and outer 3 casings. Gas forces of other turbine stages are taken by only outer casing. As this power structure is self-contained, a special attention must be paid to the problem of free thermal expansion of components that form external and internal links.

3.3.2.2 Power scheme with outer and internal combustion chamber casings not linked together in a zone of nozzle box

Such power structure (see Fig. 3.4, b) suits engines with annular combustion chambers, where rear rotor bearing cannot be arranged upstream the turbine.

The external loads are distributed between external and internal combustor casings as follows. Gas-dynamic forces acting nozzle vanes of all turbine stages are taken by inner and outer casings same distributed between external and internal cases same as was described for previous power structure (see Fig. 3.4, a). If a rear support is arranged upstream first stage of turbine, acting rotor forces bend the internal casing same to cantilever beam. In case if rear rotor support is arranged downstream first turbine stage all forces are taken by an external casing.

3.3.2.3 Power structure with only external power case

This power structure (see Fig. 3.4, c) suits TFE with rigid two-support rotor of gas generator, engines with short nozzle vanes of first turbine stage and engines

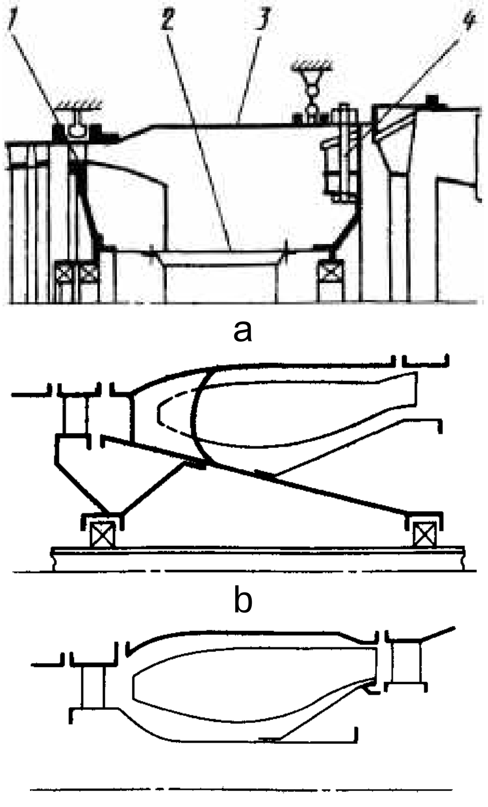


Figure 3.4 – Power schemes of combustor casings:
a – with power external and internal casings; b – with cantilever internal case, not linked to outer casing in a zone of the turbine nozzle box;
c – with only external power casing

with high turbine inlet temperature. The marked features do not allow radial linking of chamber cases. Linking of cases is made in front part of the chamber. Front link elements transmit only forces (inertia and gas-dynamic) from internal casing to the external one. There are no supports upstream first stage of turbine and downstream the compressor. Thus, external casing of combustion chamber takes all loads from turbine due to high hardness obtained by placing the casing at big diameter. Such power structures are applied for short-rotor lift engines and for engines with significant internal volume of CC.

Flame tube can not be power link, because when operates it is heated and needs the freedom of thermal expansion to prevent thermal stresses originating. Therefore flame tubes are mounted in combustion chamber casings in the way to allow free thermal expansion.

Exercise 3.2

Classify combustion chambers of engines situated in the room by constructive features and the way power elements are linked.

3.3.3 Elements of combustion chamber

3.3.3.1 Burner casings

Casing is a tube-like construction with flame tubes inside.

The casing is the most loaded element of combustion chamber. Casings are power links forming power structure of engines with annular and tube-annular chambers. The main load acting casings is the air gauge pressure inside the chamber.

The burner casing consists of external and internal cylindrical (conical) shells. These shells are linked together by power ribs close to diffuser (see AI-25 turbofan, poster №7). The considered elements form a cavity, to place flame tube inside.

The outer casing consists of front and rear flanges and shells welded together. Outer casing is also applied to fix fuel nozzles and igniters (see posters of combustion chambers), to pin flame tubes and to mount the drain valve needed to remove a fuel from inside combustion chamber in case of unsuccessful starting.

Burner casing is usually welded from heat-resistant cobalt and nickel-based alloy (Х18Н9Т, ВЖ102). Width of burner walls is 1 … 1,5 mm.

3.3.3.2 Diffusers

Diffuser is a front part of combustion chamber, designed in a form of divergent duct to decelerate the airflow coming from compressor discharge.

Aircraft engines have air speed at the compressor discharge close to 150 m/s which is too high for fuel combusting, not only because of problems with burning stability but also because of the greater total pressure losses. Summing up all above mentioned, the mission of the diffuser is to decelerate the airflow and to reduce pressure losses up to acceptable values.

Except main mission (slowing down the air) diffuser must deliver air to annular ducts at minimum pressure losses and to create a steady uniform velocity field at a flame tube inlet at all operational conditions.

Stationary GTPPs with “single-mode” engines have combustion chambers with long **smooth contoured wall diffuser.** This diffuser type provides minimum pressure losses during air deceleration. **Isograde diffuser** (Fig. 3.5) is a diffuser with constant gradient of pressure changing along diffuser length: dp/dl = const.

The following equation is used to profile this diffuser type:

$$F_i = \frac{F_d}{\sqrt{1+\left[\left(\frac{F_d}{F_c}\right)^2 - 1\right] \times \frac{l_d - l_i}{l_d}}}, \quad (3.2)$$

where ℓ_i и F_i – the distance from diffuser entrance to current station and the cross-sectional area of the station;
F_d – area of the diffuser discharge station;
F_c – area of the compressor discharge station;
ℓ_d – diffuser length.

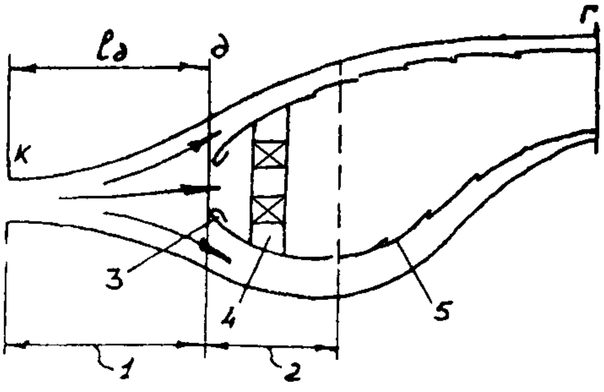


Figure 3.5 – Diagram of isograde diffuser:
1 – diffuser; 2 – diffuser with a central body; 3 – cowls creating air scope; 4 – combustor dome; 5 – flame tube

Head loss factor of the isograde diffusers is ξ_d = 0,1...0,35.

Engine operation at different modes is associated with the problem of various airflow velocities and pressures at CC inlet. To solve this problem diffusers are designed **dump**. This diffuser type (Fig. 3.6) allows steady diffuser operation at all modes and its length reducing.

Deficiency of such diffusers is the origin of extra pressure losses because of non-uniform velocity profile at any station downstream a breakoff point.

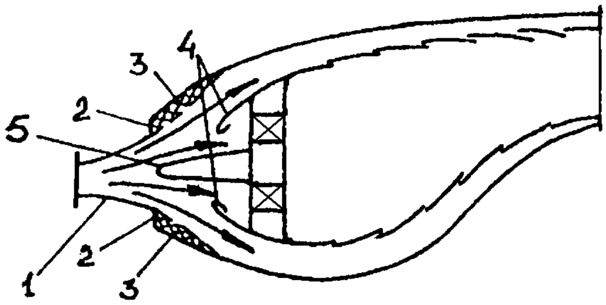


Figure 3.6 – Diagram of dump diffuser with stabilization of flow separation zones:
1 – diffuser; 2 – steps; 3 – flow burbling zones; 4 – flame tube cowls; 5 – screen for a skid of flow in a diffuser

To make the diffuser as short as possible the angle of divergence is designed as big as possible, that may result in flow separation from diffuser wall. To prevent this harmful phenomenon the aerodynamic screen 4 (see Fig. 3.6) is applied which partially changes a shape of stream-lines by “pressing” them to walls. As a result the extreme possible expansion ratio of a diffuser $\mathbf{n_d = F_d/F_c}$ rises.

Further development of diffusers with stabilized flow separation is the **diffuser with sudden expansion** (Fig. 3.7).

This diffuser is two-staged. Flow initially decelerates in pre-diffuser duct 2 (first stage). The duct is optimally shaped to get the given expansion ratio at minimal hydraulic losses and as uniform as possible flow velocity at discharge station. Further (second stage) deceleration occurs downstream solid wall of diffuser end in divergent duct formed by gas already present in stagnant zones 4.

The second stage of air diffusing gives some benefits in diffuser operation:

- there are practically no hydraulic losses during the second stage;
- dilating stream is divided by an air scope of the combustor dome on three parts – first one enters the combustor dome and two others enter corresponding annular ducts; at change of hydraulic resistance in these ducts the jet segment 3 automatically redistributes airflow between them making practically no additional losses;
- sizes of the stagnation zones 4 can be increased by designing combustor casings cylindrical (dotted line 6 in a Fig. 3.7) without changing flow pattern and total hydraulic losses of diffuser.

The head loss due to friction may reach values **ξ_d = 0,4...0,45**, but only when throughput capacity of the combustor dome and its air scope are coordinated.

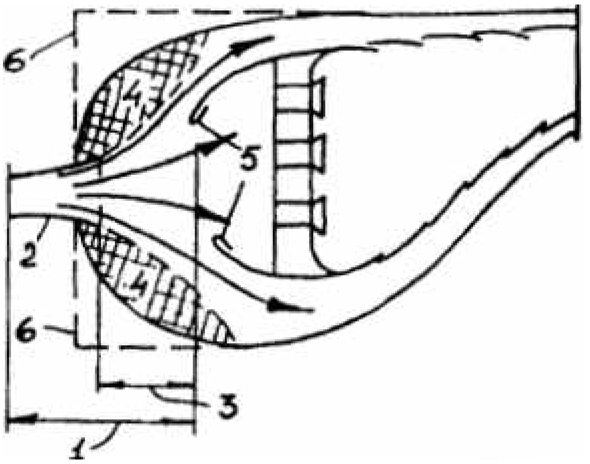


Figure 3.7 – Diffuser with sudden expansion (channel-jet diffuser):
1 – diffuser; 2 – pre-diffuser (channel segment); 3 – jet segment; 4 – stagnant zones; 5 – cowl of flame tube, realizing as an air scope; 6 – range of the combustor casing's shape possible variation

Modern turbine engines have combustors providing high turbine inlet temperatures. They are designed to supply more air to combustor dome. That entails increasing transversal sizes of the flame tube frontal part. Under these conditions only channel-jet diffuser can ensure reasonable hydraulic losses at small length and rapid changes in streamlines conFiguration. Therefore this diffuser type is of priority for modern and perspective combustion chambers.

Presence of power racks, pipelines and other structural elements in diffuser gas path results in additional pressure losses and increased non-uniformity of velocity field at flame tubes inlet and complicates the combustion chamber operational development.

Therefore if diffuser cannot escape power racks presence in its gas path than the racks are placed inside hollow struts or covered by screen to provide streamlined shape of diffuser. There is possible to improve the diffuser's aerodynamics by bleeding or blowing off the boundary layer. Bleed air can be utilized for cooling turbine blades and other components.

The combustion chamber of the engine AI-222 has a dump diffuser with intake tube of deicing system fastened to back flange of the diffuser (see the drawing of AI-222 turbofan).

Exercise 3.3

Compare diffusers of combustion chambers of engines located in the room. Draw sketches of diffusers of the D-36 and AI-25 turbofans.

3.3.3.3 Flame tubes

Flame tube is a shell, mounted inside annular duct of CC, where air/fuel mixture combustion takes place.

Front part of the flame tube forms the combustor dome (see section 3.3.3.4). Lateral surfaces of the flame tube are covered with series of different-size holes, drilled for progressive admixing of air to combustion zone, intermediate zone and dilution zone. Correct holes positioning provides necessary air distribution between zones and along each zone. Secondary air enters flame tube dispersedly to prevent local overcooling of combustion products.

Radial distribution of turbine inlet temperature needs correct choosing of number, location and diameters of holes.

Opposing to combustor casings, the flame tube is never used as a power link. It takes only load from rather small pressure difference. Nevertheless, flame tubes operate in very difficult conditions, as the process of combustion occurs at high temperature with oxygen. High temperature gradients with thermal loads at start, shut-down and change of engine power setting originate large thermal stresses in flame tube components. Presence of unburnt oxygen at high temperature – to gas corrosion and even in walls burn-through of walls. Safe operation of a flame tube determines the safety of the combustion chamber as a whole.

Safe operation of the flame tube needs considered below design and technological means:

1. ***Flame tubes are not used in engine power structure.***

Therefore the flame tube is fixed inside a combustor casing in both axial and radial directions.

The flame tube wall is heated by flame up to temperature 600…900°C and higher, while casing has lower temperature. Therefore the combustion chamber has the structure for providing free thermal expansion of a flame tube in both axial and radial directions. Besides it is necessary to take into account possible distorting of a flame tube shell (especially for annular CC).

Freedom of axial thermal expansion is ensured by manufacturing the flame tube of two separate parts (first is the flame tube itself and second is gas collector fastened to nozzle box).

Exercise 3.4

Draw a scheme of flame tube fixation in AI-25 turbofan (see poster № 7). Attract in your report specific features of fixation the flame tubes of D-30 turbofan and R11F-300 turbojet.

2. ***Flame tubes design from separate single-piece parts***, joined among themselves by welding. The sectional construction of flame tubes increases their hardness and facilitates placement of elements providing supplying and direction of the cooling air. The workpiece is a thin-walled sheet material.

For decreasing temperature stresses separate sections of the flame tube joint among themselves elastically; that is provided due to numerous cuts executed on sections along generatrix (so-called "expansion joints"). The cuts finish by holes reducing stress concentration. Diameter of each hole is little bit more than width of a cut (Fig. 3.8).

3. ***Walls of the flame tubes protect from heating on the flame side***. This is achieved by a film of cooling air flowing along the inside surface of the flame tube wall, insulating it from the hot combustor gases. This air passes the flame tube from the ring channels between the combustor casing and the flame tube (Fig. 3.9).

To increase efficiency of the film combined cooling a length of section of a flame tube is decreased up to $\mathbf{L_{cool} = 12…15}$ **mm** at a slot size $\mathbf{h_v = 1,0...1,5}$ **mm**. The holes for cooling air are made of low diameter **d = 0,8 ... 1,2 mm**, and relation of pitch between holes to their diameter is **t\d = 1,5….2**. Length of a visor **(L_v)** is to be not less then 2,5…3 of a slot size.

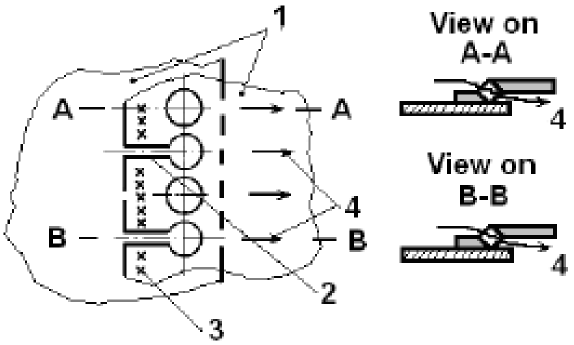


Figure 3.8 – Elastic connection of the flame tube sections:
1 – sections of a flame tube; 2 – cuts – «thermal seams»; 3 – weld seam;
4 – jets of a wall air veil

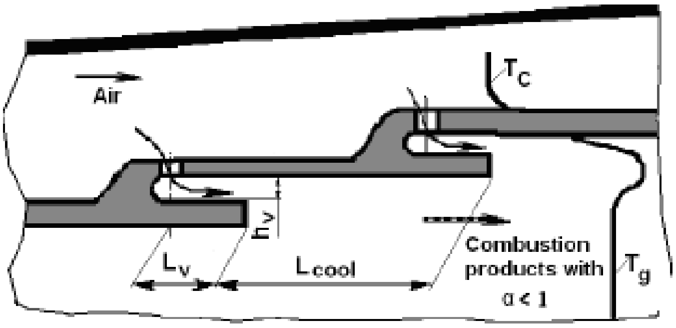


Figure 3.9 – Diagram of the jet combined (film-convex) cooling of the flame tube

Supplying the air through holes guiding it along an internal surface due to a declination of axes of holes and visors is shown in the poster № 9. Some constructions of devices ensuring convective and barrage-film cooling external and internal surfaces of flame tubes there are shown.

Increasing heat rejection by means of longitudinal ribs located on outside surface of the flame tube, is applied rather seldom, that is explained by small efficiency of convective cooling as contrasted to film, and also increasing mass and complexity of manufacture of a tube.

Researches new more effective systems of cooling such as film and punched cooling with forced-circulation (see poster № 10) now are carried out.

4. ***The edges of holes for supply a secondary air inside of the flame tube are intensively cooled by passing air***, owing to what on small distance from edge of hole there is a considerable differential of temperatures causing temperature stresses in a wall. This phenomenon promotes origin of considerable temperature stresses frequently resulting in to cracks and damages of flame tubes. Edging holes by **cups** 2 (Fig. 3.10, a) reduces this temperature differential, as the cup precludes with heat removal from edges of a hole. To heightening hardness of the holes edges apply their ***attachment*** 3 with a consequent blunting and polishing ridges (see Fig. 3.10, a).

The depth of secondary air penetration in a cavity of the flame tube can be increased by moving shear of hole inside of tube by means of slotted branch pipe (Fig. 3.10, b). A deficiency of such construction is the often flash-off or burnout of branch pipes. The construction of branch pipe ensuring cooling its leading edge by specially supplied air (see a Fig. 3.10, b and poster № 8) is applied to eliminate the specified defect.

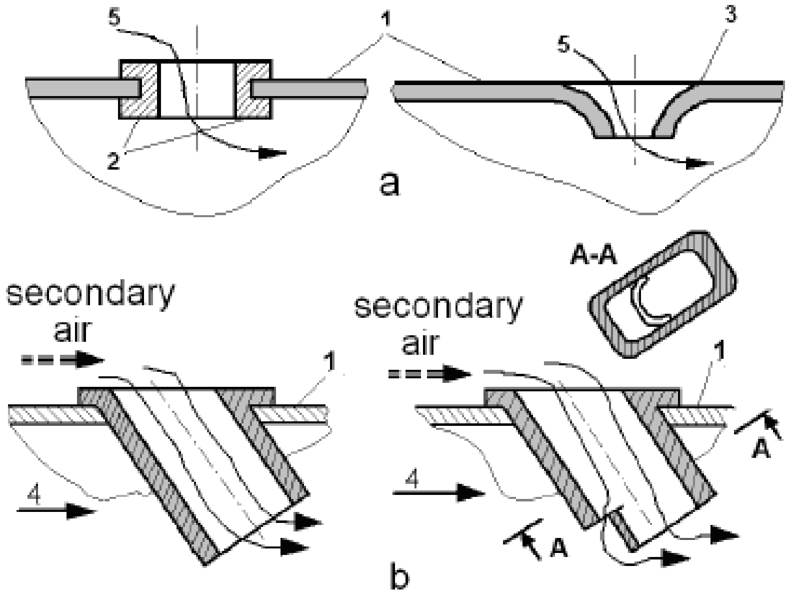


Figure 3.10 – Elements of the flame tube:
a – edging by a cup (at the left) and attachment (at the right); б – slotted brunch pipes: conventional (at the left) and with protection of front edges from burnout (on the right); 1 – wall of the flame tube; 2 – cup; 3 – ending; 4 – gas flow; 5 – secondary air flow

Exercise 3.5

Using posters of combustion chambers and mockups of engines, study cooling systems of flame tubes and organizing dilution air supply. On engines AI-20, AI-25 and D-36 study development of constructive elements of a flame tube. On engines AL-7F and VK-1 look at ending holes and attachment of cups. Using posters 9, 10, draw sketches of the elements of the flame tube.

5. ***For manufacturing flame tubes the high-quality heat-resistant and high-temperature capable nickel-chromium alloys are applied*** (Х20Н80Т, ХН75МБТЮ, ХН38ВТ, ХН60В, ХН70Ю, Х25Н16Г7АР, Х24Н25Т). For flame tubes operating at temperature 900^{o}C may be used alloys Х20Н80Т, ХН75МБТЮ, ХН38ВТ, at temperature 900…1000^{o}C – ХН60ВТ. These alloys have high strength, stability to gas corrosion, good resistance for vibrations, ensure sufficient ductility, ease of an extrusion, hauls, inflection both welding. Chemical composition and strength properties of heat-resisting alloys used for manufacture of flame tubes of combustion chambers of modern turbine engines are listed in the Table 3.1.

Table 3.1 – Properties of materials used for manufacturing the flame tubes

Material name	ХН60ВТ ВЖ105 (ЭИ-868)	ХН60ВТ ВЖ98 (ЭП -718)
Chemical composition, %	C≤0,10; Si≤0,4 Mn≤0,8; Cr=14-16,5; Ni=43-47; Ti=1,9-2,4; Mo=4-5,2; Al=0,9 -1,4; W=2-3,5; Nb=0,8 -1,5; B≤0,008; Zr≤0,02; Cl≤0,1; S≤0,01; P≤ 0,015.	C≤0,10; Si≤0,8 Mn≤0,5; Cr=23,5-26,5; Ni=base; Ti=0,3-0,7; Al≤0,5; W=13,0-16,0; Fe≤4,0; S≤0,013; P≤ 0,013.
t_{oper}, ^{o}C	up to 700	900-1000
α, 1\\$^o$C	$14,5\cdot10^{-6}$ (20-600 ^{0}C)	$16,2\cdot10^{-6}$ (20-900 ^{0}C)
σ_l^{20}, MPa	1150	750-900
$\sigma_{0,2}^{20}$, MPa	700	No data

6. ***Internal walls of the flame tube cover with layer of high-temperature enamel coatings***. Such coating with low thermal conductivity ensures lowering of wall temperature due to heat-insulating properties and fractional reflecting radiation from yields of combustion. For typical conditions of CC operation a ceramic coating by width of 1 mm with a heat conductivity α = 0,66 W\(m K) ensures lowering temperature of the wall on 100 K. Besides the enamel coating protects metal of the flame tube from oxidation at high temperatures. So the enamel such as ЭВ-55 is applied to alloy ХН60В which principal components are dioxide of silicon and oxide of chrome (due to last the enamel has green color). The high-temperature enamels considerably deceler-

ate oxidation of metals at heightened temperatures. So the coating ЭВ-55 decreases oxidation speed of alloy 1Х18Н9Т in 6–8 times. Essential deficiencies of enamel coatings are their low thermal stability and shock strength.

During maintenance of combustion chamber the enamel coating is completely or fractionally outworn because of erosive ablation by gas stream, but can be reduced by secondary deposition at the engine repair.

Exercise 3.6

List in your notebook studied engines in which the enamel coating of a flame tubes is used.

7. ***Careful checking of each operation of technological process*** of the flame tube manufacture is provided.

8. For connection of separate elements of flame tubes a ***riveting with special adapters, or welding*** is applied (electro-contact, argon-arc, electron-beam).

3.3.3.4 Combustor domes

Combustor dome is inlet part of the flame tube in which fuel supplying tools and channels for supplying air to initial area of combustion are placed.

The combustor dome doses a quantity of primary air going to combustion zone, and organizes the initial preparation of a fuel for combustion (its spraying, vaporization and mixing with air), and then ─ steady and complete combustion of fuel by forming zones of reversed flows. The combustor dome includes the unit of **burners** located uniformly on a circle in a forward part of the flame tube. Each burner has **flameholder** and **diffuser**; in its center the **fuel nozzle** is placed.

In already made combustor domes meet mainly three types of flameholders:

- *blade* (swirl vanes);
- *jet* («grater» type);
- *conical* (based on effect of a flow stall).

The **swirl vanes** represent a circular airfoil installed between two concentric rings (Fig. 3.11). The fuel nozzle is placed into internal ring, and by external ring the vortex generator fastens to a forward wall of the flame tube. The air passing through swirl vanes is twisted and rejected to walls of the flame tube, owing to what the pressure in its central part is depressed. Due to pressure difference a reversed current of air and gas on axis of the chamber is originated.

The blades of swirl vanes can be made shaped or straight lines. In swirl vanes with airfoil-section blades the bulkhead channels for air are designed of variable cross-section: a large sectional area on input and smaller ─ on exhaust. In swirl vanes with straight blades the area of a flow is constant.

Swirl vanes usually design with number of blades 8─12. With further increase of number of blades the flow pattern varies a little, and the hydraulic resistance increases. The angle of blades installation lies within the limits 45…65°.

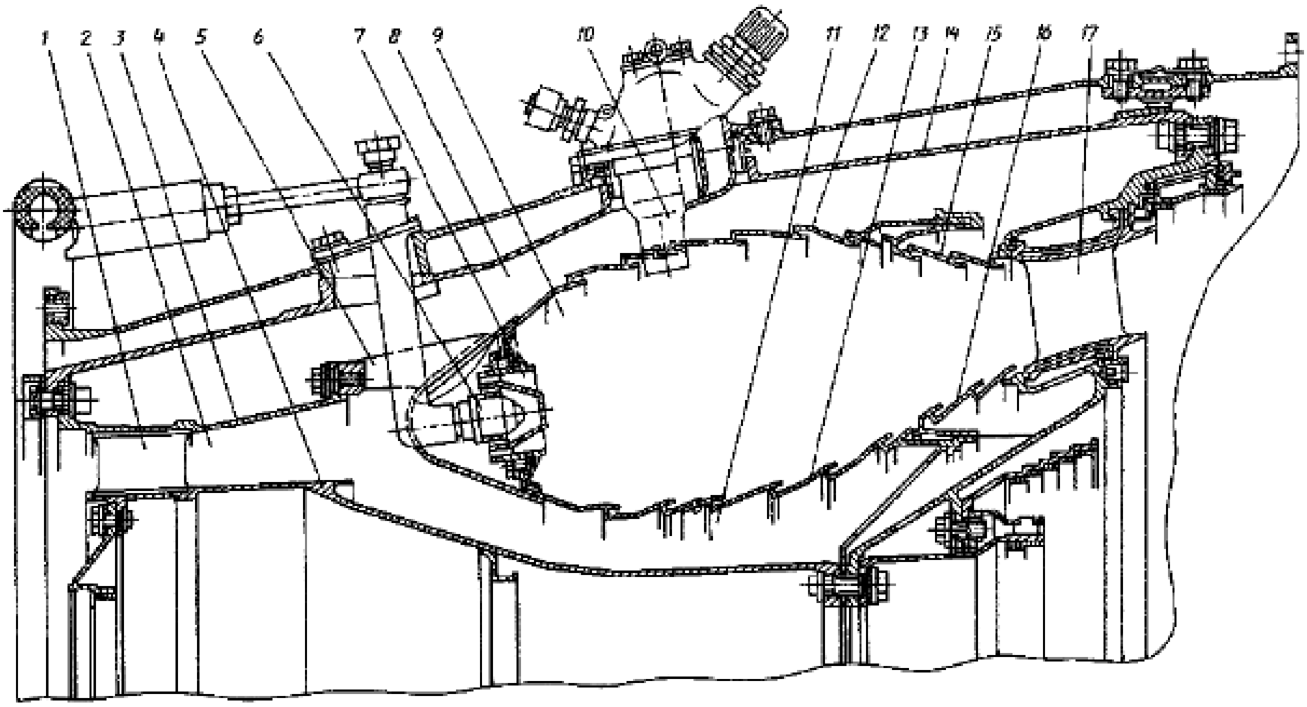


Figure 3.11 – Combustion chamber of the engine D-18T:
1 – compressor strengthening vanes; 2 – diffuser; 3 – outer wall of diffuser; 4 – inner case; 5 – bracket; 6 fuel nozzle; 7 – combustor dome; 8 и 11 – outer and inner ring channels; 9 – flame tube; 10 – starting igniter; 12 и 13 – inner and outer walls of the sectional flame tube; 14 – outer case; 15 и 16 – outer and inner sections of the gas collector; 17 – turbine nozzle box

With increasing the installation angle the diametric size of the zone of reversed flows is augmented, total pressure losses in a chamber however increase (see combustion chambers of the engines D-30, AL-7 and the poster № 3).

The **jet flameholder** represents a great number of small holes or slots, situated in a head of the flame tube (Fig. 3.12, b). The area of holes is rather small as contrasted to cross-sectional area of the flame tube; therefore running jets of air create underpressure in center of the flame tube with formation of the zone of reversed flows, which ensures stabilization of flame (see CC of the engine AI-20, poster № 13).

Conical flameholders operate as bluff bodies. If the bluff body is placed in airflow, behind it the zone of vortex generation, separated flows and reversed flows are formed.

In conical stabilizer (Fig. 3.12, a) the air flow goes in annular space and burbles as ring vortexes. With the help of vortexes underpressure and zone of backflows are formed.

Distinguish combustor domes equipped with fuel nozzles which spray fuel directly in a zone of reverse flows, and combustor domes in which fuel is previously immixed or sprayed in some of air before mixture supplies in a cavity of the flame tube.

The combustor domes of the first type (with swirl-type flameholders) are widely applied in combustion chambers since the first turbine engines. The example of their design is shown in Fig. 3.11. The combustion chambers with such combustor domes steadily operate in a broad band of air-fuel ratios α and flow velocities; they also have satisfactory starting performances.

However a number of essential deficiencies are proper in them which in the greatest measure are shown in the schemes such as "grater" type (see Fig. 3.12, b), namely:

- heightened propensity to distorting;
- high level of smoking;
- high density of a thermal radiation of flambeau on walls of the flame tube;
- unsatisfactory emission performances.

The marked deficiencies in combustion chambers of modern engines were eliminated by different means:

- application of burners with preliminary aeration of a fuel flambeau by primary air and minor leaning of a primary zone;
- application of burners using kinetic energy of the filling air flow for fuel spraying due to what a mixing at operational modes with small pressure drop on nozzles is improved (AI-20). This method of a fuel-air mixture preparation in the majority of combustor dome schemes is combined with preliminary warm-up and evaporation of fuel part (CC of the engine D-36, poster 8; CC of the engine NK-8-2, poster 11).

Schemes with pneumatic spraying (due to use of the energy of ram airflow) allow realizing lowering pressure in a fuel supply system. However a range of stable combustion in chambers with such combustor domes as a rule, appears by narrower than in chambers without premixing fuel with air.

The combustor domes, in which tfuel goes into a cavity of the flame tube in completely vaporized view, are termed **vaporizing**. In such devices fuel and air are supplied to a special **vaporizing tube** placed at flame. The fuel-air mixture is heated up from a wall of the tube up to temperature exceeding boiling point of the heaviest fraction of hydrocarbons and effuses from it as a mixture of vapor and air (Fig. 3.12,c and the combustion chamber of the engine RB-199, poster 14).

Vaporizing combustor domes have the next advantages:

- smaller formation of nitric oxides and soot due to preliminary mixing fuel and air in evaporative tubes;
- low pressure head in a fuel supply system;
- practically invariable uniformity of fuel distribution in combustion zone at change of its consumption (as contrasted to by distribution for a centrifugal dual injector) and, hence, constant field of the gas temperature on exhaust of combustion chamber;

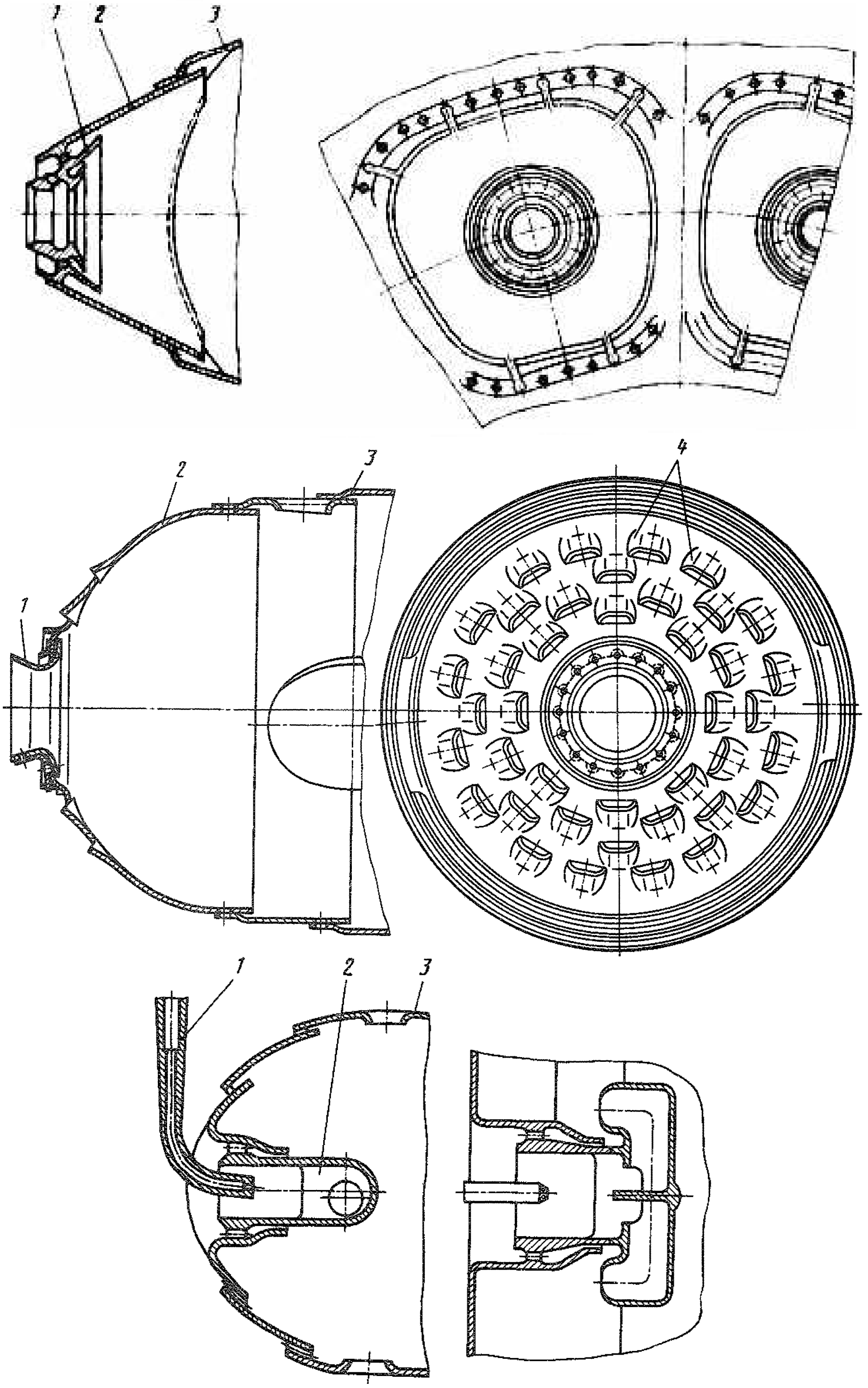


Figure 3.12 – Combustor domes:
a – with conical stabilizer (engine AI-25);1 – conical stabilizer; 2 – head; 3 – sections of a flame tube; б – with slot head (engine AL-21F); 1 – sleeve; 2 – head; 3 – section; 4 – slots of a “grater” type; в – evaporative type (engine «Olympus» Мк-602-610); 1 – jet nozzle; 2 – evaporative tube; 3 – flame tube

– simplicity and low cost (as contrasted to by combustor dome with centrifugal dual injectors).

However evaporative combustor domes have a number of essential deficiencies:

- narrower than for injector devices, range of stable combustion;
- relatively heightened emission of yields of poor combustion on idling modes;
- impossibility of the combustion chamber start directly from a sparking plug (for heating an evaporative tube a firing torch igniter will be utilized);
- poor start of the chamber in high-altitude conditions owing to low combustion efficiency on windmilling;
- low durability of evaporative tube located in the combustion zone.

Number of burners in the combustor dome select sufficient to ensure reliable propagation of flame from a source of ignition to all other burners and solid ring flame front. With increase of number of burners a length of a flambeau formed by burners of the smaller sizes is decreased; thus required length of the combustion chamber is decreased too. Reliability of a flame transmission from sources of ignition to all burners at start of the chamber is improved. Circumferential non-uniformity of the turbine inlet temperature field is decreased. In executed constructions of the gas turbine combustion chambers the number of burners reaches 10…140. Observable tendency to number of burners increasing and a fuel-air mixture leaning restrains because of a contraction of stable combustion range on lean mixture, lowering operation reliability of sprayers because of their small size, complicating a system of fuel distribution and manufacturing complexity increasing.

Exercise 3.7

Compare combustor domes of the studies engines and draw a sketch of the combustor dome of the engine D-36 using poster 8.

3.3.3.5 Fuel nozzles

Fuel nozzle is a device for supplying and spraying the fuel in the combustion chamber.

Decomposition of a continuous jet of a fluid on drops is appreciably stipulated by relative velocity between fuel and air, which can be formed by two ways:

- flowing the high-speed jet of fluid into a slowly moved or fixed air;
- streamlining the slowly moved fluid by the high-velocity air flow.

Nozzles operating on the first way are termed **mechanical**, and on the second one - **pneumatic**. To group of mechanical belong **centrifugal**, **rotated** and **spray nozzles**. In so-called **aero-nozzles** both ways of spraying are combined.

From mechanical nozzles the broadest application in a turbine engine was found by **centrifugal nozzles**. In such nozzles the fuel is effective sprayed by centrifugal forces. The principle of operation of the centrifugal nozzle consists of the following (Fig. 3.13, poster 3).

The fuel under a pressure goes on a ring channel of the nozzle body 1 in the twisting chamber, restricted by walls of cover 2 and nozzle-vortex generator

3, through tangential holes 6, providing intensive twist to fluid flow. Under action of centrifugal forces the fuel nestles on walls of the chamber, and in its axial part the air vortex is formed. The rotated fluid outflows through a hole of nozzle as a ring film which under action of centrifugal and axial forces forms outside of the nozzle a hollow conical sheet 4, subsequently breaking up on a drop.

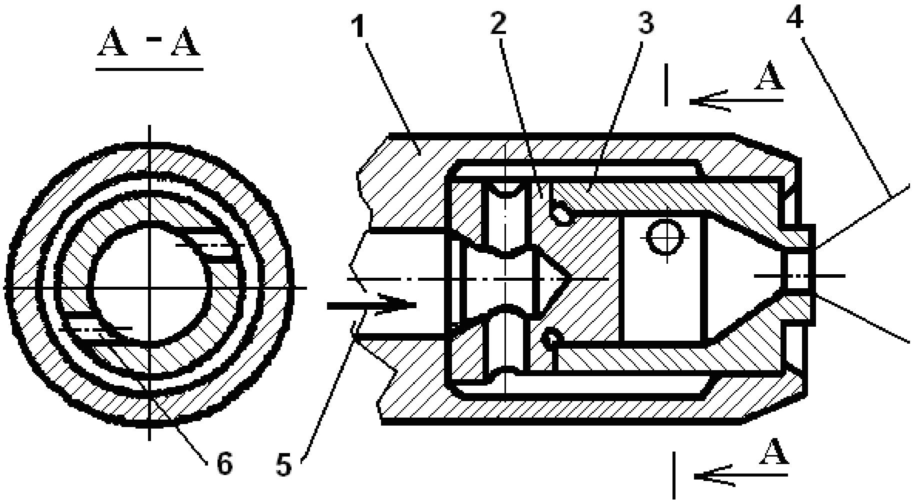


Figure 3.13 – Diagram of the centrifugal nozzle:
1 – nozzle case; 2 – cover; 3 – nozzle vortex generator; 4 – fuel cone;
5 – fuel inlet; 6 – tangential hole

These drops are mixed with primary air also making vortex motion.

Character of the fuel outflow from a **swirl-type nozzle** essentially depends on pressure difference on it. At small pressure drops on a nozzle the fuel outflows from it as unstable and random stream of drops. At increasing pressure drop the cone is shaped of the ring film of fuel. Streamwise under action of surface-tension forces this cone is subtended in a bubble again. At further increasing pressure drop on a nozzle the slugged forces begin to predominate above forces of surface-tension and bubble is opened forming a sheet of the taper which with removal from a nozzle becomes more thin and breaks up at first to thread and then on drops forming a hollow cone of aerosol.

The minimal pressure difference on a nozzle at which satisfactory quality of spraying kerosene is reached, makes approximately 100…150 kPa. For obtaining good and high quality of spraying the pressure difference assign within the limits of 6–12 MPa.

Depending on quantity of vortex chambers and nozzles the swirl-type nozzles are single-stage (single-channel, single-nozzle) and two-stage (two-channel, two-nozzle).

The main advantages of a **single-stage swirl-type nozzle** are simplicity of construction and operational development, rather low cost.

The main deficiency is large difficulties in high quality of spraying in a broad band of fuel consumption variation. It is explained that the fuel consumption through nozzle varies proportionally to square root of pressure drop on it.

Therefore at throttling the engine on fuel consumption, for example, in 40 times the pressure drop on a nozzle should be reduced in 1600 times. The elementary calculations display that at rated values of pressure difference in 6–9 MPa the same values on a minimum mode should make 4–5,5 kPa, that does not ensure even of satisfactory quality of a spraying. Elimination of this deficiency is possible at the expense of application of two-stage fuel nozzles (see below).

The second deficiency is practically constant angle of spray while it is desirable to reduce it at start.

In connection with specified deficiencies the single-channel nozzles are applied in engines of airplanes and helicopters intended for low-altitude flights with small range of fuel consumption variation.

In **two-channel nozzle** (two-stage on modes of start and idle) the fuel goes in a central nozzles having the smaller size and ensuring smaller propellant consumption, and on modes of large consumptions both nozzles operate simultaneously. Advantage of two-channel nozzles is good spraying of fuel at all conditions. Deficiency of them is a presence of the distributive valve, after which opening there is a spatial content of pipelines of the second stage nozzle manifold. This opening needs some time during which the oscillation of combustion parameters is possible.

Jet nozzles representing a cylindrical or conical metering jet are characterized with high range and small angle of spray. Therefore they are inconvenient for using in main combustion chambers of turbine engines having a rather small volume (spray nozzles will be widely used in afterburners having considerably large overall dimensions as contrasted to main chamber). In main combustion chambers the spray nozzles apply only in composition of evaporative combustor domes (see Fig. 3.12, c) and in starting igniters (see item 3.3.3.6).

In low-power turbine engines having annular reverse-flow combustion chamber, the fuel supply can be realized with the help of **rotated nozzle**. The scheme of a fuel spraying by such nozzle is shown in Fig. 3.14, and example of the design solution is shown in the poster of CC of the turbine engine GTD-3F (see also the mockup of this engine).

In modern constructions of combustion chambers the increasing propagation have the **pneumatic nozzles** with a low-pressure fuel supply system and aerodynamic (air) spraying of fuel – so-called **aero-nozzles**.

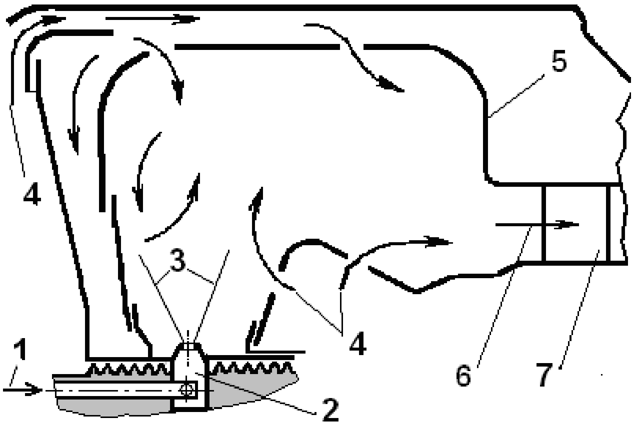


Figure 3.14 – Diagram of the loop combustion chamber with rotated nozzle: 1 – fuel supply; 2 – rotated ring nozzle; 3 – fuel spray cone; 4 – air flow from compressor; 5 – flame tube; 6 – gas stream; 7 – turbine nozzle box

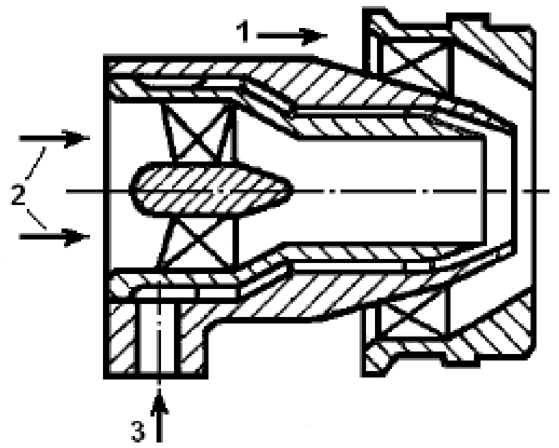


Figure 3.15 – Nozzle with aerodynamic fuel spraying:
1 – air flow throw the external swirler; 2 – air flow throw the internal swirler; 3 – fuel supply

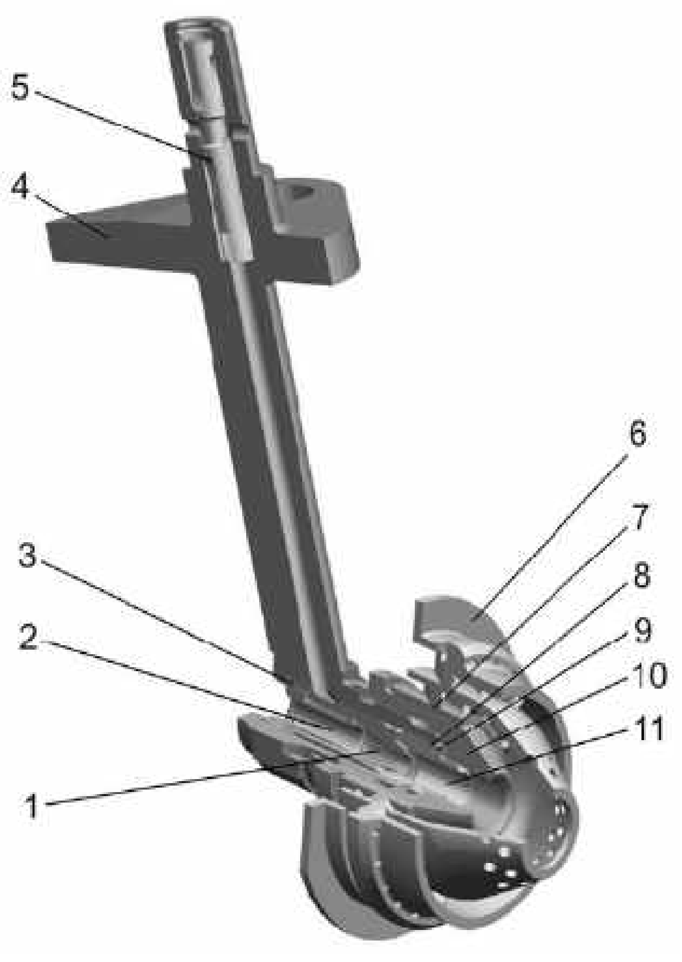


Figure 3.16 – Aero-nozzle of the combustion chamber of the TFE AI-22:
1 – sleeve; 2 – protective cover; 3 – seal ring; 4 – nozzle casing; 5 – thread filter; 6 – outer swirler; 7 – inner swirler; 8 – seal ring

In Fig. 3.15 the scheme of aero-nozzle with a double vortex generator is shown. In such nozzle a fuel film is sprayed by ram flow of air and the created aerosol moves on demarcation of airflows which are opposite rotated from vane swirlers.

In Fig. 3.16 the aero-nozzle of the engine AI-22 is shown. The fuel under rather small pressure enters aero-nozzle and through a narrow ring slot is displaced on the film-creating surface 1 of large diameter. Being broken with its end ridge, the film of fuel is blown from two sides by high-speed airflows: straight-flow (past through the central hole 2), and twisted (past through the internal vortex generator 7). Due to such ventilation the film of fuel fails on set of drops. The shallowest drops, following to streamlines of air, are carried out in primary zone of the CC, and larger - collide with the internal wall conical muzzle 3, also forming on it a liquid film. Consequent drops, falling on a wetted surface, are partly immersed by it and, besides "beat out" from it secondary (more shallow) drops, which are carried out by air flow in primary zone of CC. Again formed liquid film, escaping end ridge of the conical nozzle 3, exposes to bilateral multi-directed action: from inside acts the airflow, twisted by outside vortex generator, and from outside acts the deploying (due to presence of reversed flows zone) stream of yields of combustion. As a result the padding set of shallow drops is formed. Such multiphase fuel spraying promotes forming of multi-disperse drop aerosol, prompt vaporization of drops, best mixing vapors and drops of fuel with air and necessary distribution them in space.

The pneumatic nozzles have a number of advantages as contrasted to by mechanical nozzles, especially in a turbine engine with a high air pressure ratio. They do not require high-pressure fuel supply and well spray it. The low pressure fuel supply systems allow considerably to increase safe life and reliability of fuel pumps and to lower a mass of aggregates that is especially important for aero-engines. Besides, owing to effective mixing of fuel with air at its pneumatic spraying the contents of nitric oxides and soot in yields of combustion are minimal. Last descends a radiation level; that is favorable for cooling of a flame tube walls. Besides, the pneumatic nozzles ensure identical fuel distribution in CC at any consumption. Therefore distribution of turbine inlet temperature at conditions with high pressure can be predicted precisely, determining fields of gas temperature at low pressure that facilitates operational development of the CC on a non-uniformity of exhaust temperature field.

Due to the mentioned above advantages the pneumatic principle of a spraying has received universal propagation in modern turbine engines.

Deficiencies of pneumatic nozzles are relatively difficult development of CC on start and stall performances in conditions of increased uniformity and leaning of the fuel-air mixture.

Exercise 3.8

Study posters of CC and mockups of engines and write in your notebook what fuel nozzles are used in the engines AI-25, TV3-117, D-36, R11F-300, AL-7F, NK-12, NK-8-2, GTD-3F. Analyze in what case the one-channel and multi-channel nozzles are applied.

3.3.3.6 Sources of ignition

For start of a turbine engine it is necessary to ignite a fuel-air mixture which is composed in combustion chamber. In GTE combustion chambers basically two types of sources of ignition are applied: **igniter plugs** and **firing igniters** of the flame type.

Now in a turbine engine instead of high-voltage electrical sparking plugs (similar to used in reciprocating engines) the special **semiconductor igniter plugs of surface discharge** (see Fig. 3.13) are applied. A power of discharge in them practically does not depend on combustion chamber pressure (in usual sparking plugs a power of discharge is proportional to square of a gas pressure). For power supply of surface discharge plugs the special rather low-voltage electrical systems with the accumulative capacitor will be utilized.

The **igniter plug of surface discharge** (Fig. 3.17) contains the central electrode 2 and external electrode 4. The electrodes are separated by the ceramic insulator 5, passing on working ("hot-fire") back of a new inch in the lamina of a semiconductor material 3. The semiconductor material facilitates ionization of air in inter-electrode interspace and break-down of an interspace by a spark from power source with rather low voltage. The important performance of the semiconductor is that its electrical resistance drops at increase of temperature. Thus when the capacitor is discharged also current begins to transit through the semiconductor, last is fast heated, ensuring ionization of an air interspace between electrodes. As soon as there is ionization, there is main discharge as an intensive arc similar to flame.

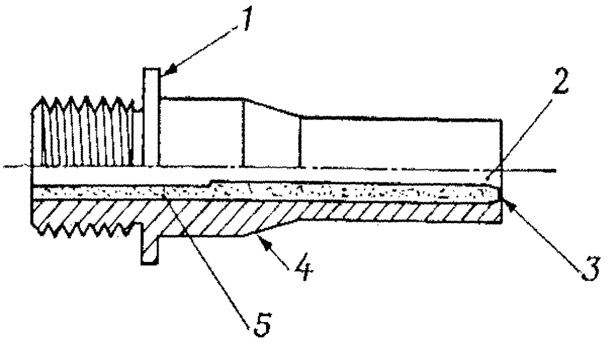


Figure 3. 17 – Surface discharge plug: 1 – mounting flange; 2 – central electrode; 3 – semiconductor; 4 – external electrode; 5 – insulator

The implemented range of energy of igniter plugs electric discharge makes 1…12 J.

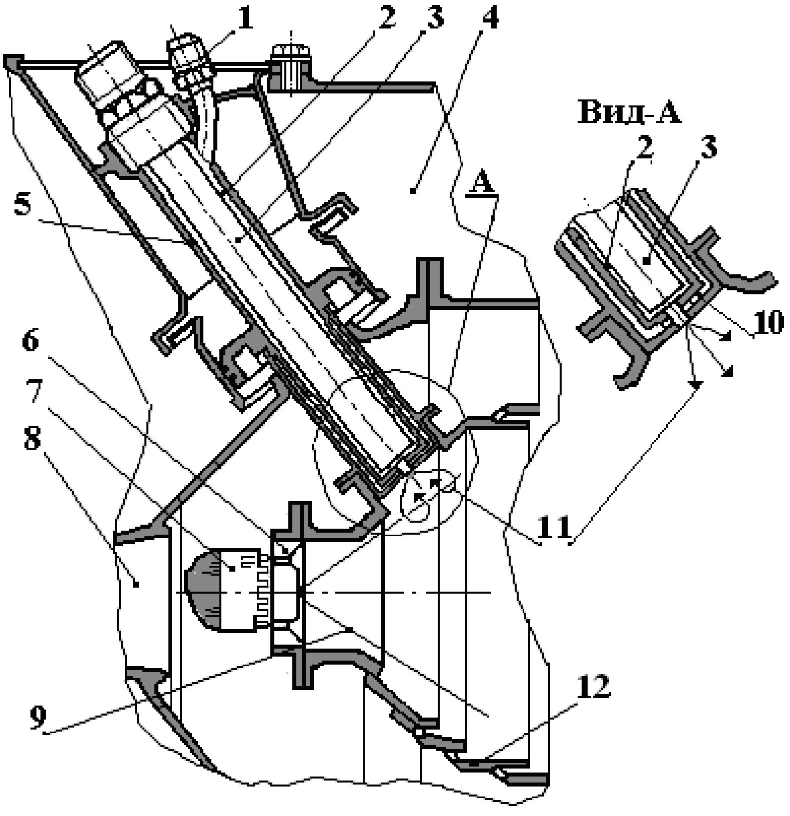


Figure 3.18 – Combustion chamber direct ignition system: 1 – oxygen replenishment union; 2 – backlash for supplying oxygen to a plug; 3 – surface discharge plug; 4 – zone of the TFE secondary flow; 5 – sleeve; 6 – swirl vanes; 7 – fuel nozzle; 8 – diffuser; 9 – fuel spray cone; 10 – backlash for plug ventilation by a fresh air; 11 – zone of oxygen supply and electric arc propagation; 12 – flame tube

Inflaming a fuel-air mixture in combustion chamber in a number of cases can be implemented directly from a plug.

The main advantages of a **direct ignition system** are simplicity of the construction and reliability in maintenance. A deficiency is restricted capability in selection of the plug location which has determining influence both on performances of inflaming, and on durability of a plug.

In Fig. 3.18 the structural element of annular combustion chamber with a plug of direct ignition placed in the head of the flame tube is shown. The plug 3 is placed in the special sleeve 5. For increase of ignition reliability a backlash between the sleeve and plugs 2 the oxygen is supplied through special holes in a zone of the head of a flame tube 12. The fuel in a zone of the plug supplies with nozzles of the main fuel manifold 7. For protection of the plug from overheating during long-period operation of combustion chamber the ventilation of casing and back of the plug by secondary air through the backlash 10 is ensured.

The effect of oxygen on process of inflaming consists of lowering thermal energy necessary for ignition of a fuel-air mixture and increasing thermal energy of the initial center of combustion; therefore the altitude performance of start can be essentially increased. Evident deficiencies of oxygen replenishment are considerable mass of oxygen system, explosion hazard and necessity of its filling.

Another method of GTE combustion chamber start also having broad propagation in aero-engines is ***inflaming of a fuel-air mixture in a flame tube from a gas jet*** (flambeau) of the firing igniter.

The **torch firing igniter** (Fig. 3.19) represents extra-small combustion chamber with elementary control system of fuel supply which is optimized only on start conditions and has a short time in operation. Inside firing igniter a firing swirl-type nozzle of the simple construction and electrical ignition plug are mounted. For providing reliable start in especially unfavorable conditions the special firing fuel (benzene) can be supplied into a firing igniter, and, besides a combustion zone may be replenished by gaseous oxygen.

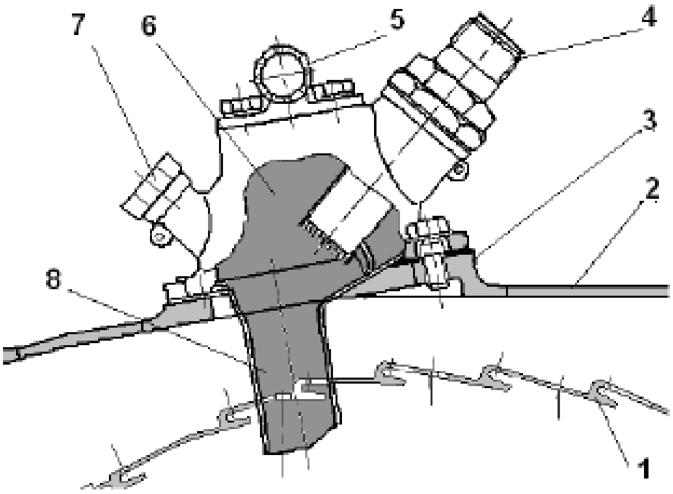


Figure 3.19 – Torch ignition system:
1 – flame tube of the main combustion chamber; 2 – external casing of the main combustion chamber; 3 – flange for attachment the start igniter; 4 – surface discharge plug; 5 – start fuel manifold; 6 – start igniter combustion chamber; 7 – start fuel nozzle; 8 – flame propagation tube of the start igniter

Main advantages of the torch inflaming system are:

- high thermal power (two order is higher one than at a plug);
- high safe life of ignition plug and firing igniter as all time, except for start, they adjoin to cold air going from the compressor, at absence of effect of the flame from the flame tube;
- low required power, and, hence, small mass and cost of the power source of a plug, due to targeted designing for providing the most favorable conditions for fuel ignition by a plug;
- capability of relative freedom in the montage of a firing igniter in relation to a flame tube;
- capability (due to application of pulsating fuel supply) to create optimal for ignition composition of a fuel-air mixture, depending on atmospheric conditions, without application of special padding aggregates;

– possibility to use one base firing igniter practically for all type sizes of engines; it essentially reduces expenditures to operational development, purchase of components and service.

For increasing start reliability in combustion chamber some sources of ignition operating in parallel are placed.

If an engine is equipped with the tubular or tube-annular combustion chambers, sources of ignition ensure inflaming of a fuel-air mixture only in two or three flame tubes of combustion chamber. Inflaming other tubes implements with the help of torches of the flame spreading from already operating sections of combustion chamber throw the special **flame propagation tubes**.

Exercise 3.9

Make a sketch of the starter igniter of the engine AL-7F, setting schemes of a gas flow (air both oxygen) and the starting flambeau creation. Look at igniters and start ignition units on the engines RD-10, RD-20, RD-9B, AI-24, R11F-300, AL-7F, D-20P, TV3-117 and also the flame propagation tubes of tube-annular combustion chambers.

3.4 Answer the questions about combustion chambers

1. What is a designation of the main GTE combustion chamber?
2. What is the difference between transmissions of heat to the propulsive mass in GTE from analogical process in reciprocating engine?
3. Explain sense of terms “fuel”, “oxidizer”, “fuel-air mixture”, “combustion-mixture”, “products of combustion”.
4. What is a difference between lean, rich and stechiometric combustion mixtures?
5. What specific parameters characterize perfection of combustion chamber?
6. What are the main requirements to combustion chambers?
7. How is the main combustion chamber arranged?
8. What is the reason of different design schemes of combustion chambers existing?
9. Why are practically all GTE of last generations equipped with annular combustion chambers?
10. What are used for two-zone combustion chambers?
11. What main loads act on constructive elements of combustion chambers?
12. What is the reason of different power schemes of combustor casings application?
13. Why is the flame tube excluded from engine’s power scheme?
14. What design-scheme decisions provide a freedom of the flame tube thermal expansion?
15. Name design means directed on prevention of buckling and burnout of flame tubes.

16. What functions does the combustion chamber diffuser execute?
17. Why are the dump diffusers applied in modern turbine engines?
18. What means are used to provide a set safe life of the flame tube?
19. What elements of a combustion chamber need an enforced cooling and how is it implemented?
20. Name tasks solved by the combustor domes?
21. What design means are used for stabilization of a flame in the combustion chamber?
22. Why is a majority of combustion chambers of modern gas turbine engines equipped with the swirler vanes?
23. What are main advantages and disadvantages of the evaporative combustion chambers?
24. What type of fuel nozzles is the most propagated in modern aircraft engines and why?
25. What design means provide a necessary turbine inlet temperature field?
26. How does the combustion chamber start to be implemented?
27. When is the oxygen replenishment applied?
28. What constructive materials are used for manufacturing the combustion chambers?

4 SHAFTINGS OF GTE

4.1 General information about shaftings

The term “**shafting**” has the synonym “**transmission**” of Latin origin. In engineering the term “shafting” is used to describe set of shafts, couplings, gears and control mechanisms to transmit motion from power sources (drives) to consumers (working machines).

Concerning aircraft engines this term involves shafts of turbines and compressors as well as their couplings. This manual also considers some problems related to power systems of engine rotors and casings including design features of rotor supports.

In order to decrease engine weight, to simplify its designing, manufacturing, assembling as well as maintaining processes it is desirable to reduce a number of supports and power frames, carrying bearings. These frames include radial struts which intersect engine gas path. Thus, every strut results in aerodynamic shadow (track) downstream this strut, which excites rotor blades oscillations.

Shafts are designed hollow to obtain high bending rigidity and torsion strength at minimum weight. In spans between supports they usually have a shape of thin-walled cylindrical or conical shells. However, in the place where supports are mounted diameter of shaft is limited by bearing because bearings themselves have constraints on rapidity and their internal diameters.

Providing a shaft static strength is not complex problem. More complex are problems of eliminating dangerous resonances of shaft bending oscillations, precession motion and too large sags which originate at a critical rotational speed of the shaft.

Both transmission design and its analysis should be based on understanding a nature of all dynamic effects, which characterize elastic system, consisting of shafting and stator. The engine operational reliability is ensured by proper accounting of elastic system properties, including its elements: shafting, casings and supports.

4.2 Construction schemes of GTE rotors

The principal problems concerning the engine rotor construction are rotor supports type, their number and disposition choosing. According to number of supports rotors are classified as two-, three- and four-support rotors.

4.2.1 Two-support rotors

The engine rotor can be one-piece and have minimum supports number, equal to two. This scheme is usually applied at low number of compressor and turbine stages, and also if compressor is centrifugal and combustion chamber is short. The main advantage is constructive simplicity. Thus impellers of compressors and turbines can be mounted between supports, in cantilever or one − between supports and other − in cantilever.

Common feature for all two-support rotors is presence of one radial thrust bearing and another radial, ensuring freedom of temperature elongation and axial relative displacement of rotor and stator.

The radial thrust bearing takes both axial and radial loads that originate in turbine and compressor. For providing desirable value of axial force, acting radial thrust bearing, the backs of rotor are sealed from gas path, thus creating front and back cavities. A front cavity is pressurized and a rear cavity is vented.

The bearing is placed inside rotor drum-disk part; supports are arranged as close as possible to a centre of gravity. This allows:

- reducing the construction length;
- reducing the rotor sag, caused by bending moment of inertial forces;
- increasing natural frequencies of rotor bending oscillations (rotor becomes more rigid).

Scheme with supports after compressor and before turbine is shown in Fig. 4.1.

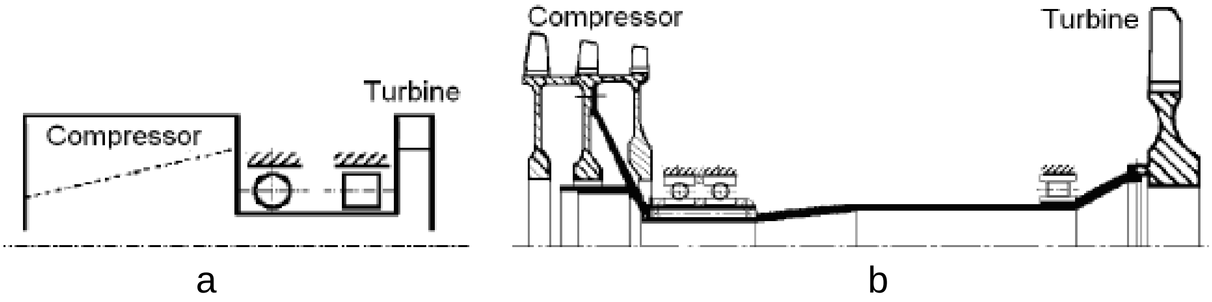


Figure 4.1 – Two-support rotor with supports after compressor: a – scheme; b – construction

Combustion chamber length determines a distance between compressor and turbine. Therefore application of this scheme allows obtaining the shortest rotor, thus reducing length and mass of casing. Besides, front support casing doesn't intersect the gas path of compressor inlet. Lacks of this scheme are rather low transversal bending rigidity, because of cantilever compressor and turbine positioning and limitation of shaft diameter at places where bearings are.

Fig 4.2 represents a scheme with front support arranged before a compressor, and rear support – before a turbine.

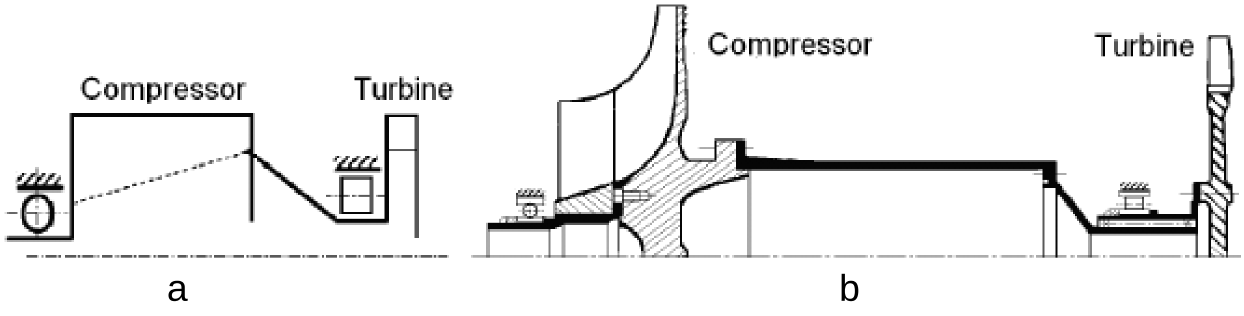
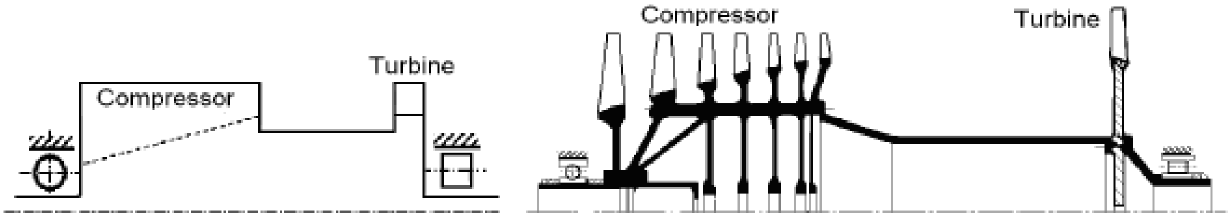


Figure 4.2 – Two-support rotor with supports disposition before compressor and turbine: a – scheme; b – construction

Advantage of this scheme comparing to previous one is possibility to increase the rotor rigidity due to shaft diameter increasing as it is not limited by bearings. The engine assembling becomes simpler.

Deficiencies are significant variation of axial clearances in turbine, encumbering the compressor inlet by load bearing frame and more complicated lubrication system. Total mass increases a little.

The scheme with front support arranged before compressor, and rear support −after turbine is shown in Fig. 4.3.



a b

Figure 4.3 – Two-support rotor with front support placed before compressor and rear support placed after turbine:
a – scheme; b – construction

Advantage of this scheme comparing with first one is higher rotor rigidity due to shaft bigger diameter.

Deficiencies are more complex construction of casing, significant variation of axial clearances in turbine, complexity of rear support lubricating and cooling.

The two-support scheme is successfully used in many single-shaft engines at moderate pressure ratios.

They include:

- disposable engines, started from a carrier; total pressure ratio of such engine is provided by joint operation of intake and compressor, thus the turbocompressor needs small number of stages; the construction becomes lightweight and shot;
- short-time operation engines, for example turbine starters, auxiliary power units, lift engines; for such engines the primary feature is mass.

Usually high pressure rotors of two-spool engines are arranged according to two-support scheme, for example R11F-300, AI-25, NK-8-2.

All three rotors of the D-36 turbofan are arranged according to two-support scheme.

4.2.2 Three-support rotors

Three-support rotor scheme is used for rotors, where two-support scheme provides insufficient rigidity and big mass. In three-support scheme the compressor and turbine cannot have one-piece common shaft because of technological complexity to provide strict coaxiality of all supports. To prevent the shaft deflection caused by non-coaxiality of supports, compressor and turbine shafts are manufactured separately and joined together by special unit, known as joint coupling which provides hinge joint of shafts.

The **joint coupling** transmits the following from the turbine shaft to the compressor shaft:

- ***torque*** of the turbine;
- ***axial force*** of the turbine;
- ***transversal*** (radial) ***force,*** originating on the front end of the turbine shaft from all loads acting on it.

The coupling ***ensures freedom of angular displacements*** (about 0,5…2^{o}) of both rotors, thus being a universal hinge.

The three-support split shafting with joint coupling provides the least weight and distance between supports at high reliability. This scheme provides separate, parallel and simultaneous (so accelerated) development and modification of turbocompressor units. Therefore the considered scheme is used in a number of different single-spool gas-turbine engines (TJE, TPE, ATJE), low-pressure rotors of two-spool engines (for example R11F-300, NK-8-2) and high-pressure rotors with multistage compressor (D-30).

Disadvantage of the three-support rotor is difficulty of access to shaft coupling; that results in extra problems at assembling and disassembling, and also monitoring assembling correctness.

The scheme with radial-thrust bearing placed after compressor is widely used. In this case the radial thrust bearing operates in a zone of moderate temperatures. Besides, turbine axial clearances variation is low.

When turbine consists of small number of stages and has low mass (RD-9B, R15-B, AL-7F, AM-3, AI-20), a scheme with rear radial bearing placed before turbine is applied (Fig. 4.4).

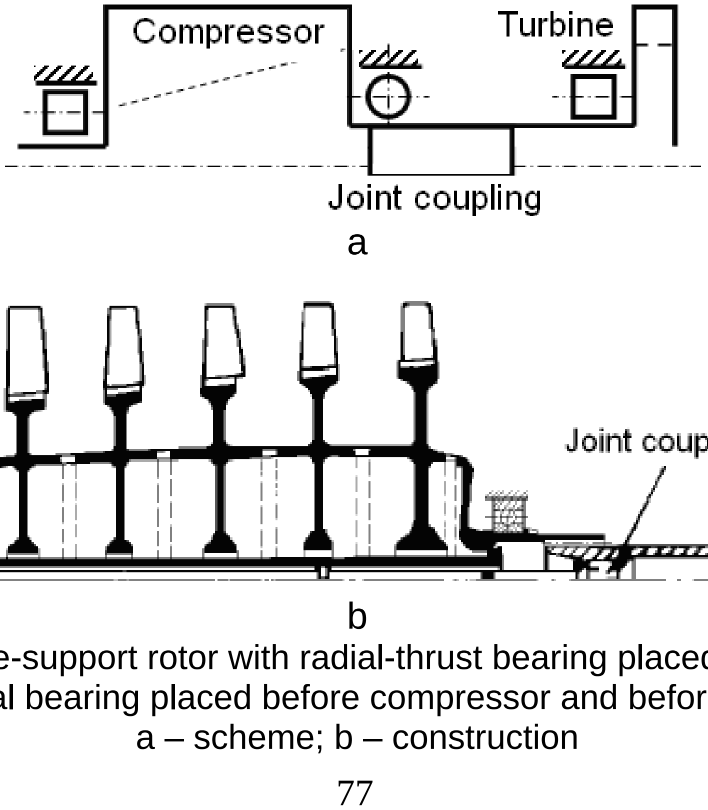
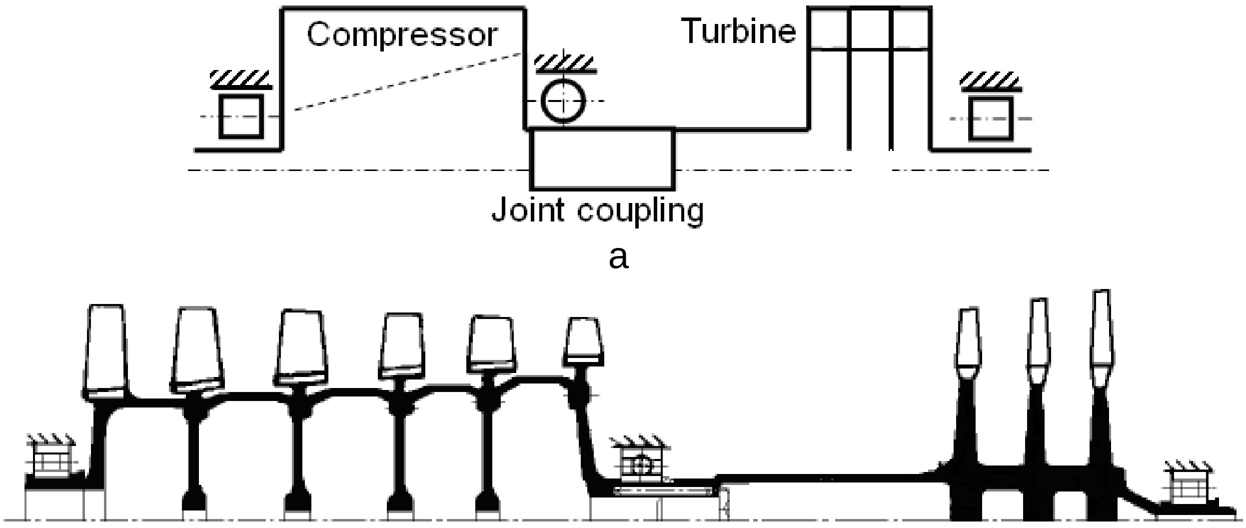


Figure 4.4 – Three-support rotor with radial-thrust bearing placed after compressor and radial bearing placed before compressor and before turbine:
a – scheme; b – construction

When turbine consists of big number of stages (NK-12, AL-21) a scheme with radial bearing placed after turbine is applied (Fig. 4.5).



a

b

Figure 4.5 – Three-support rotor with radial-thrust bearing placed after compressor, front and radial bearing placed before compressor and rear radial bearing after turbine:
a – scheme; b – construction

There is an option to place radial-thrust bearing before compressor (Fig. 4.6). In this case the heavily loaded ball bearing operates in a low-temperature zone. Thus its cooling is simplified, but turbine axial clearances vary significantly.

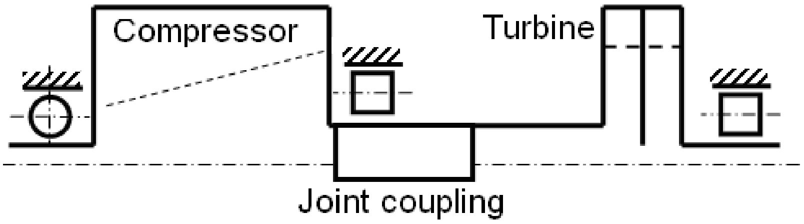


Figure 4.6 – Three-support rotor with radial-thrust bearing placed before compressor

Exercise 4.1

1. Draw a diagram of two-support shafting.
2. Draw a diagram of three-support shafting.
3. Write in report all single-shaft TJE, ATJE and TPE present in classroom, which have three-support shafting.

4.2.3 Four-support rotors

At limited rigidity of stator and long shafting the last one is divided into two parts. Each part is mounted in two supports; the torsion from one part to another is transmitted by torsion shaft or by coupling through splines. Clearances in splined junctions (circumferential and axial) ensure shafting operation, even with rotors misalignment and their axes being not parallel to each other. So, in early single-shaft TJE (TR-1, RD-10, RD-20) rotors were designed four-support. Turbine and compressor had two supports each, joined together by splined coupling. In modern two-spool engines this scheme is often used for low-pressure rotors (D-20, D-30, AI-25 etc.).

The four-support rotors, as a rule, are applied for three or more stage turbines.

Compressor and turbine rotors are mounted in two supports each. Rotor is fixed to stator by one of following ways:

- by two radial-thrust bearings, mounted separately on each rotor (RD-20, TR-1);
- by one radial-thrust bearing, which is common for both rotors (NK-12).

Scheme with two radial-thrust bearings is shown in Fig. 4.7.

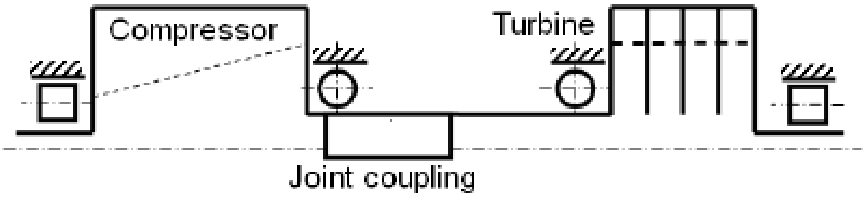


Figure 4.7 – Four-support rotor with two radial-thrust bearings

In this scheme a joint coupling transmits only torque from turbine to compressor. It has simple tube like construction with internal splines on the ends. However, in this scheme each radial thrust bearing takes full axial load of its shaft; that requires forces bearings and elements, transmitting load to case.

In a scheme with one radial-thrust bearing (Fig. 4.8) the radial-thrust bearing perceives difference of axial loads acting on compressor and turbine. The shaft coupling besides torsion torque should transmit also axial force of the turbine rotor. This coupling must have no one degree of freedom (as in three-support scheme), but two degrees of freedom for providing axes misalignment as well as axes displacement.

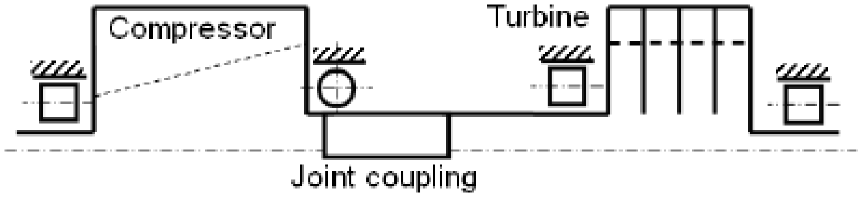


Figure 4.8 – Four-support rotor with one radial-thrust bearing

Shaft of four-support rotor is unloaded from extra bending stresses only in case when coupling has two hinges. If only one hinge is used, extra bending of shaft occurs at rotor mounting, because there is impossible to prevent shafts misalignment.

The four-support rotors have high bending rigidity and allow designing the compressor and turbine separately. However, the fourth support essentially increases weight and complicates engine construction.

Exercise 4.2

Draw a diagram of the four-support low-pressure rotor of the AI-25 turbofan.

4.2.4 Coaxial (telescopic) shaftings of multi-shaft rotors

Advantages of two or three-spool compressors comparing to a single-spool are following: the facilitated engine start-up, higher compressor gas-dynamic stability, higher pressure ratio at the same number of stages. Such multi-spool compressors need multi-shaft rotors arranged coaxially.

Coaxial (telescopic) shaftings are specific feature of TFEs, two-spool TJEs and TPEs.

Each compressor spool must have axial link to the turbine which drives it. Thus the axial force, acting radial-thrust bearing, decreases.

Apparently, two essentially different concepts of two and three-spool GTE shaftings are possible:

1. Each rotor supports directly on a stator. As elastic systems rotors in this case are independent. In the simplest case each rotor is one-piece and two-support (engine D-36).
2. The rotors are joined by intershaft bearings. If these bearings are radial (roller), then axial fixing and axial forces transmitting from each rotor to the casing is provided by its own radial-thrust bearing (AI-25, D-30).

Scheme with external independent supports (Fig. 4.9) is simple in development, because axial fixing of each rotor is independent, lubrication and cooling systems are rather simple. However, number of supports casings increases that is its turn results in engine axial size and mass increasing.

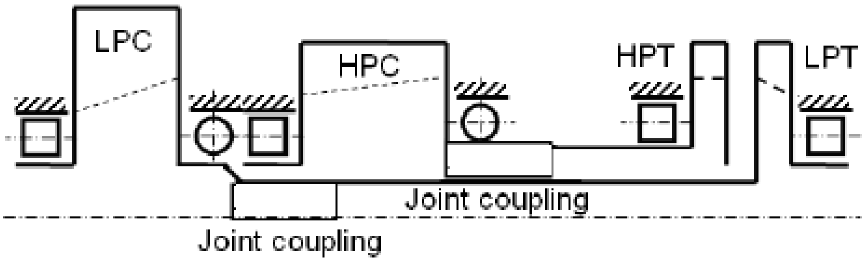


Figure 4.9 – Scheme of D-20P turbofan shafting

Scheme with internal intershaft bearings (Fig. 4.10) allows essential engine shortening and mass reduction. Some supports of low-pressure rotor are inside high-pressure rotor, and loads from a low-pressure rotor pass to a casing

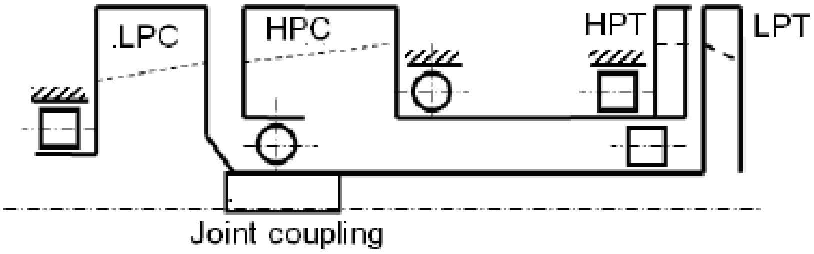


Figure 4.10 – Shafting of two-spool ATJE with intershaft bearings

through high-pressure rotor. Radial thrust bearing placed after a low-pressure compressor prevents rotor from axial displacement. This bearing transmits axial and radial load to a high-pressure rotor, then being added by loads from high pressure rotor, total force passes to a load-bearing frame through the radial-thrust bearing. placed after a high-pressure compressor.

Disadvantages of rotors with intershaft bearings application are complexity of design, lubrication and cooling intershaft bearings and problems of diagnosing their current condition.

Turboprop engines have multiple support shafting, composing from shafts and supports in gearbox in addition to shafts and supports of gas generator.

If though one intershaft bearing is designed as radial-thrust (ball), the shafts in this case interact not only on transversal radial load causing a bending, but also on longitudinal axial force. In this case the total axial force of all rotors is transmitted to a stator by radial-thrust bearing, usually of high pressure rotor (R11F-300).

Each rotor of two and three-shaft systems with intershaft bearings may be split or all-in-one and have different number of supports. So, for example, the high-pressure rotors of the engines R11F-300 and AI-25 are all-in-one on two supports, the high-pressure rotors of D-20 and D-30 are all-in-one on three supports, the low-pressure rotors of AI-25, D-20, D-30 are split and based on four supports.

At a design operational mode the ratio of high-pressure to low-pressure rotor rotation speed usually is 1.0-2.0. Therefore, if rotors rotate on the same direction and there are intershaft bearings non-loaded by axial forces, then, because of smallness of shafts relative velocities these bearings have low fast-track load.

Rotors of some engines rotate oppositely (RB-202, lift turbofan, Rolls-Royce Corporation, RB-199, propulsive ATJE to power the "Tornado" airplane). This scheme provides partial compensation of gyroscopic moments acting on a stator and on the engine mount to aircraft. But the intershaft bearing is extremely loaded.

4.2.4.1 Shafting of the two-spool ATJE R11F-300

Let’s consider design features of the two-spool engine shafting (ATJE R11F-300) At saving invariable design-arrangement scheme and main units, during a long period the engine was modified and perfected (engines R-11, R-13, R-25, R-27, R-29, R-35, R-95, R-195). Its sizes were varied; thrust, turbine inlet temperature and compressor pressure ratio were increased. Some constructive features of such shafting are used in ATFE RD-33.

The **high-pressure rotor** is two-support**.** Three-stage high-pressure compressor and single-stage turbine are placed in cantilever. The front support has two ball radial-thrust bearings operating in parallel. They provide axial fixation of both rotors to a case and perceive their total axial force.

Uniform distribution of the axial force between double bearings is provided by selection of the distance sleeves placed between external and internal racers.

The rear support of the high-pressure rotor has roller bearing. The torque is transmitted through splines from turbine to compressor. The accuracy of the high-pressure rotor semi-shafts relative position is ensured with centering cones.

A high-pressure rotor assembly is ensured only at the unique relative position of its parts to prevent misbalancing after dismounting. For this purpose one of splines on a driving part is cut off, and on a driven part the plate is put into one of slots and reinforced by a screw.

The driven part of a high-pressure rotor splined coupling bears a compartment of a low-pressure rotor ball-bearing. Such construction eliminates limitations on the radial size of the low-pressure rotor radial-thrust bearing.

The **low pressure rotor** is designed split three-support. Its front support with roller bearing is joined to the guide vanes (GV) of the LPC second stage. Five of vanes are hardened by thickening of profile. The thin leaf-spring axle of the low-pressure rotor rotation speed gauge, centrifugal regulator and oil scavenge pump passes through a down thickened vane. Cavities of four other thickened vanes are used for air and lubricating communications.

The first supersonic compressor stage is situated in cantilever, it has no inlet guide vanes, so the inlet flow is non-disturbed. The spinner is rotated together with impeller and is heated by hot air.

The low-pressure rotor intermediate bearing is designed as inter-shaft one. Its internal racer is fixed through a sleeve to rear end of the LPC shaft, and the external racer is fixed in the compartment, forced by pins to a driven part of high-pressure rotor splined coupling. This bearing appears "drowned" in a HPC drum-disk part. The axial distance between ball-bearings of both rotors is small. Bearings have a big radial size. So this segment of shafting has very high bending rigidity.

Precisely on a plane of the low-pressure rotor mean support the splined coupling joining low-pressure compressor and turbine rotors is placed.

The LPT impeller is located in cantilever. The low-pressure rotor rear roller bearing, as well as mean ball bearing, is made intershaft. It is placed in the cavity of a high-pressure rotor shaft. Its housing is intensively cooled by air, which is taken after 3-rd stage, flowing through LPT shaft and bleeding to atmosphere.

The torque is transmitted from LPT to LPC by "free" splines; axial force – by a nut, which is mounted on the forward end of the turbine shaft. The support surface of the shaft has a spherical shape.

The distance spacer is put between the low-pressure compressor and turbine shafts for correct mounting of the LPT rotor in relation to a stator. Axial clearance is necessary for operation of splined coupling at axial misalignment of joined shafts. In order to provide this clearance the gauged spacer under forcing nut is put.

A nut is fixed by the lock. In operational position of this lock the splines are run in a gear by a spiral spring, and the lock turn is excluded by a pin, screwed in the turbine shaft.

At the LPC rotor dismantling the spinner and nut (under a spinner), fastening impeller of the first LPC stage, are sequentially removed. Then the impeller and the splined lock fixing the bolt head are removed. The bolt is turned on a half of pitch of internal splines on a journal of the front roller bearing. Thus this bolt is also removed, supplying access to low-pressure rotor central coupling.

The lock of coupling is squeezed aside the turbine by a tool which looks like a rod. This axial displacement of the lock is ensured with presence of cut in its body. The splines of the lock go out a gear with splines of the nut. Thus it is possible to unscrew the nut and to take out the low-pressure rotor.

Taking the splines of the low-pressure compressor and turbine rotors out of gear and applying a key to splines of the LPT shaft, it is possible to unscrew the nut tightening sleeve of bearing on LPC journal. Thus the LPC dismounting is possible. The unit of low-pressure rotor mean bearing remains thus inside the high-pressure rotor.

The problem of intershaft bearings oiling is difficult and is usually solved by placing of feeding pipelines on axis of shafting. Construction of the engine R11F-300 is example of other original and witty solution.

Looking at this engine, it is necessary to note that its gas path is extremely perfect. The engine has no conventional cast intermediate case with radial power racks. Main air and oil communications, the drives to accessories and starter-generator are situated in covers placed between the flame tubes of combustion chamber in the secondary air cavity.

Exercise 4.3

Using drawing and mockup of the engine R11F-300, study how (by what parts) the axial force from the low-pressure rotor passes to the engine mount. Study the construction of LPC first stage disk mount and oil supply system to lubricate bearings. Make sketches.

4.2.4.2 Two-spool AI-25 turbofan shafting

The high-pressure rotor is placed on two supports. The 8-stage compressor of the drum-and-disc design is placed between supports, and a single-stage turbine is mounted in cantilever.

The high-pressure rotor is fixed in axial direction by the front ball bearing. The rear bearing is radial.

For decreasing rotor length and inter-support span the front bearing together with the journal and carrying it cone are “drowned” in a cavity of drum-disk part of the rotor. The bearing is placed on a plane of first stage impeller, and the cone is fixed on a plane of third impeller.

The rear journal of the rotor, on which the radial roller bearing is mounted, is joined with compressor and turbine also by thin-walled cones. At small weight they resist to torsion, transversal bending and thrust forces well.

Torsion from turbine to compressor is transmitted through the blind tightened splines located behind radial bearing. Such structure is very compact, light and rigid.

The low-pressure rotor has three-stage fan with articulated rotor blades and single-stage turbine.

The compressor front ball bearing is radial-thrust. It provides axial fixing the low-pressure rotor, perceives a difference of compressor and turbine axial forces.

The bearing is "drowned" in a cavity of power disk-drum part and located in immediate proximity from the gravity centre of the compressor rotor. It decreases the length of construction and the moment acting the rotor transversal bending.

Between the ball bearing and stator the shaped elastic ring is put. So this support is **elastic-damping**.

The LPC rear bearing is roller.

The advantage of the engine arrangement is that the number of power frames-racks intersecting the compressor gas path, is minimal. One row of hollow aerodynamic racks contains lubrication communications and axles of aggregates driving. The same racks join the external case with housings of two supports: LPC and forward support of HPC.

The rotor of two-stage LPT supports on two roller bearings. Impellers are mounted between supports. The housing of epy rear bearing is supported on the power racks. The front bearing is intershaft, supports on the high-pressure rotor shaft and is situated so close to a plane of high-pressure rotor support, that a mutual influence of the shafts transversal bending is almost eliminated.

The intershaft bearing is designed small-size. The lubricant is supplied to it by a tube, placed on a rotor axes, and is bleed by radial channels into carter.

The rotation is transmitted from turbine to compressor by hollow torsion shaft of compressor with two girdles of free (with clearances) splines on the ends. Clearances in splines ensure a construction functionability at misalignment of shafts axes. This misalignment may occur at mounting and may be resulted by a strain of casings under action of operating loads.

The turbine axial force is transmitted to the front ball bearing through the tie bar, which one end is screwed to a turbine shaft, and the second end is fixed by a special lock to a compressor shaft. Such a long bar may have a low critical rotational speed. In order to increase its rigidity, the bar is equipped with additional legs (shoulders). Thus the critical rotational speed of the bar is increased and resonant operational modes are eliminated.

The sealing of oil cavities of shafting is ensured with the split shaped rings made of wear-resistant graphite. The face pressing of graphite rings is provided by a wave-shaped spring, the radial pressing – by centrifugal forces.

Exercise 4.4

Using the engine mockup and posters «Rotor system and kinematic diagram of the AI-25 turbofan» and «Turbine of the AI-25 turbofan», study construction of the engine shafting, the ways of torques and axial forces transmission, make sketches.

Exercise 4.5

Look individually for the two-spool D-30 turbofan shafting. Give short characteristics of rotors, their links and supports, make sketches.

4.2.4.3 D-36 three-spool turbofan shafting

D-36 shafting is of the following specific features:

1. It is telescopic one.
2. Each rotor is two-support, front support is radial thrust and rear one is radial.
3. One of supports is rigid; other one is elastic-dumper or elastic with non-linear performance.
4. There are no intershafts bearings, so both axial and radial forces pass to the stator from each rotor separately. This allows eliminating one rotor bend affecting another rotor.

Each rotor may be conventionally considered as isolated system. Thus, designing and development of shafting is simplified, construction becomes simpler, and engine mass reduces.

Exercise 4.6

Draw a diagram of the D-36 turbofan shafting. Compare it with shafting of the three-spool Rolls-Royce RB-211 (see poster) and Rolls-Royce Trent-800 (Fig. 4.11) turbofans, name their advantages and disadvantages.

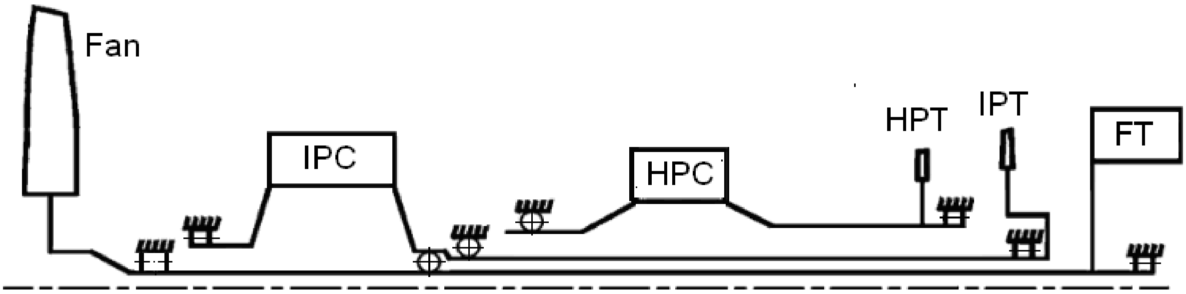


Figure 4.11 – Shafting of three-spool TFE Rolls-Royce Trent

4.2.4.4 Short information about shaftings of the turboshaft engines with free turbine

Exhaust (power) shaft in these engines is driven by a turbine which has no mechanical link with a turbine of compressor. So the engine shafting includes the shafting of turbocompressor and the shafting of free turbine.

Exercise 4.7

Using mockups and drawings study helicopter engines D-25V, GTD-3F, TV3-117 and D-136 shaftings.

4.3 Loads acting GTE rotor

Forces and moments, acting a rotor during engine operating are scheme independent.

Turbine enables a **torque** and delivers it compressor, causing torsion stresses appearing in a shaft segment between turbine and compressor. In TPEs the torque is transmitted to compressor and propeller.

The **axial gas-dynamic forces** originate on rotary blades and side surfaces of discs as a result of impeller and air or gas stream acting each other. They cause tension stresses in a shaft.

Total axial force of compressor rotor acts in thrust direction. Total axial force of turbine rotor acts oppositely, downstream. Compressor and turbine rotors are joined; therefore total axial force acting a rotor is equal to difference between axial forces acting compressor and turbine rotors. It acts in thrust force direction and is taken by radial thrust bearing.

The **mass forces** including gravity and inertia originate during aircraft accelerations. They are applied to centers of gravity of engine units. Their values are determined by overloads. Inertia, acting along the engine axis, results in tension stresses increasing or decreasing. Inertia, acting in transversal direction, results in additional bending.

The **gyroscopic moment** originates only when aircraft turns around one of side axes (any axes, except axis of engine rotor); this moment causes rotor sag, additional bending of a shaft and loads bearings.

The **centrifugal forces and moments** appear only in misbalanced rotors and cause additional bearing reactions and bending stresses in shafts. Any rotor is some misbalanced in determined limits. The centrifugal forces and moments can excite dangerous oscillations of rotor and engine as a whole, thus causing fatigue destruction of components.

The **thermal loads** in a rotor appear when thermal elongation is limited and joined components cannot expand freely. They cause temperature stresses in components.

4.4 Construction of shafts and joint couplings

A shaft is designed for torque delivering from turbine to compressor. It is to be strong, rigid and light for reliable torque transmitting, axial forces and bending moments perceiving and rotor durability increasing. Therefore GTE shafts are usually hollow with maximally possible external diameter.

Compressor and turbine shafts of two-support rotors are joined rigidly using flange-bolt or tight splined junction.

If rotor has three or more supports then shafts junctions are designed hinge-movable using special coupling sleeves.

If rotor has three or more supports, then shafts must be hinge-joined by special coupling sleeves to let some axes misalignment.

Coupling must provide:

- mutual positioning and fixation of components during engine operation;
- simple assembling and disassembling with an opportunity to check the quality of assembling and its correctness;
- opportunity for simple arranging lubrication and cooling movable splined junctions.

If these requirements are not satisfied, it may cause rotors disconnection, rotor misbalancing, splined and hinged junctions deteriorating.

4.4.1 Splined sleeve with a screw

4.4.1.1 General description

The arrangement of coupling to transmit torque, axial and transversal force at possible small misalignment of shafts, is shown in Fig. 4.12.

Shaft edge with external splines is mounted inside other shaft with internal splines. Torque and transversal force are transmitted by splines. To prevent shafts pinching, splines are loosely fitted (with some side clearances), considering permissible axial misalignment of rotors (up to 0,5…2,0 degrees).

Axial force is transmitted through hinge junction, which also provides operation of shafts, mounted with small axial misalignment. The axial force may be transmitted through a screw, fixing sleeve or flexible bar, which no pinch a junction. Hinge fragments (spherical spacers) are used instead of entire hinge.

Real implementation of this scheme may differ. These couplings are simple in construction and widely used (AI-20, AI-24, AL-7, RD-9B, D-25V etc.).

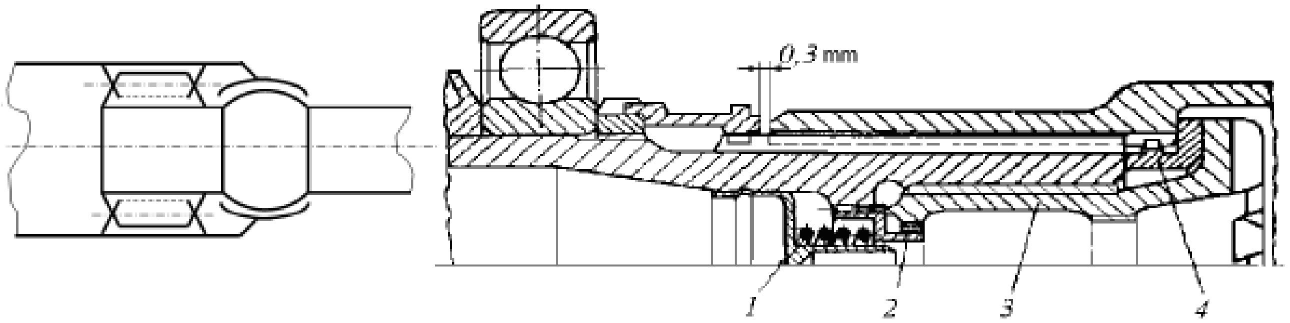
The main disadvantage is the necessity to have long splines with increased side clearances, because of small diameter of the shaft; therefore at rotors angular misalignment flowing tooth contact and local tooth overload appear.

4.4.1.2 Turboprop AI-20 coupling

Fig. 4.12 represents example of this type of junction (engine AI-20). Axial force is transmitted by the screw 3. The splines have side, radial and axial clearances. The load which appears between adjacent splines and its distribution along splines length vary cyclically with turbocompressor rotor rotation.

The screw 3 is screwed to a trailing-edge of the compressor rotor chock-a-block on the rest spacer 4, which supports on a back of this rotor. This spacer prevents displacement of the turbine shaft to the right − to the direction of axial force of the turbine rotor.

To eliminate a tear on contact surface when the screw is tightened, the spacing collar 4 is fixed from turning by external splines that are in contact with splines of the turbine shaft. The screw 3 is locked by spring-splined lock, which



a b

Figure 4.12 – Telescopic hinge-movable junction by splined ends of shafts:
a − scheme of junction; b − construction; 1 − spring; 2 − fixing sleeve;
3 − screw; 4 − spacing collar (rest spacer)

consists of the splined fixing sleeve 2, the guide pin-gag and spring. The pin-gag is beaded in a trailing-edge of the compressor shaft and serves as a guide bush for the spring 1. The splined fixing sleeve 2 sits on splines of the compressor shaft trailing-edge. Being acted by the spring, this sleeve engages splines of the screw 3 and locks it. To unlock the screw 3, it’s necessary to turn the sleeve 2 to the left. Spacing collar 4 selecting provides axial backlash 0,3...0,5 mm. Both axial backlash and splines free fitting allow some misalignment of rotors axes. Coupling assembling is carried out by the long key through hollow turbine shaft before the turbine impellers assembling.

The considered coupling has simple design, small sizes and low weight. Being limited in external diameter by bearings presence, the shaft needs long splines to transmit torque. Long splines need increased radial clearances. Long tooth is undesirable, as increases local overload at misalignment.

Similar constructions of couplings have engines NK-12 and NK-4.

Exercise 4.8

Using drawing and mockup of the engineTV3-117 consider coupling of turbine and compressor rotors, make a sketch of a threaded sleeve.

Exercise 4.9

Find in drawings and mockups of the engines NK-12, AI-20 and AI-24 differences in construction of couplings.

4.4.1.3 Coupling with spherical support

Consider the engine D-25V turbocompressor coupling. Its apparent advantage as contrasted to already surveyed, is the spherical support, which center is combined with a plane of rotor support and a middle of splines length. Hence the shafts are isolated on a bending, and non-uniformity of a load, acting on splines, originating at a misalignment of axes of shafts, is minimally possible.

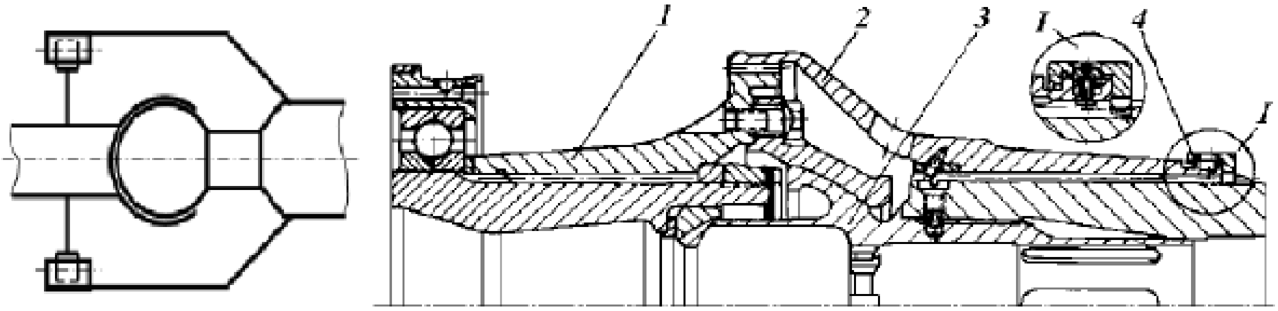
The splines are made in the hollow compressor journal for a torsion torque transmission, and the tube is screwed for transmission of an axial force.

The coupling screw is screwed and fixed by the split ring on a rear side of this tube.

The tubular construction of the coupling main details allows to place inside it one more shaft, that gives possibility to utilize this scheme after small modernizing for the two-support TFE (D-20, D-30, D-30KU).

4.4.2 Coupling with one teeth row splined sleeve

This type of junction (Fig. 4.13) is applied in TJE VK-1, AM-3 and RD-3M-500.



a b

Figure 4.13 – Telescopic hinge-movable junction with one teeth row splined sleeve: a − scheme of junction; b − construction; 1, 2 − splined sleeves; 3 − spherical shank; 4 − lock

In this scheme diameter of intermediate splined sleeves is more then a shaft diameter. This allows decreasing length of splines and increasing teeth number. Operability of shortened splines in conditions of shafts misalignment is improved.

Axial link is provided through a hinge which unloads shafts from additional bending at misalignment, fixates turbine rotor in axial direction and transmits radial bearing reaction of turbine rotor to compressor shaft. So both axial and transversal forces are transmitted through a spherical hinge. Its center is located precisely on a plane dividing length of free splines in halves. The bending one shaft is not transmitted to another, due to a small distance between a plane of support and a center of spherical hinge. Free splines and hinge are strongly oiled.

At shaft dismantling the driving splined sleeves are displaced on elongated splines of the turbine shaft. Axial fixing of driving sleeve in operational position provides a lock, which teeth are put in cuts against splines on turbine shaft and splines on external surface of sleeve. Lock position is fixed by spring key.

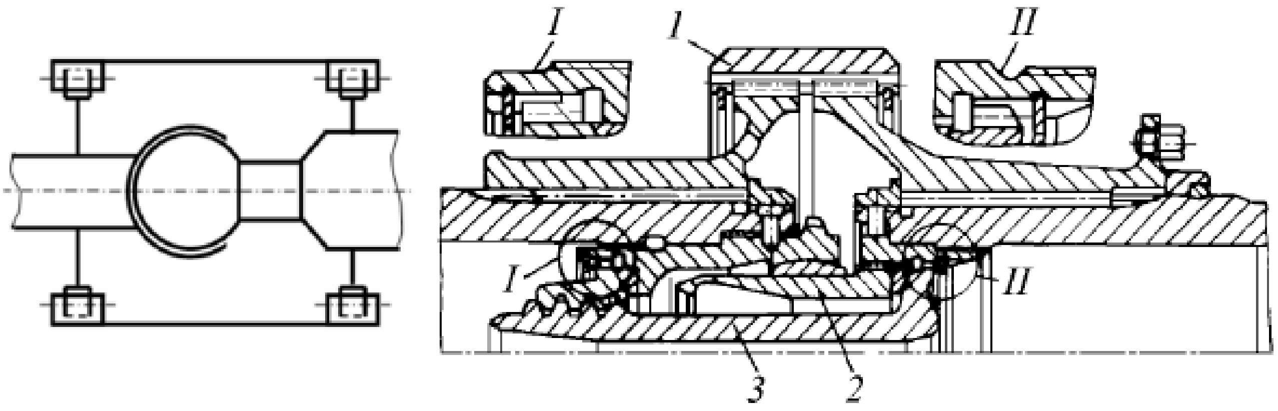
After driving sleeve of the engine AM-3 coupling is displaced on shaft and is removed from gearing, to remove the turbine rotor it is necessary to dismantle a socket of a large hemisphere. For the engine VK-1 it is enough to turn the turbine shaft in relation to the compressor shaft on angle 120^{o}. On the engine VK-1 a sphere on the turbine shaft and a lied-on part of the socket have three cuts. After specified rotational displacement the cuts take position allowing pick up of the turbine rotor. Thus the driving sleeve remains inside a coupling body.

Exercise 4.10

Using drawing and mockup of the engine AM-3 (RD-3M), study design features of the coupling. Look for transmission of the torsion torque and the axial force from the turbine rotor to the compressor.

4.4.3 Coupling with two teeth row splined sleeve

Each splined teeth row has short splines and side clearances, thus operates like a hinge. A two teeth row sleeve operates like a double hinge, therefore shafts are prevented from pinching not only in three-support rotor but also in four-support one. Construction of such junction is shown in Fig. 4.14.



a b

Figure 4.14 – Telescopic hinge-movable junction with two teeth row splined sleeve: a − scheme of junction; b − construction used in TJE VD-7; 1 − two teeth splined sleeves; 2 − hinged support; 3 − coupling bolt

Axial connection of shafts is provided by a bolt which has a hinge-movable junction with turbine and compressor shafts, or by a flexible stub (low-pressure rotor of the engine AI-25).

Compressor and turbine four-support rotors of the engines TR-1 and RD-20 are fixed from axial displacement by radial-thrust bearings. Function of a coupling in this case is only transmission of a torsion torque through shafts operating with misalignment. Thus coupling construction is simplified by hinge junction excluding.

Splined junction of shafts is analyzed on bending and shearing of spline teeth.

Hinged junction of shafts (hinge or spherical spacers) is analyzed on shearing, connection stub − on tension.

Exercise 4.11

Using drawings and mockups of the RD-20, TR-1, VD-7 turbojets and low-pressure rotor of AI-25 turbofan consider construction of couplings, analyze transmission of a torque and axial force.

4.5 Rotor supports

The rotor support consists of bearing with fixing elements, labyrinth and contact seals, elements of lubrication and cooling system.

Construction of support depends on its functions and placement on rotor.

4.5.1 Bearings

The gas turbine engine supports are designed with rolling-contact bearings which take high static, dynamic and thermal loads, which vary on during engine operating modes and flight conditions. Their basic advantages are low friction factor at the engine starting and steady-state operation, reliable operating at high rotational speed, low mass and sizes, simple construction and maintenance.

Depending on taken forces and rotor ability for axial displacement, ball or roller bearings are applied. The ball radial thrust bearings (Fig. 4.15) takes both radial and axial forces. Ball bearing prevents rotor from axial displacing; its inner racer is fixed by joining to a rotor, and outer racer − to a stator. At high loads the ball bearings with three and four contact points are applied.

The roller bearings (Fig. 4.16) can perceive high radial load.

Considering a fact that roller bearings operate at high rotational speeds, their rollers are separated with cages (separators), made of forged bronze or duralumin. Separator uniformly arranges balls (rollers) in a circle and ensure their contactless (among themselves) operation.

Outer racer is loosely placed (0,02…0,04 mm) in rigid steel cage for ensuring its thermal expansion when heated. Inner racer is built-up on a shaft with low tightness (0,005…0,03 mm) to prevent joint opening when heated. Such bearing mounting provides good rotor centering and prevents jamming of balls when support is heated.

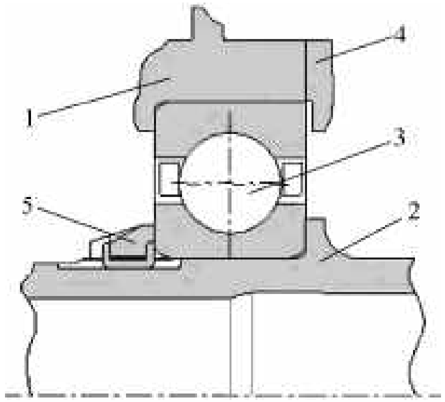


Figure 4.15 – Ball bearing of GTE rotor support:
1 − stator part of support; 2 − rotor part of support;3 − bearing; 4 − flange;
5 − thrust nut

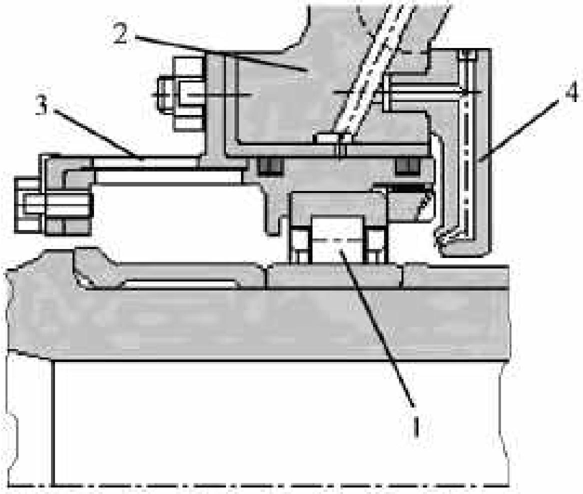


Figure 4.16 – Roller bearing of GTE rotor support:
1 − bearing; 2 − casing; 3 − elastic ring with oil damper; 4 − oil nozzle

If axial force is too high, two radial-thrust bearings are placed together (AM-3, R11F-300). Construction of support and bearings selection are complex and multi-aspect task, because many contrary requirements must be met (rigidity on a plane of bearings, sizes of bearings and clearances are to be similar etc.). This support is adjusted by choosing of proper size of special spacer rings in outer and inner components.

To decrease axial load acting the radial-thrust bearing, special unloading cavities are arranged.

The cages are centered on inner racer. Such construction provides more intensive lubrication of centering surface, improves heat conduction from a bearing due to oil supply under a cage. Cage balancing is improved too due to its run-in.

4.5.2 Heat protection of supports

Bearings belong to heavily-loaded high-speed engine parts.

Bearings temperature, especially in turbines, approaches 200…250 ^{o}C, rotational speed varies from 5000 rpm for TJE to 60000 rpm for auxiliary power plants. Bearings operate reliably when temperature of outer ring is 40…50 ^{o}C less than a tempering temperature of material. For example, tempering temperature of steel ШХ-15 widely used for bearings manufacturing, is 175 ^{o}C; therefore such bearings operate reliably at temperatures less than 120…130 ^{o}C. By improved thermal treatment and special modified steels, the operational temperature may approach 225…250 ^{o}C. So bearings significantly influence the engine reliability and life time.

The heat is transmitted by radiation, convection and thermal conduction. To protect bearings from overheat the next methods are used:

- screens reflecting the radiant heat flux;
- cover support housings with shells made of heat-insulating materials (asbestos, fiberglass);
- “heat throttles” in “thermal conduction lines” from rotor to bearing.

Exercise 4.12

Find the methods of heat protection of the HPC rear support of the D-30 turbofan and TV3-117 turboshaft. Make sketches.

4.5.3 Supports lubrication and cooling

Oil cools and protects bearings from corrosion, decreases friction losses, decreases wearing and cold-hardening of parts, cleans bearing and decreases a noise level.

Oil mass flow through a roller bearing is 1–3 l/min, through a ball radial thrust bearing – 4−12 l/min. Filtered oil passes to oil spray nozzle at pressure enough to provide pressure drop 2−5 atm (0,2−0,5 MPa). Pressure rise is ensured by pressurizing pump. To lubricate one support 3−8 nozzles can be used. Oil is sprayed into a gap between inner racer and cage. Then under centrifugal forces action rollers and inner racer carry oil to lubricate outer racer. At poor lubricating, temperature of inner racer and rollers rises resulting diminution of all clearances that may finally result in jamming of bearing.

To improve oil circulation, prevent oil getting out of support cavity and oil foaming, waste oil is pumped to oil collector, providing total support scavenging. Therefore total capacity of scavenging pumps is designed 3−4 times more than a capacity of lube-oil pump.

In two- and three-cascade compressors some difficulties of intershaft bearings oiling exist. The oil is usually supplied to such bearings by a pipeline situated on axis of internal shaft. The oil bleeds from a cavity in external shaft to a cavity in stator (casing) under action of centrifugal forces.

Fig. 4.17 represents construction of the turbine supports and one of methods of intershaft bearing lubrication.

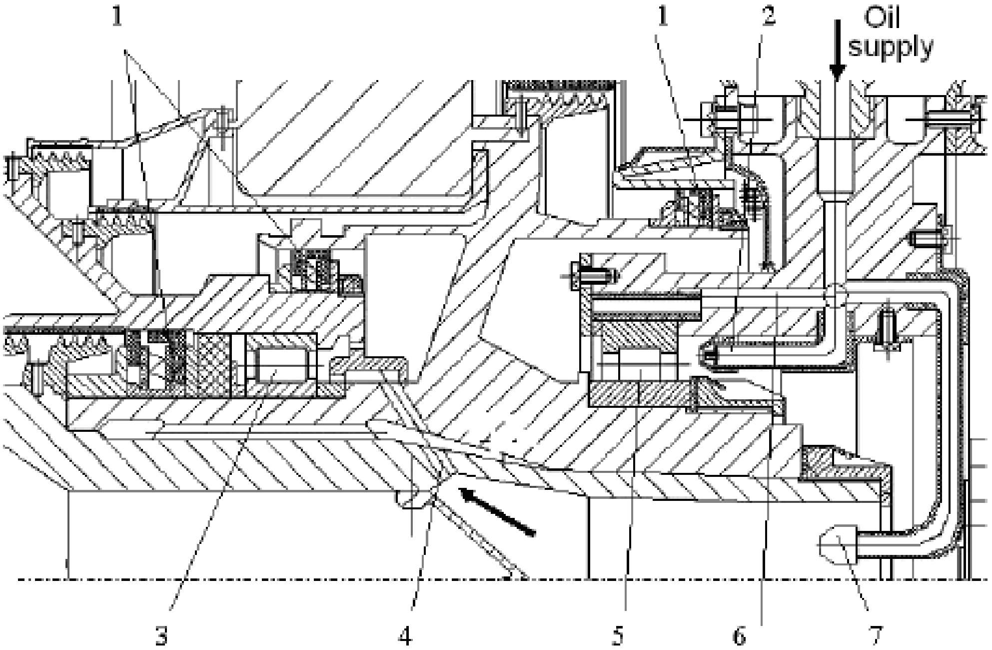


Figure 4.17 – ATFE turbine supports lubrication:
1 − contact seals; 2 − rear bearing oil supply nozzle; 3 − intershaft bearing;
4 − channel for oil supply to intershaft bearing; 5 − main bearing; 6 − channel for oil supply to oil damper; 7 − nozzle for oil supply to intershaft bearing

Exercise 4.13

Study the oil supply of the engine TV3-117, LPC rear support of the engine R11F-300 and engines D-20, D-30 intershaft bearings. How is oil taken off the intershaft bearings?

It is necessary to provide free oil flowing out from support cavity to a settler with **defoaming device**. This device is usually a wire netting or perforated sheet. From this device the oil is pumped off, passing through **deaerator** and being cooled with fuel coming into the engine, or with air in special **heat exchangers**.

Cross-sections of overflow channels must be big enough to prevent overflowing of supports cavities, excessive oil foaming, increasing of power consumed on pumping, oil temperature rise and oil leakages through seals.

Cavities of supports are drained through the **centrifugal breather**.

4.5.4 Sealing of oil cavities

In turbine engine there is no need in terrain clearance isolation of oiling system cavities; the small leakages from lubrication system and hit of small quantities of air and gases are permissible. The contactless labyrinth seals, contact seals with split rings and their combinations are applied to isolate the turbine engine oil cavities. The cups and hydrodynamic seals (impellers and worms) are applied in very rare cases in combination with stages of other seals.

In order to decrease a length of seals they are designed two- and three-tier. Cavities between rotors can be drained or be pressurized by air from the compressor so that the small air consumption in oil cavity is supplied and the oil film is not blown off from working surfaces of the bearing.

Exercise 4.14

Find in the engines represented in the classroom (and write in your notebook some of them) examples of oil cavities sealing with:

- labyrinths only;
- split rings only;
- combination of labyrinths and split rings.

Find and sign in your report examples of the multi-tier labyrinths design with pressurized inter-labyrinth cavities.

4.5.5 Elastic and elastic-damper supports

Majority of modern GTE rotors are mounted in elastic-damper supports.

General purposes of elastic-damper supports are to decrease vibrations level of rotors and engine as a whole, to prevent dangerous resonant oscillations or to move them out of operational range. To reach these goals the supports positions and parameters are to be coordinated with dynamic properties of rotors.

The whole varieties of elastic-damper supports perform two main functions:

1). Provide elastic compliance of supports what enables:

- changing elastic system of rotor and engine as a whole;
- decreasing system’s natural oscillation frequency;
- eliminating resonances in engine operational range;
- changing of rotor and case oscillation mode shapes;
- changing dynamic stresses acting engine components.

2). Absorbing energy of elastic oscillations and converting it into a heat that prevents increase in forced oscillations and dynamic stresses in components. Each support has its own optimal damping factor, providing maximum oscillations damping.

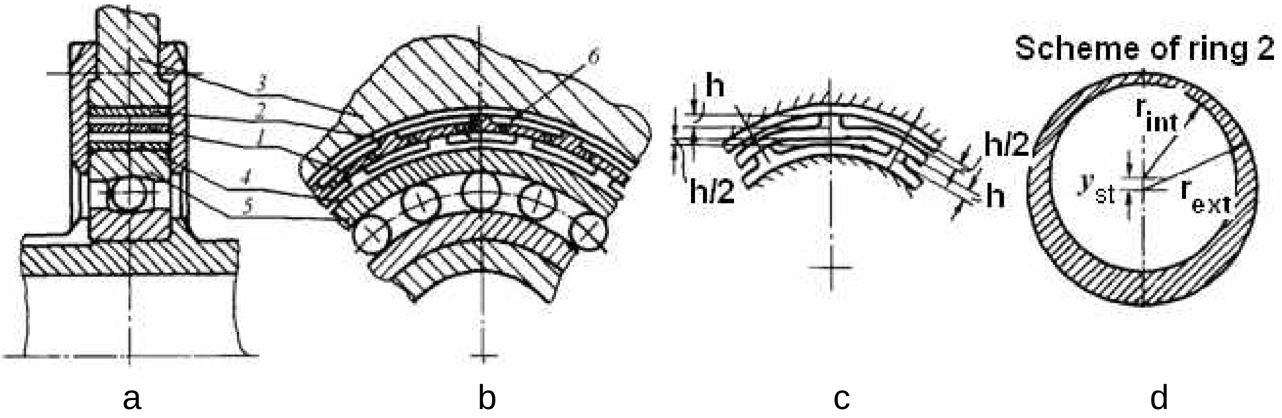
The elastic or elastic-damper elements are placed between outer racer of bearing and housing. Their size depends on size of hubs and bearings. The rotor support with elastic and damper elements form the elastic-damper support.

According to elastic and damper elements applied, all supports differ as:

- with ring elastic elements;
- with rod elastic elements ("squirrel wheel");
- hydrodynamic.

4.5.5.1 Support with ring elastic elements

Main elastic element of a support (Fig. 4.18, a) is the thin-wall elastic ring 1, inserted between a casing and outer ring of a bearing with determined tightness, and supports by its ridges on the ring 2, placed in the casing 3, and also on ridges of the ring 4, placed on the bearing outer ring 5.



a b c d

Figure 4.18 – Elastic-damper support with ring elastic elements

When bearing displace in radial direction, it results segments of elastic ring bending and initiates elastic reaction of bearing. The elastic ring usually consists of 9−12 ridges and elastic segments. The ridges are positioned in checkrow, and rings position is fixed by special lock.

Thickness and width of elastic ring and number of segments determine support rigidity. Height of ridges determines tolerant bending flexure of ring segments.

To provide operation of all ring segments the ring is mounted in a casing with tightening on ridges which is equal to half of a ridge height (Fig. 4.18, b). To eliminate a backlash on internal ridges of the ring 4 the elastic ring 1 must be tightened. Enough value of this tightening is about 0,02 mm.

Deformation of ring segments pumps oil providing its extrusion and suction. Finally this results in damping effect. The oil flows throw flange gaps and specially calibrated holes 6.Maximal damping effect may be reached if to make special choice of gaps and holes sizes. Besides, holes 6 prevent possibility of oil films braking off at suction stroke and prevent deterioration of support damping properties.

Fig. 4.19 represents rings constructions. The ring with a special flexure limiter (Fig. 4.19, c) provides more precise calibration of a ring flexure what is important for prevention of a ring overload and its rigidity deterioration. The elastic system consisting of two or three rings (Fig. 4.19, d) is applied when it is necessary to decrease support rigidity.

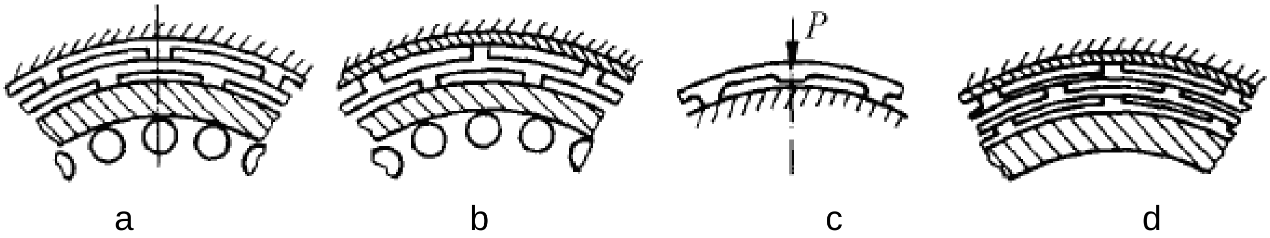


Figure 4.19 – Constructions of elastic rings:
a, b – single-ring schemes; c – ring with flexure limiter; d – double-ring scheme

Construction of elastic support with elastic rings is compact and light, but needs the very precise manufacturing of rings (especially coupling diameters). To provide correct operation at given elastic-damping performances, supports need improvement in special rigs.

4.5.5.2 Support with rod elastic elements ("squirrel wheel")

The name "squirrel wheel" appeared because the support with rod elastic elements looks like a real squirrel wheel. The elastic-damping support (Fig. 4.20) is a sleeve with a lot of slots. This sleeve has a flange from one side for attaching to the case, and place for bearing mounting from the other side.

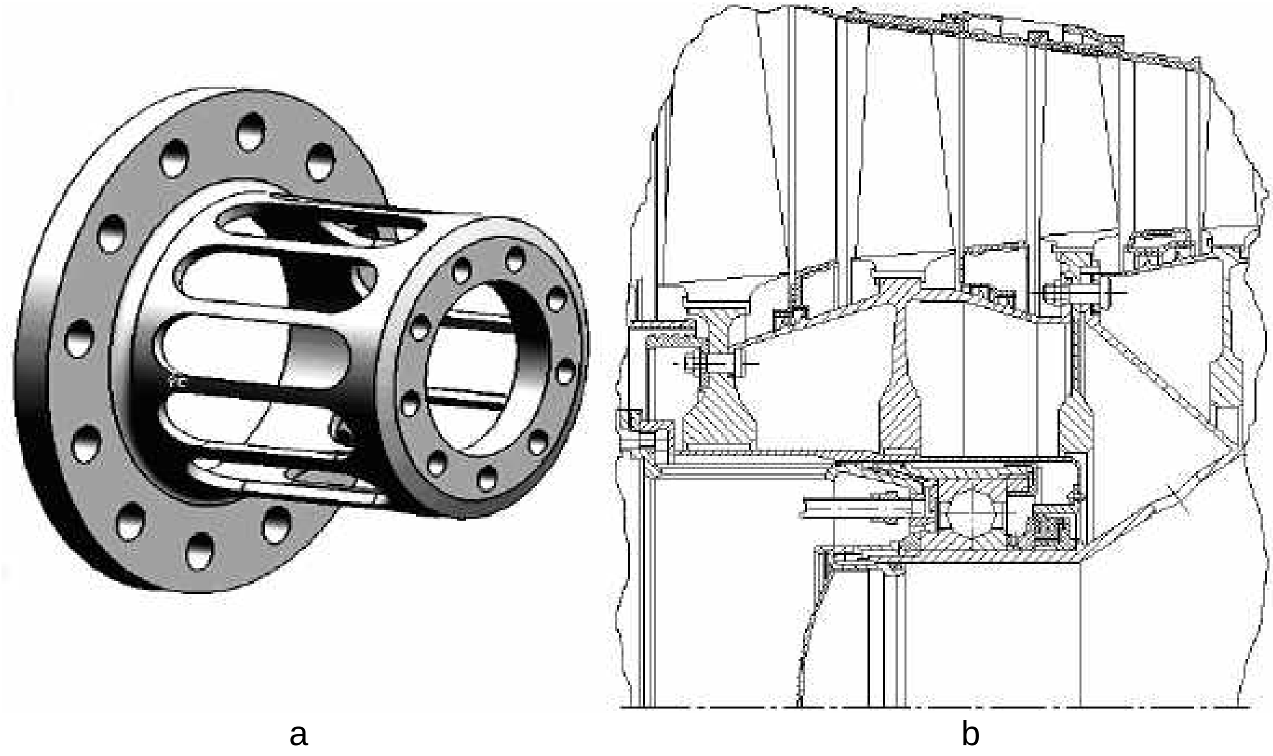


Figure 4.20 – Elastic-damper support of a "squirrel wheel" type:
a – elastic sleeve; b – construction of the engine D-136 LPC support

Radial force acts rod elements bending them. The support rigidity is determined by thickness of a sleeve wall, width of slots, number and length of rod elements.

The damper of support is thin oil layer of 0,2…0,3 mm thick between sleeves. It determines support radial deformation. The oil enters slots from ring channel in casing through uniformly distributed holes in the sleeve. Length of damping oil layer is determined by displacement of sealing rings. The support damping properties depend on thickness and width of oil layer. Therefore these parameters are the point for optimizing support construction which is usually improved experimentally.

The oil layer provides not only hydrodynamic damping effect. The radial centrifugal force acting rotor is a rotated vector which rotation speed is equal to a rotor rotation speed, so the oil layer operates like a hydrodynamic bearing. Thus a hydrodynamic radial force supplements a radial force initiated by rods of the support.

4.5.5.3 Hydrodynamic damper support

Hydrodynamic support doesn't contains elastic elements (Fig. 4.21) and damps only by hydrodynamic oil layer. This layer provides not only dumping but also takes loads from bearing during engine operation.

The main advantage of this support is simple construction.

Simplest constructions implement the concept, when oil is between outer ring of bearing and casing sleeve. The oil is supplied into a clearance at ordinary pressure without additional pumping, thus operability of oil layer is determined by its sealing. Therefore axial clearance between rings and floating sleeves is to be as small as possible (0,02…0,04 mm).

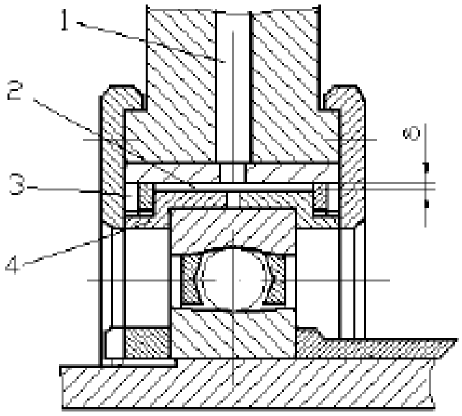


Figure 4.21 – Hydrodynamic support:
1 – oil supply; 2 – oil layer; 3 – elastic rings; 4 – floating sleeves

The oil layer in hydrodynamic support is heavily loaded, because first of all, a lot of heat evolves to the layer, and finally oil viscosity significantly varies at different rotational speeds. Therefore to provide stability of the support operation with needed performance it is necessary to design intensive oil pumping through the support.

Exercise 4.14

Find the oscillation damper devices used in supports of the AI-25, D-30, D-36 turbofans and NK-12 turboprop.

Note support type, operating principle of each in your report.

Draw “squirrel wheel” support.

4.5.5.4 Bending limiter

The bending limiter is the bearing normally put in a housing but with a backlash to a shaft. So during a normal operation of the engine this bearing has no contact with a shaft, thus doesn't operate. It enters activity only at occurrence and development of the shaft flexure (at a resonance, at rotor critical velocity). Thus the padding support of a rotor actuates, the base frequency of a system is changed and the flexure propagation decreases.

4.6 Answer the questions about shaftings

1. What is named as shafting?
2. Classify loads, acting in GTE, by origination.
3. Where to do axial forces of compressor and turbine rotors act?
4. Explain origination of axial force acting on radial thrust bearing?
5. What flight modes initiate gyroscopic moment that acts engine rotor?
6. Name advantages of double-support rotor scheme.
7. Why three-support rotor scheme is most widely used?
8. What is the reason for using intershaft bearing?
9. What units of the engine structure take axial force acting engine rotor at aircraft deceleration?
10. Why only one shaft support is ball bearing, and all other are roller?
11. Name functions of rotor joint couplings.
12. What elements does rotor support consists of? What for are they applied?
13. What is a reason for elastic-damper supports application?
14. How the required temperature of bearings is provided?

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