MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE

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SYSTEMS AND UNITS OF AIRCRAFT POWER PLANTS

Synopsis

Kharkiv “KhaI” 2015

UDC 629.7.036 (075.8)
BBL 31.76я73
Y-44

Разглянуто загальні відомості щодо будови систем і агрегатів авіаційних силових установок. Наведено основні дані, описано область застосування, принцип роботи, методи розрахунків і компонувальні схеми різних типів авіаційних силових і енергетичних установок та їхніх агрегатів.

Для англомовних студентів, які вивчають системи і агрегати авіаційних силових і енергетичних установок.

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Y-44 Systems and units of aircraft power plants [Text]: lect. summary / S. Bezuglyi, S. Yepifanov, R. Tsukanov. – Kharkov: National Aerospace University «Kharkov Aviation Institute», 2015. – 100 p.

ISBN 978-966-662-413-3

This guide will be useful for students studying systems of aircraft power plants in English.

This guide addresses the base technical data, arrangement and design of aircraft power plants systems and their units. Most diagrams let students get familiar with working process features and design of main components.

The information is presented in the order suitable for using at practical classes and during individual work. This guide is also helpful for students studying aerospace engineering to get general overview of the air-breathing engines power plant systems and their units.

Figs. 67. Tabl. 2. Bibliogr.: 9 names

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CONTENT

INTRODUCTION

The task of aircraft designing includes extensive complex of related problems. It is necessary to satisfy requirements of aerodynamics and flight dynamics, strength and stiffness, reliability and survivability, repairability and effectiveness. A number of factors directly influencing economic efficiency of aircraft are related to power plant designing solutions. Rational choice of type and number of engines, their arrangement on aircraft essentially effects efficiency of the designed aircraft. Rational selection of engine mounting scheme and correct choice of its parameters impact not only to strength and stiffness, but also allow to eliminate resonance, discomfort condition for passengers onboard, increased crew fatigability, fast equipment wearing and provide maintainability and repairability. Finally these influence profit brought by aircraft and its competitiveness. Quality of fuel system designing determines reliability and fire safety of power plant, direct and indirect aircraft maintenance expenses, for example, due to greater or less mass of unusable fuel, required fuelling time etc.

The aircraft power plant (PP) consists of thrust (gas turbine or piston) power plant and auxiliary power plant.

The aircraft gas turbine power plant is structural combination of gas turbine engine with inlet and exhaust systems and with all systems and units that provide its maintenance.

The aircraft auxiliary power plant is structural combination of auxiliary gas turbine engine with inlet and exhaust systems and with all systems and units that provide its maintenance and serve thrust and lift engines and aircraft on ground and in flight.

The gas turbine power plant must supply required take-off and landing performance and maneuverability of aircraft, required flight range, rate and climb. Economic fuel consumption must be provided in wide range of flight altitude and air speed. 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 results in designing of engines, their systems and units.

The auxiliary power plant serves energetic needs of the gas turbine power plant and aircraft on ground and in flight. It can be used for starting thrust and lift engines by pneumatic, electric or hydraulic starters, for air conditioning of aircraft cabins and compartments, for supplying on-board equipment with electric or hydraulic power etc.

Quality of above mentioned functions depends on effectiveness of the systems that constitute the power plant. These systems consist of *units (components, assemblies, accessories)* and *communications* that are mounted directly on the engine, and also of the elements integrated into aircraft.

This manual is composed for studying systems and units of aircraft power plants. It contains seven parts: Systems and Units General Information, Fuel Systems of Power Plants, Fuel Supply Systems of Engines, Oil Systems, Turbine Engine Starting Systems, Turbine Engine Protection Systems and Accessory Drives. For checking knowledge concerning each of the parts, the lists of control questions are applied.

1 AIRCRAFT POWER PLANTS SYSTEMS AND UNITS GENERAL INFORMATION

1.1 Overview of basic systems and units of aircraft power plant

Aircraft power plants can be classified by engines type, number of engines, their arrangement on the aircraft etc.

Aircraft propulsion systems may be very diverse in design depending on appointment of aircraft and engine type.

The engine type is the major factor determining a power plant design; therefore it is now accepted to classify power plants by the type of the engine used.

The power plant is a part of an aircraft, which besides a power plant contains airframe, systems, equipment etc. In turn, the power plant contains a number of systems, elements, components and units. These systems can be considered as functionally and structurally independent parts of the power plant.

The system is defined as an integrated entity made up of diverse parts that function together to perform required task. For a gas turbine power plant the following major systems are essential:

1. Propulsors (air propellers or main rotors with control mechanisms and mounting).
2. Engine mounts (for reliable attachment of engine with units installed on it (i.e. pumps, generators, cowlings) to aircraft structure).
3. Cowling system (engine nacelles and cowlings).
4. Air ingestion system (air intakes with their ducts).
5. Aircraft part of fuel system (to feed engine with fuel and to provide fuel storage onboard the aircraft).
6. Engine systems:
   - engine part of fuel system;
   - oil system;
   - starting system;
   - cooling system;
   - air intake control system;
   - exhaust system with thrust reversal and noise suppression devices;
   - fire-protection system;
   - ice-protection system;
   - engine automatic control system;
   - engine condition monitoring system;
   - air bleeding system.
7. Electric system.

The power plant structure includes some systems, which provide the engine operation. In turn, each system consists of several components connected among themselves by hydraulic, pneumatic or electric communications.

Structurally independent component of power plant that performs determined function on service of the engine is called as a unit.

Units may be classified and named in accordance with different features.

In accordance with functions, there are differed units of fuel system, oil system, starting system, automatic control system etc.

By functional attributes, there are differed units such as pumps, motors (engines), compressors, governors, metering devices, servomotors, starters, etc.

By used power, there are differed units with mechanical, electric, hydraulic, pneumatic and other drives.

Now the majority of units is unified products and can operate in combination with various types of engines. Such units include booster and transfer pumps, starters-generators, compressors, components of starting system, control units etc.

The power used by units of modern A/C, averages 3…5 % of total engine power and reaches 100…200 kW and more.

1.2 Requirements to aircraft power plants

A number of ways are used to increase speed, range and flight altitude, load-carrying capacity and also to improve aircraft take-off and landing performances.

In power plant developing, it is necessary to consider first of all a plane basic purpose (passenger, transport, sports-training etc.). Designers should adapt a power plant for the set basic purpose of the plane.

For example, at designing of the maneuverable plane, the key parameters are maximum flight speed and rate-of-climb, but it is also necessary to provide preset values of take-off and landing speed and range of flight.

For the passenger plane, primary economic indicators are cost of transportation of cargo and people, but at the same time the non-stop flight range, flight speed etc. play a considerable role.

Let's formulate the basic requirements to the aircraft power plant:

1. The power plant must generate required power or thrust.

Conventional aircraft produces 5…12 N lift per each 1 N of thrust depending on flight mode and lift-to-drag ratio.

For vertical/short take-off and landing (VTOL/STOL) aircraft, thrust of engines at a hovering mode must be more than AC weight (usually P / G = 1.3 … 1.4). These engines have no outstanding fuel economic properties but they reach minimum specific weight (m_{sp} < 0.007 kg of weight/N of thrust).

2. Minimum relative mass of power plant and fuel (ratio of mass of power plant (fuel) to take-off mass of the airplane)

$$\bar{m}_{PP} = \frac{m_{PP}}{m_0}, \ \bar{m}_f = \frac{m_f}{m_0}.$$

Type of aircraft	$\bar{m}_{PP}$	$\bar{m}_f$
Subsonic passenger and cargo	0.08...0.14	0.18...0.40
Maneuverable	0.18...0.22	0.25...0.30

3. Minimum specific fuel consumption (the mass of fuel necessary for creation a unit of thrust (power) at one hour). For the most powerful engines it makes:

$C_P, \left[\frac{kg}{N \cdot hour}\right]$	$C_e, \left[\frac{kg}{kW \cdot hour}\right]$	Engine
0.033	-	GE90-115B
-	0.224	NK-12
-	0.251	VD-4K
0.0662	-	D-36

4. The power plant must have minimum overall dimensions and weight, favorable aerodynamic configuration. Reduction of a power plant weight allows increasing payload, capacity of fuel tanks and consequently, flight distance.

5. The power plant should have high efficiency which is defined as

$$\eta_{pp} = 1 - \frac{\Delta N_{pp}}{N_e},$$

where N_e - effective power of the engine;

ΔN_{pp} - expenses of the engine`s power, related to power-plant placing on an aircraft.

6. The power plant must have *reliable start,* to be *trouble-free* in operation and *fire-safe* at all modes of flight, in a wide range of atmospheric conditions and admissible aircraft attitudes.

Correct and rational fire-safe designing of a power plant not only eliminates firing at normal operation, but also considerably reduces possibility of firing and fire propagation at emergencies.

7. The power plant must possess *high survivability*. (That is survivability must be provided at all operation modes of power plant in all conditions allowable for an aircraft).

8. The power plant must be efficient during the specified life-time at all

expected operating conditions.

9. The power plant must be convenient in operation, i.e. have easy access to structural elements for their inspection, checking, adjusting, mounting and dismantling, and be simple in repairing (has the minimum requirements to special equipment, tools and scarce materials).

1.3 Stages of power plants operating development

Correspondence of the engine to the requirements is provided at designing and proved at operating development and certification.

This is done by using scientific and technical groundwork and previous experience of engine development and maintenance. Experimental researches to ensure efficiency are carried out at all stages of the engine development.

The operating development occupies an important place in power-plant creation. It includes parametric, structural and strength operating development of engine parts, components and systems. Operating development is a method to solve problematic tasks that cannot be solved by fundamental science in current conditions. At operating development, lacks and errors are eliminated, which were committed at designing stage, and the working documentation of the engine is released.

At designing stage, the engine correspondence to requirements is proved experimentally.

Testing of the power plant is carried out on ground and in air. It consists of the following steps:

1. Testing of the engine using ground test rigs, where processes that take place in the engine and its systems are studied and analyzed. At this stage, construction of individual units, components and engine as a whole is studied, choice of materials and technology of manufacturing parts that determine the engine life time are checked, and recommendations for engine life time increasing and further engine improvement are formed.
2. Testing of the engine using special ground test rigs that provide conditions of high altitude flight. Climatic, altitude and speed performances of the engine are obtained, stable and reliable operating range is determined, starting and combustion at different conditions are checked, etc. High altitude lab is a complex, costly and high energy consuming system.
3. Testing of the engine on a specially equipped aircraft - flying laboratory. The flight performances of the engine are customized, its advantages and lacks are revealed.
4. The final testing of the power plant is carried out on the plane, for which the engine is designed.

The accumulated experience in engines designing, the availability of reliably operating prototype engines, the widespread use of computer technology combined with high level calculation models that are based on the finite element method (MFE) reduce the amount of finishing work and special inspections.

1.4 Modern directions of **GTE systems and components perfection**

1. The modern trend to reduce weight and cost of systems and components is the use of new materials, for example, composite material based on organic and metal matrices. Simultaneously, construction of units and parts is simplified.

2. Integration of units (for example hydraulic actuators with microprocessor-based system of positioning); this also decreases mass of the power plant.

3. Designing and application of pumps, which are operable at high temperature conditions. In engines with high bypass ratio, it allows transferring a gearbox with accessory units to the engine compartment between primary and secondary ducts, thus decreasing total weight of accessories and decreasing the engine midship diameter.

4. Application of gas-dynamic and active magnetic bearings.

Thus, accordingly to the program Oil Free Turbine Engine Technology (OFTET) NASA jointly with Williams International and Mohawk Innovate Technology develops small-sized engine without oil system, which will use the gas-dynamic bearings. This will allow:

- excluding the oil system;
- reducing engine weight by 15 %;
- reducing the labor content of power plant maintenance works;
- increasing reliability and safety;
- reducing operating costs by 8 %.

Rolls Royce Company announced designing of the engine based on the concept of MEE (More Electrical Engine). This is a three-shaft turbofan engine. It involves close integration of the engine, airframe and their systems, as well as transition to active magnetic bearings and elimination of oil system and gearbox.

5. Wide application in these systems of electric drives instead of the hydraulic ones.

Electric drives can improve fuel metering and ensure the work of the combustion chamber closer to the margin of the lean flame blowout. This provides high performance on emissions of nitrogen oxides. Application of electric drives in compressor mechanization and compressor air bleeding valves can exclude possibility of fuel vapors entering the interior.

An electric generator mounted directly on the fan shaft is proposed to use as an energy source of the system.

The engine is started by electric starter-generator mounted in the high-pressure shaft.

This program needs researches out in the area of electric and magnetic materials, materials with constant properties and electrical insulating materials.

2 FUEL SYSTEMS OF POWER PLANTS

The fuel system represents a complex of interacted subsystems designed to feed the engine with fuel at all operating conditions allowable for aircraft, moreover fuel systems can perform a number of additional functions such as cooling of oil, hydraulic fluid, air, electronic devices, keeping specified position of airplane center-of-gravity (CG), wing load alleviation, etc.).

The main functions of fuel system are:

- storing of required amount of fuel;
- fuel tanks refueling/defueling;
- fuel tank venting;
- reliable fuel supplying to engines at all of possible conditions and flight modes;
- ensuring specified aircraft CG position during flight;
- ensuring minimum unusable fuel in the tanks.

In addition, the fuel system should have minimum dimensions and weight, to be fire-resistant, have high survivability (for damage), and ensure the simplicity and speed of fuelling and the ability to fuel dumping (*jettisoning*).

2.1 Requirements to fuel systems

The fuel system must satisfy a number of requirements, which have general or specific (depending on the type of aircraft) character:

1. Reliable supplying of fuel to all engines at all expected operating conditions on ground and in flight.
2. Ensuring survivability and flight safety (including fire-prevention):
   - fuel tanks must not be arranged near passenger cabin or crew;
   - all metallic elements of a fuel system must be interconnected and also connected to the aircraft (and to ground at parking) in order to prevent discharge of static electricity;
   - at the distance of 500 mm from the tip, the wing must not be filled with fuel; to be on the safe side at lightning stroke.

Fuel pipelines are desirable to be placed inside the fuel tanks. In case of a leakage, the fuel bleeds to the fuel tanks, instead of blowing to the airframe.

3. The fuel tanks must contain reserve of the fuel required for flight with the specified maximum range (duration) and a stand-by reserve of fuel for 45 minutes of flight.
4. To maintain the specified CG position, fuel must be taken from different fuel tanks in a specified sequence automatically. In case of failure of the automatics, there must be a capability of manual control by fuel tanks usage.
5. Fuel must be filtered from mechanical impurities and water. The water dissolved in fuel and allocated from it in the fuel tanks or in some elements of the fuel system, must not disturb the fuel system operation.

6. It is necessary to protect units of the fuel system from corrosion, frosting-up, microorganisms, discharges of static electricity, overheating.

7. It is necessary to provide sufficient strength, vibration proofness and leak proofness.

8. It is necessary to provide full defueling on ground through easily accessible valves.

9. It is necessary to provide reliable and continuous control of the fuel system operation.

10. The fuel system must be simple in control, convenient in maintenance. Maintenance ground time of the fuel system must be minimum (this property is named as maintainability).

2.2 Aviation fuels and their properties

The main fuel for up-to-date aviation piston engines and jet engines are liquid mixes of hydrocarbons. They are recovered by crude oil refining. For jet engines, aviation kerosene is used. Working process of the piston engines limits period of fuel mixing with air, firing and combustion. Therefore easily inflammable fuel - aircraft petrol - is applied for aviation piston engines.

The engine start-up, thrust, efficiency, reliability of operation, etc. depend on fuel quality.

Let's consider the main properties of fuels, which should be taken into account when designing fuel systems.

1. Energy properties of fuel are determined by its ***calorific power and density***.

The mass calorific power of kerosene and petrol is approximately equal to 43000...44000 kJ/kg.

At the temperature of 20 °C density of petrol makes ρ = 720...740 kg/m^3, and of kerosene makes ρ = 755...850 kg/m^3.

Volumetric calorific power is the product of density of fuel by its mass calorific power. Hence, when storing the specified mass of fuel onboard the aircraft, smaller tanks are required for the fuels with greater density. Volumetric calorific power of kerosene is approximately 15 % higher than that of petrol. Therefore, kerosene is preferable.

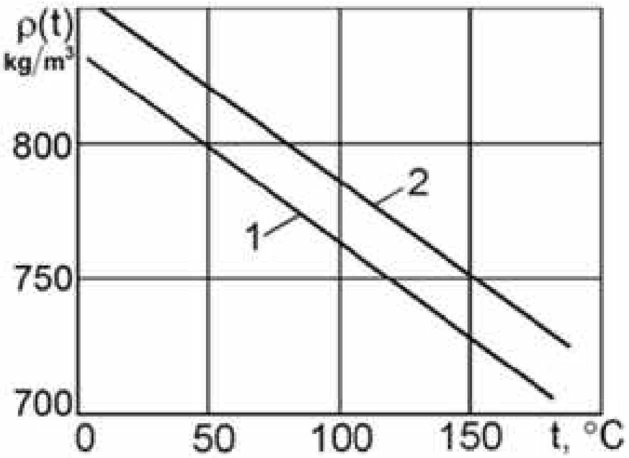


Figure 2.1 - Dependence of fuel density on its temperature:
1 - for fuel T-1; 2 - for fuel T-5

Density of fuel depends on its temperature by the following relation (Fig. 2.1):

$$\rho_t = \rho_{20} - \alpha(t - 20),$$

where ρ_{20} - density of fuel at the temperature of 20 °C; α - temperature correction to density (α = 0.7...0.9 kg/m^3 °C).

Decrease of density when being heated results in increase of the fuel volume. This fact shall be taken into account, when designing the fuel tanks. Otherwise there will be a pressing-out of fuel through the vent system. It can cause a fire. It is also inadmissible because we lose fuel.

2. ***Saturated vapor pressure*** (steam tension) of fuel is the important characteristics of fuels. It determines their evaporability, impacts to the altitude performance of the fuel system. The pressure p_t is the greatest vapor pressure being above fuel, which is reached at evaporation into a closed vessel at the specified temperature.

Aviation fuels are multicomponent liquids. Their saturated vapor pressure in a fuel tank depends on a ratio of volumes of steam and liquid phases. When pressure decreases, light fractions of fuel first pass in a gaseous state into the over-fuel space of the fuel tank. These light fractions have a high saturated vapor pressure. Thus steam tension of the remained fuel is reduced.

At evaporation in the closed volume, the equilibrium state steps with the greater steam tension of liquid part of fuel and the earlier, the smaller ratio of volumes of vapor and liquid phases occurs. The standard ratio of volumes of vapor and liquid phases is assumed equal 4/1. Thus saturated vapor pressure is designated by $p_{t4/1}$.

Fuels with higher saturated vapor pressure (for example petrol) vapors faster. It improves start-up qualities of engines.

Saturated vapor pressure grows with increase of temperature (Figure 2.2).

3. ***Viscosity*** of fuel determines hydraulic resistance in the fuel system, impacts to activity of the fuel system equipment, to engine start-up.

For instance, let's cite some values of factor of kinematic viscosity of aviation fuels:

Factor of kinematic viscosity, m^2/s depending on temperature, °C			
Fuel	-40	20	40
Petrol Б-70	$1.75\ 10^{-6}$	$0.69\ 10^{-6}$	$0.58\ 10^{-6}$
Kerosene T-1	$8.59\ 10^{-6}$	$1.63\ 10^{-6}$	$1.21\ 10^{-6}$

As it is shown in the table, the kinematic viscosity exponentially drops with increase of temperature (Figure 2.3).

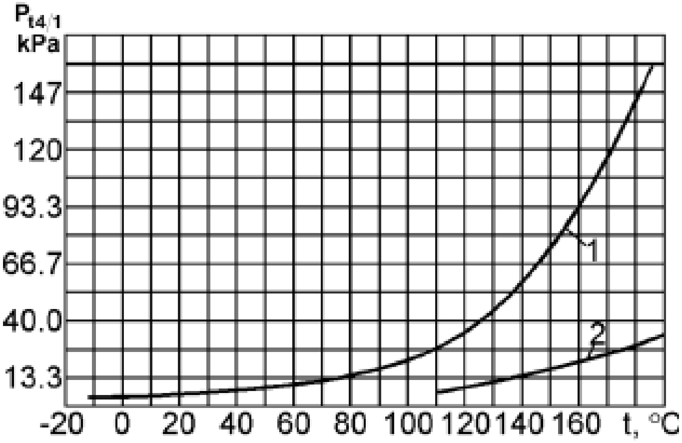


Figure 2.2 - Dependence of fuel saturated vapor pressure on its temperature:
1 - fuel T-1; 2 - fuel T-5

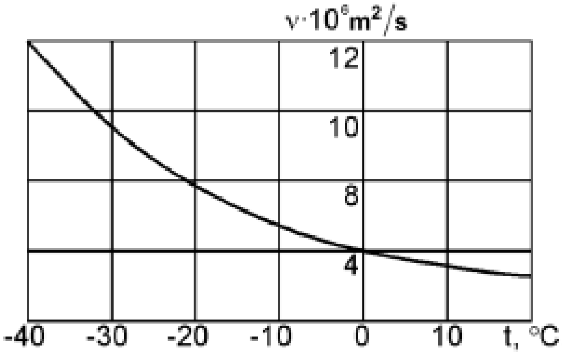


Figure 2.3 - Dependence of fuel kinematic viscosity on its temperature

4. Presence of ***water and mechanical impurities in fuel*** (dust, products of corrosion of pipelines and units of the fuel system, etc.) impairs operation of the fuel system.

Water penetrates into fuel as a result of dissolution of water vapors in air or as a result of condensation in volumes with fuel. Water can be contained in fuel in dissolved and not dissolved condition.

With fuel temperature increase, solubility of water in it increases. Thus an additional quantity of water from air dissolves in fuel. When temperature of fuel decreases this process goes in reverse order. Solubility of water decreases and definite quantity of water vapors. Some part of water falls out as water-fuel emulsions and precipitations.

Presence of water increases corrosion activity of fuel. It results in corrosion of pipelines, appearance of leakages, clogging of fuel by products of corrosion. Besides, forming of ice crystals is possible at cooling of fuel. These crystals clog fuel filters, equipment, pipelines.

Solubility of water in petrol is higher than in kerosene. However negative effect of water in the fuel system on kerosene is stronger than in the fuel system on petrol. It is caused by the greater viscosity of kerosene. Kerosene keeps the water educed from solution in suspension. In petrol, water rapidly falls out by gravity. Besides with increase of viscosity, water can be hardly separated in fuel filters.

To fight against ice formation in the fuel system, the following methods are applied:

- applying additives (for example, liquid ethylene glycolmonoethyl), lowering temperature of ice forming;
- injection of alcohol into the most vital filters;
- heating fuel by hot air taken from compressor of the engine or by oil from the engine oil system before passing the fuel in filters.

5. ***Solubility of air*** in fuel. About 10... 20 % of total volume of fuel consists of dissolved air. Solubility of air in fuel is directly proportional to tank pressure

and inversely proportional to density, viscosity and value of surface tension of fuel. With increase of flight altitude, the pressure drops, and air starts to separate intensively from fuel. It results in power swirling of fuel (cool boiling). The stream becomes two-phase, compressible, which leads to pressure fluctuations, vibrations and irregularity in fuel feeding to engine and its termination.

Oxygen dissolves in fuel better, than nitrogen. Therefore, the separated air has more oxygen than atmospheric. It increases explosibility of air-fuel mixture in the (over-fuel space) ullage.

When increasing the content of air in fuel, steam tension of fuel increases too.

6. ***Thermal stability*** of fuel. When increasing the temperature above 120...150 °C, a number of aviation fuels form insoluble precipitates and retinoid sediments. It results in violation of fuel system equipment operation. Filters clogging can result in full failure of the system. The reason of it is oxidation of chemical compounds containing sulfur and nitrogen. These chemical compounds are present in fuel in a small amount.

7. ***Charges of a static electricity*** store at motion of fuel in pipelines and units of the fuel system. To prevent accumulation of the charge they apply careful filtering of fuel from impurities, which reduces conductivity of fuel. Some antistatic fuel additives are also applied. To eliminate discharge of static electricity all pipelines and units of the fuel system are electrically bonded. E.g. they are connected in one loop.

There are a lot of aviation fuels. They are divided into two groups: petrol and kerosene. Aviation petrol is marked by the letter and a figure. This figure designates the octane number of the petrol. Aviation kerosene is marked by the letter "T" and a figure. This figure designates a fuel specification. Characteristics of particular fuel can be found in handbooks.

Let's shortly consider the fuels.

Fuel T-1. Specification of aviation kerosene, used for the jet aircraft, differs in relatively small kinematic viscosity in a design temperature range [-60, +60]°C, but has a relatively high saturated vapor pressure of fuel $p_{t4/1}$. This fuel production is very limited.

Fuel TC-1. Specification of aviation kerosene, intended for jet aviation, differs in small kinematic viscosity in a design temperature range [-60, +60]°C, and a high saturated vapor pressure of fuel $p_{t4/1}$. The abbreviation is decoded as “Fuel sulfurous first” as it is made of the petroleum grades containing big quantity of sulfur. It results in essential carbonization into fuel nozzles of jet engines. But it is cheaper than previous. It is the main domestic fuel.

Fuels Jet A and **Jet A-1**. Specifications of aviation kerosene, intended for commercial jet aviation. They distinguish high freeze point ($-\mathbf{40}\,{}^{\circ}\mathbf{C}$ for Jet A and $-\mathbf{47}\,{}^{\circ}\mathbf{C}$ for Jet A-1), increased flash point ($\mathbf{38}\,{}^{\circ}\mathbf{C}$) and relatively high density (***771...830*** kg/m^3).

2.3 Structure of fuel systems and their arrangement **in the aircraft**

Fuel system is designed to arrange required fuel capacity onboard aircraft and to uninterruptible fuel supply into engines at all possible modes and operating conditions of the aircraft. The fuel system of modern aircrafts can be conditionally divided into plane (airframe) and engine parts.

Airframe Fuel systems consist of:

- subsystem of fuel storage (fuel tanks);
- subsystem of fueling;
- subsystem of fuel transfer;
- subsystem of venting and pressurization of the fuel system;
- fuel jettisoning subsystem;
- subsystem of support of the specified center-of-gravity position;
- measuring subsystem of the fuel consumption and remaining fuel control subsystem of the order of fuel use.

Engine fuel feed system is designed to supply fuel to the main fuel nozzles and pilot fuel injectors in amounts to provide engine performance at all engine operating modes and under all operating conditions. Engine fuel feed system will be considered separately later.

The plane part includes the following basic elements: tanks, pipelines, intakes, valves, shut-off valves, filters and separators, pumps, fuel level indicators, flow meters, synchronizers, fuel equalizers etc.

Besides, many modern fuel systems include various command lines - electric, hydraulic and pneumatic.

The listed elements of fuel system on functional attributes can be combined in the mentioned above subsystems.

When designing fuel system the following rules are usually carried out.

To increase survivability of the system, fuel tanks are combined in several groups with independent fuel feeding of engine from each group to ensure that the failure of one pipeline or tank did not lead to failure of the entire system.

It is recommended to install a supply (feed, sump, recervior) tank near the engine so it is easier for protecting from damage. Fuel feeding in this case becomes simpler at plane evolutions, switching of tanks and also reduces the number of booster pumps and decreases power for their driving.

It is necessary to avoid lining of fuel pipelines close to heated engine parts. If this is not possible, the pipes must be insulated and placed under the hot parts of the engine. At loss of tightness fuel must not get on hot parts, to a cockpit, accumulate in closed compartments.

Tanks and fuel pipelines are arranged in such a way that at landing with gear retracted the possibility of their damage was minimal.

Fuel lines must not be subjected to bending, vibration, torsion, rupture, so they are connected with the aircraft by means of flexible hoses, expansion joints, etc.

For ease of use, individual units of the system (such as filters, pumps, valves, etc.) are desirable to group together.

To prevent the formation of steam and air pockets and water freezing in the fuel line, elbows pipe bends must be avoided at 180° in the vertical plane.

For reliable operation of the system all fuel entering the engine must pass through filters. Fittings of fuel returning to the tank must be removed from intake fittings.

2.4 Schemes of fuel system

The following ways are applied to supply (use) the fuel from tank: gravity feeding, forced out feeding and pump feeding.

At gravity feeding (Figure 2.4, a), fuel goes into the engine due to potential energy of the difference of levels between the fuel tank (which must be higher) and the engine. This scheme is the easiest and simplest. However at changes of aircraft attitude, this fuel feeding stops. It is applied on aircraft (especially on super light aircraft) with low-powered piston engines because the required pump inlet pressure of such engine is rather small.

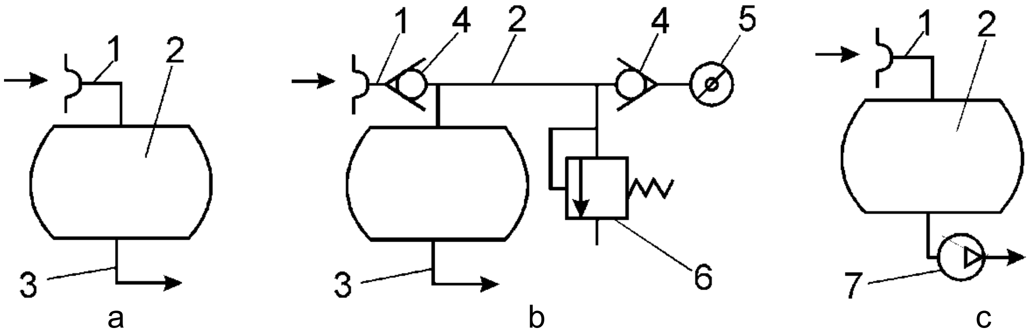


Figure 2.4 - Ways of fuel feeding from fuel tanks:
1 – air intake from atmosphere; 2 – fuel tank; 3 – fuel supplying pipeline;
4 – check valve; 5 – air intake from compressor;6 – safety valve;
7 – buster pump of an airplane

At forced out feeding (Figure 2.4, b), gas is fed into the ullage of the fuel tank. It can be air from atmosphere, exhaust gas of piston engine, inert gas from bottles with overpressure (15...30 kPa) which forces out fuel into the pipeline (thus the fuel tank can be even below the engine though it is undesirable). It results in increasing the altitude performance of the fuel system without using booster pumps. However the mass of fuel tank, loaded outwards with pressure, also increases. The system has low survivability at a fault of the fuel tank. It is applied usually in combination with pump feeding. It is applied in the pure state in external tanks and in rockets or sometimes to transfer fuel into the supply fuel tank.

The pump feeding (Figure 2.4, c) allows providing: emptying of fuel tank arranged below the engine; sufficient altitude performance without increasing mass of the fuel tank. However the mass of fuel system increases due to pumps; fire danger increases at the installation of electric pumps in the fuel tank. Now such way of feeding, in a combination with small overpressure, is the most efficient by mass and is widely used.

Let's consider schematic diagram of the pipeline of fuel feeding to the engine by booster pump (Figure 2.5). The fuel tank 3 is fueled through the filler neck or the pressure fueling connection 2. The fuel tank is vented through the venting subsystem 1. On up-to-date aircraft the multistage fuel boost is applied. Usually one boost pump is installed in the fuel tank; it is so-called *boost pump of an airplane* (BPA) 5. Then one more boost pump is placed at the inlet fuel line of the engine, it is so-called *fuel boost pump of engine* (BPE). Then the engine main pump follows; it is so-called main fuel pump (MFP) 20. Thus BPA generates required pressure at the BPE inlet. BPE provides required pressure at the main fuel pump inlet. Advantages of such two-stage scheme of fuel supplying are the following:

– smaller total mass of BPA and BPE, and smaller power to drive them comparing to scheme with one pump;

– the smaller pressure in pipelines, hence the smaller leakages of fuel.

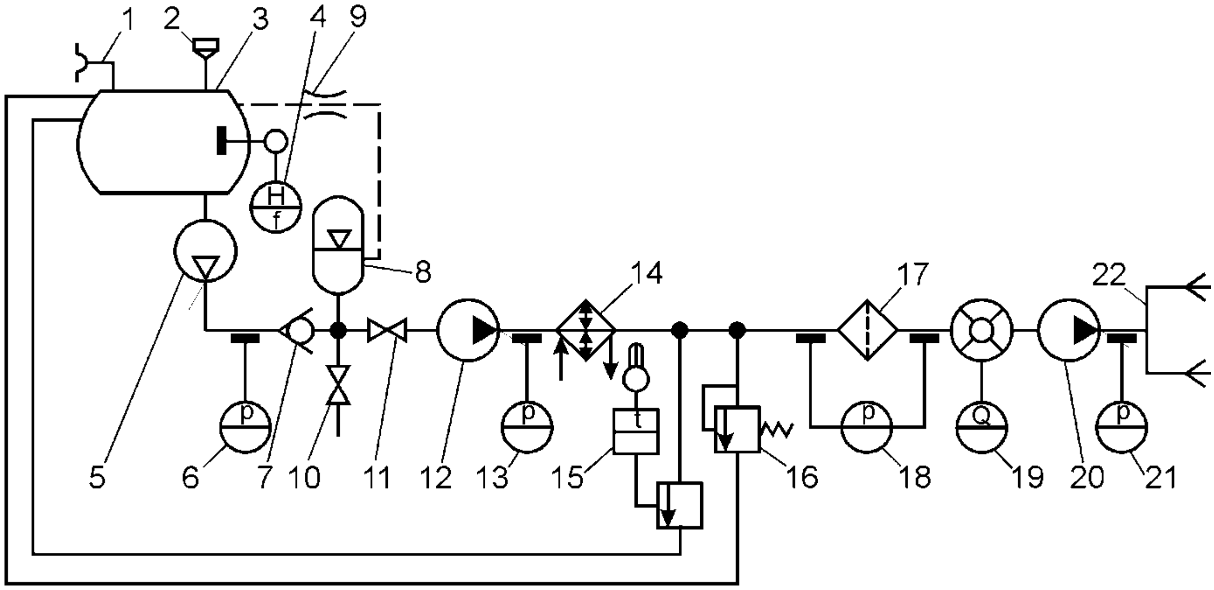


Figure 2.5 - Scheme of fuel feeding to engine by booster pump

The check valve 7 provides the required direction of fuel motion. It is required at the parallel installation of two BPA. When one of them fails, fuel will not overflow back in the fuel tank. The check valve is also required before connection of the fuel accumulator 8 or at opening the cross-feed valve 10. The fuel accumulator serves for short-time supply of the engine with fuel at outflow of fuel from the pump, and also for damping of pressure fluctuation behind the pump. Air from the accumulator chamber of the fuel fed into the tank via the bleed (orifice) 9.

The fuel emergency shut-off valve 11 cuts off the fuel feeding to the engine at a fire, and also at on-ground replacement of the engine. At cooling oil by fuel, the fuel-oil cooler 14 is installed in the fuel feeding pipeline. It also heats fuel.

Thus the filter 17 is protected from a frosting-up, and fuel atomization is improved. If the fuel flow consumed by the engine is less than the fuel flow required for oil cooling, a part of fuel passed the cooler returns back the fuel tank by interconnecting pipeline supplied with the thermostat 15. The relief pipeline with the relief valve 16 bypasses fuel to the fuel tank at overpressure (after the engine stops).

The test and measuring equipment is represented by: the fuel quantity gauge 4, the pressure switch 6, the pressure gauge 13, the filter failure switch 18, the flow-meter 19 and the pressure gauge 21 placed before the fuel nozzle manifold 22.

At a great amount of fuel, big fuel tanks are required for its storage. Difficulties of arrangement of the big fuel tanks and the big inertial loads on their walls force to use some fuel tanks of smaller sizes (but their number increasing accordingly). Some fuel tanks can be connected in group. There are two types of fuel tanks connection: in parallel and in serial.

Tanks are combined into groups by their ***serial connection*** (Figure 2.6) to organize the rational engine fuel supply with low hydraulic pressure losses, low mass pipelines and to provide the necessary range of CG position. Thus, a group of tanks can be considered as one large tank with baffles. The tank in which the BPA is mounted is called as ***supply tank***, and pipeline connecting the supply tank and BPE – ***intake pipeline***.

The BPE driven by the gearbox and fuel system components installed behind it in supply line upstream the fuel nozzles are part of the engine fuel system.

The fuel supply line with the ***connected in parallel groups of tanks*** (Figure 2.7) enables to control the fuel flow under any program.

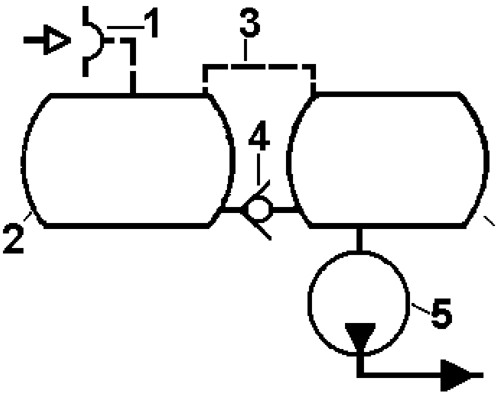


Figure 2.6. Series connection of tanks in a group:
1 – atmospheric air intake; 2 – tank;
3 – venting link pipeline; 4 – check valve;
5 – low pressure pump BPA;
6 – supply tank

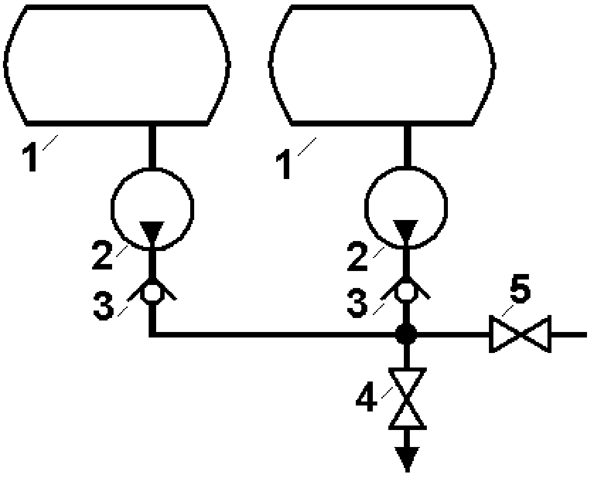


Figure 2.7 - Frame of diagram of the engine fuel feed line with connected in parallel tanks:
1 – tanks; 2 – low pressure pumps (BPA);
3 – check valves; 4 – fire-protection valve;
5 – cross-feed valve

The pump of one tank (one group) can operate at an operating mode, which is distinct from operating mode of the pump of another tank (of other group of tanks). The survivability of a fuel system at such grouping of tanks is increased. To carry out such a scheme it is necessary to dispose BPA in each group of tanks, which increases structural weight and complicates fuel supply system.

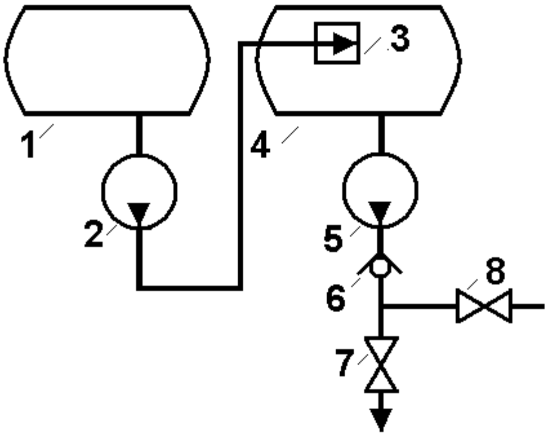


Figure 2.8 - Frame of diagram of the engine fuel feed system with serially connected tanks:
1 – tanks; 2 – transfer pump;
3 – float relief valve; 4 – supply tank;
5 – low pressure pump BPA; 6 – check valve; 7 – fire-protection valve;
8 – cross-feed valve

The fuel feed line with serially connected groups of tanks (Figure 2.8) is made so, that from each group the fuel is guided to a supply tank, and from it flows to engine. This scheme allows lowering a mass of pipeline, as it is required less pumps, the number of pipelines is reduced and it is possible to apply a prime control system. However presence of a supply tank reduces survivability of a fuel system. In fuel systems with the serially joint groups of tanks, the fuel is self-flowing to supply tank by gravity or is transferred by a pump. To perform these operations, self-flowing or transfer lines are used. The transfer pumps (TP) supply the fuel from one tank to another with pressure required only to compensate the hydraulic losses in the transfer pipeline. Therefore they need the smaller pressure head than BPA needs. The supply tank overflowing is prevented by the limiting level float valve.

Outlet connections through which the fuel flows from a tank to the pipeline must protrude into the tank to prevent the engine from entering mechanical impurities and water, settling on the bottom of the tank.

Fuel tanks of maneuverable airplanes need special equipment to provide fuel supplying at negative overloads, i.e. at inverted flight. The movable or twin intakes are applied in such tanks, which switch fuel feeding to a top of tank under action of forces throwing fuel.

Duration of operation at negative overloads is set in the technical specifications and, as a rule, does not exceeds 15 … 30 seconds; the fuel content in tanks should be not less than 25 % of a tank capacity.

To feed engine at the weightlessness, the special fuel accumulators are applied. The fuel accumulator represents a tank, which contains an elastic bag inside, constantly filled with a fuel. The cavity between a bag and a tank is filled with compressed air. The accumulator enters activity automatically if the pressure created by the low pressure pump BPA drops below the forcing out pressure of the accumulator.

If there is more than one engine in the airplane, the following schemes of fuel feeding are applied:

Independent feeding at which fuel from definite group of fuel tanks is fed to the particular engine.

Centralized feeding at which fuel from one supply fuel tank is fed to all engines.

Centralized-independent feeding at which fuel from each supply fuel tank is fed to particular group of engines (for example to engines arranged on one wing).

The reliable fuel feeding to engines is provided by applying cross-feeding or duplicating a booster pump and using recuperators.

Cross-feeding (cross-over) of engines with fuel is applied for aircraft with more than one engine, except using a centralized feeding. The cross-feeding lies in the connection of pipelines going from each supply fuel tank to each engine with additional pipeline. At normal operation, this fuel cross-feed line is blocked by valves (cross-feed valves). At failure of a pump of one of supply fuel tanks, the cross-feed valve will be opened, and fuel from the supply fuel tank with working pump will start flowing to the both engines. Thus fuel from the group of fuel tanks with the failed booster pump cannot be used, that affects the range and CG position. In other situation, when one engine fails, fuel from two consumed fuel tanks can feed the operating engine.

Duplicating of BPA represents the installation in parallel two operating BPA, each of them is capable to provide feeding of the engine with fuel.

Redundancy of BPA represents installation, in parallel with operating BPA, another BPA normally stopped each of them is capable to provide feeding of the engine with fuel. The second BPA can have other type of drive.

The recuperator represents a section of a supply fuel tank equipped with devices eliminating outflow of fuel from the pump. In the simplest case these devices are check valves which pass fuel only in section. Sometimes the fuel accumulator is applied to feed the fuel in the engine at negative overload.

2.5 Venting and Pressurization of Fuel System

The purpose of venting and pressurization system is providing pressure inside fuel tanks in the definite limits, ensuring fuel feeding to engines, fuel filling and dumping. To provide the fuel system operation without cavitation, decreasing of fuel evaporation, keeping shape and strength of fuel tanks (a thin-walled shell structure), a definite overpressure shall be supported in the fuel tanks. Otherwise during feeding or fuel dumping, pressure in the fuel tank will be decreased. It complicates feeding and makes contortion of the fuel tank possible. At pressure fueling the venting system shall provide a free vent of air from the fuel tanks. Otherwise the fuel tank can be torn by overpressure.

Depending on the type and the purpose of the aircraft, the vent system is designed under various schemes. The system connecting tank airspace with atmosphere is called an ***open vent system***. The system connecting tank airspace with any source of air (compressor of the engine, bottles with gas) is called a ***closed vent system***. The system connecting tank airspace either with atmosphere, or with any source of air, depending on flight conditions, is called a ***combined vent system***.

Venting of fuel tanks group can be separate (personal) or joint (collective). In the latter case, consecutive or parallel connection of fuel tanks is possible (Figure 2.9).

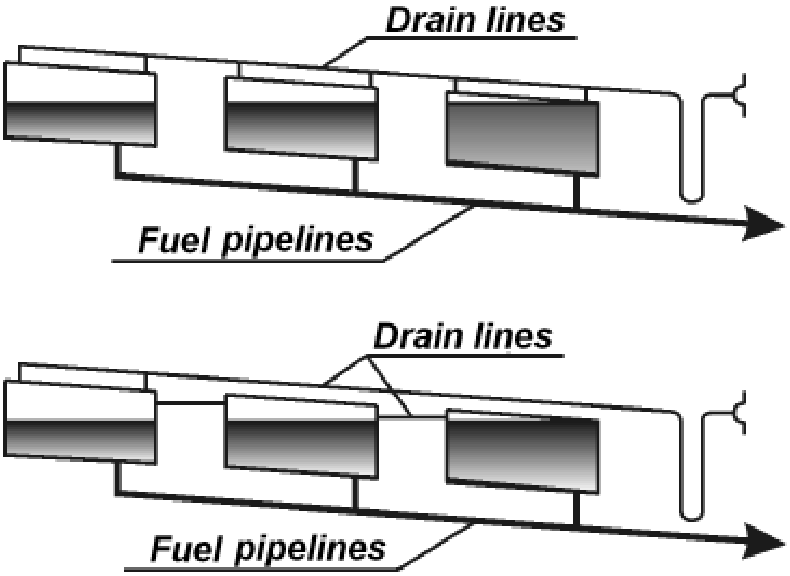


Figure 2.9 - Venting of fuel tanks group

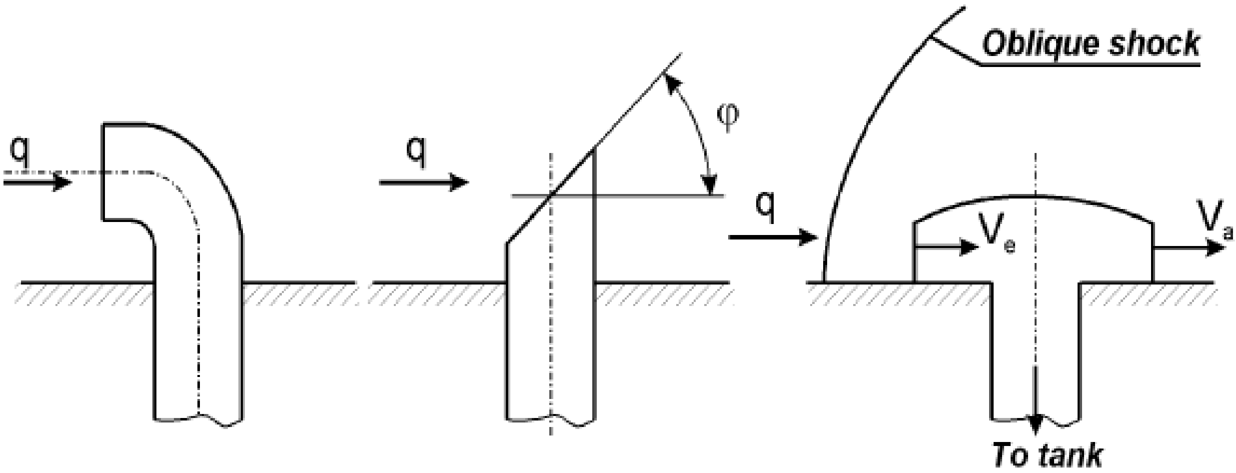
Essential disadvantage of the separate venting is different pressures in fuel tanks. This pressure difference causes uncontrolled overflow of fuel between fuel tanks. It disturbs the specified sequence of fuel usage and effects aircraft CG position.

The connection group of fuel tanks with over-all venting pipeline makes the system more complicated and heavier. But thus equal pressure in fuel tanks is provided.

Input of pipelines in fuel tanks should be designed so that at maximum fuel quantity, fuel tank were provided with direct (not through the fuel) venting of tank ullage with an atmosphere or any source of air.

When aircraft changes attitude, various points of fuel tank appear upper (that is probably in fuel tanks of irregular shape), input in fuel tank is doubled for greater reliability of venting.

At the open vent system, the air passes through small external pipes – air intakes of various types (Figure 2.10).



a b c

Figure 2.10. Types of vent air intakes

The air intake (Figure 2.10, a) fully uses the ram pressure. Thus $K_\varphi = 1$. However for up-to-date aircraft maximum ram pressure, which can be reached in the flight, considerably exceeds required fuel tank pressurization. To decrease used ram pressure, air intakes with a cant (Figure 2.10, b) are applied, or special safety valves are installed. Selection of air intake is carried out after comparison of various versions.

At supersonic flight speed, an oblique shock appears in the front of the vent air intake. Behind the oblique shock, the increased pressure is formed. It results that the overpressure in the tank can appear too big. In this case it is necessary to use safety valves.

Other solution of this problem is application of the air intake with blowing out. Such air intake can work at both supersonic and subsonic flight speeds (Figure 2.10, c).

The vent air intake is usually arranged on a bottom surface of the aircraft, to prevent dust and mud getting jointly with air into the fuel system on ground.

To prevent fuel spillage through a vent system when aircraft changes attitude, the venting pipeline is designed as a loop in a vertical or horizontal plane (Figure 2.11). However in the lower part of such loop-shape segment of pipeline, fuel is accumulated and overlaps the venting. For collecting and removing the fuel from the vent system in such cases, vent tanks are installed.

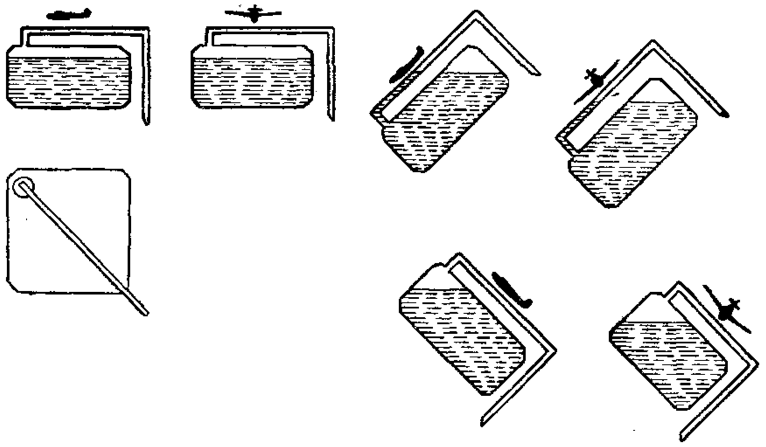


Figure 2.11 - Arrangement of venting pipeline

It is necessary to protect the vent air intakes from icing.

At the closed vent system, the fuel tank pressurization is carried out by air from compressor of the engine, air or neutral gas from onboard bottles. The closed vent system allows supporting the required pressure in over-fuel space. However disadvantages of the closed vent system is big mass of bottles and lower survivability of fuel tanks in the case of damage.

2.6 Fueling system

There are two ways of fueling: over-wing fueling and pressure one.

At ***over-wing fueling***, the filtered fuel is fed by the flexible hose through the fuel discharge nozzle directly to the filler neck from the fueling device. It is arranged on the upper side of the fuel tank. In the case of grouping of fuel tanks, fuel can overflow into the other fuel tank by connecting pipes. The filler necks are designed according to the used standards. The fueling time of all fuel tanks should not exceed the specified value (about 30 minutes).

Over-wing fueling has a number of disadvantages.

– Long fueling time. (The fueling rate in connecting pipelines is low. It is required to open and close each filler neck, to move the discharge hose, to switch on and off the pump of priming device for filling.).

– Necessity of location of ground maintenance personnel near filler necks arranged usually on the wing. Ladders, step-ladders, long hoses are required for this purpose. These movements lead to damages of paint coating of the wing. In winter these movements on icy wing face are dangerous for the people.

– Fire danger is increased at fuel evaporation.

– Moisture and a dust can probably get into the fuel tank through the upper filler necks.

These disadvantages can be removed at ***pressure fueling*** (Figure 2.12). In this case the filtered fuel is fed by the flexible hose to the single point refueling (SPR) receptacle of the aircraft from the fueling device.

The pressure fueling provides a number of advantages.

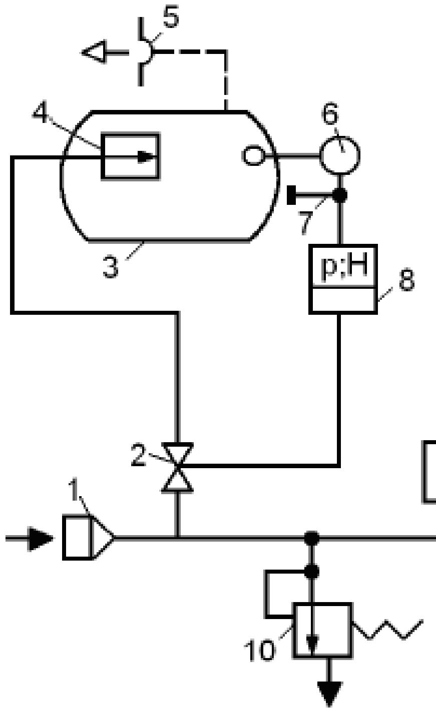


Figure 2.12 - Diagram of the single-point pressure fueling: 1 – receptacle; 2 – main shutoff valve; 3 – tank; 4 – refuel valve; 5 – outer pipe branch of the venting pipeline; 6 – magnetic level sensor; 7 – pressure sensor; 8 – control panel; 9 – vacuum valve for a fuel scavenge from the pipeline; 10 – relief valve of the limit pressure

– Low fueling time.

– The fueling is carried out through one or two fueling connections. (Therefore such fueling may also be referred to a «single-point pressure fueling»).

– To decrease the length of discharge hoses and for maintainability, these fueling connections are arranged in the lower parts of aircraft. Thus people movement on wings is not needed.

The fueling connections and nozzles of discharge hoses are designed by the international standards.

The sequence of the pressure fueling can be different serial or joint. Serial tank fueling takes more time, than joint. But the serial fueling provides a capability to fill not all fuel tanks with fuel, but only specified.

Thus there are also a number of disadvantages:

– A high speed of fuel flow within the pipelines (more than 25 dm^3/s), a big length of fueling pipelines and presence of special control devices cause in the big hydraulic pressure losses. Hence, the high power of the pumps installed at fueling devices is required.

– The fueling pipelines and the control devices are arranged onboard the aircraft and increase its mass.

– The maximum fuel quantity is impossible to be filled by press fueling owing to response of maximum level valves. Therefore over-wing fueling devices are kept onboard the aircraft.

Through a receptacle 1 the fuel flows in a filling line. The filling valves 2 are opened through cutout switches. The valve position is indicated by the lamps. After fueling of the tank 3, fuel magnetic level sensors 6 (and at recompression also the warning indicators 7) give commands on automatic closing of the filling valves. To increase reliability of overfilling prevention, magnetic sensors are duplicated by floating warning indicators of a level, which double commands on closing of filling valves.

In failing of the valve there are relief float valves of a limit level 4, not supposing overflowing of tanks and ejection of a fuel through the drain pipelines. At overpressure, the relief valve 10 operates. The vacuum valve 9 provides fuel pumping from the pipeline. The fueling control panel 8 includes indicators of the fuel content in

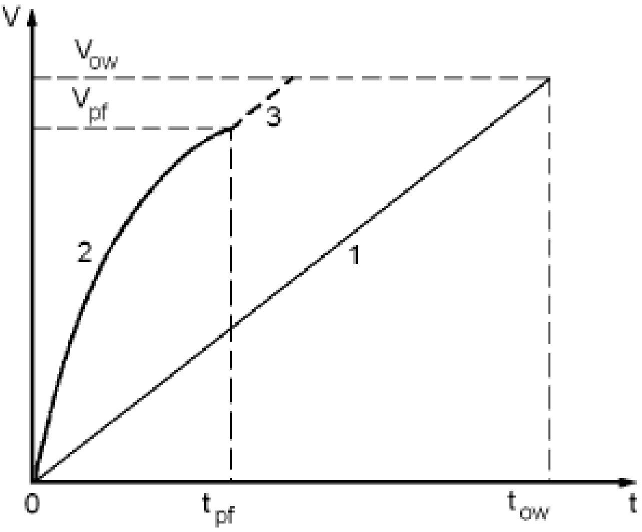


Figure 2.13 - Relation of the tank fueled volume from the time for different methods of fueling:
1 – pressure fueling; 2 – over-wing fueling;
3 – over-wing refueling

tanks. Fueling may be controlled automatically or manually.

The pressure fueling (curve 2 in Figure 2.13) is executed faster, but the filled volume is less, than at an over-wing fueling (curve 1). It is explained to that float devices, located inside a tank, (magnetic sensors, warning indicators of a level, the relief valves) work up before a full tanking. At pressure fueling, the over-wing manual replenishing (curve 3) is necessary.

Some airplanes are equipped with special system that serves fueling in air from the tanker airplanes, specially designed for this purpose. The replenishing of airplanes in air allows extending the range, facilitating take-off, increasing effective load and reducing takeoff distance.

2.7 Calculation of fuel system parameters

At designing a fuel system the following problems are solved:

- calculation the required capacity of fuel tanks;
- arrangement of this fuel on the aircraft;
- designing the scheme of fuel feeding to engines and calculating of altitude performance of the fuel system;
- designing the scheme and calculation of venting subsystem;
- designing the scheme and calculation of jettisoning subsystem;
- designing the scheme of fueling subsystem;
- calculation of sequence of fuel usage;
- designing the subsystem of supporting the specified CG position;
- designing the subsystem of fuel transferring (for tankers).

Let consider some of them in more details.

Altitude performance of fuel system

Altitude performance of fuel system is the maximum flight altitude of aircraft, at which the fuel system provides uninterruptible fuel feeding to the engine.

The primary limiting factor for flight altitude of fuel system is cavitation. Cavitation is the process of air-vapor bubbles formation in a depression zone and their following collapse in a pressure space.

Cavitation is a harmful phenomenon. Thus the two-phase medium (air + fuel) is formed. It results in decreasing of fuel mass flow through the pump, in pressure fluctuation, in malfunction of fuel feeding and even in engine flameout. Cavitation usually destroys internal surfaces of fuel system units. But as fuel is multicomponent medium, formation and collapse of bubbles is spread in time. Thus destruction does not take place. A place of the most probable appearance of the cavitation is a pump inlet. Thus the problem of designing calculation of altitude performance is determination of fuel pumps operation conditions without cavitation. The problem of checking calculation is determination of altitude performance of the given fuel system.

Theoretically, the fuel system failure (cavitation) takes place when pressure equals to saturated vapor pressure of fuel. Practically fuel contains dissolved gases which are beginning to release at a pressure greater than $p_{t4/1}$. Besides, pressure in the pump will be less than the pump inlet pressure. It results in appearing the cavitation earlier, than pressure will be lowered up to saturated vapor pressure at fuel pump inlet. That is at the smaller altitude. Therefore for reliable operation of pumps, it is necessary to create some overpressure at the pump inlet. It is called the cavitation margin Δp_{cav} (Figure 2.14). Then the minimal required pump inlet (suction) pressure providing pump operation without cavitation, is determined by the relation

$$p_{in} \ge p_{in.min} = p_{t4/1} + \Delta p_{cav}.$$

This condition must be satisfied at all flight modes, at all possible load factors and temperatures. This condition is the main condition in the altitude performance calculation.

The cavitation margin and the pressure difference, created by the pump for pumps of various purposes, are shown in the Table 2.1.

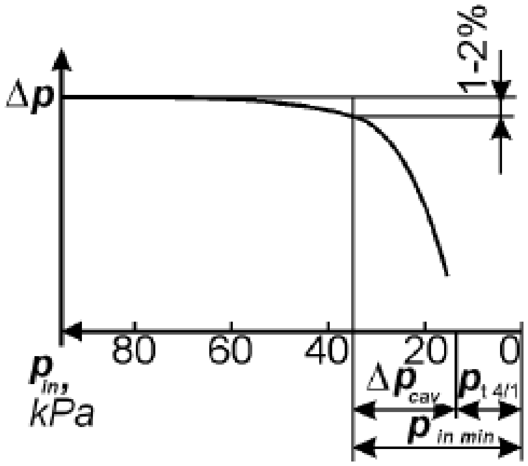


Figure 2.14 - Cavitation characteristics of pump

Table 2.1 – Characteristics of different pumps

Type of the pump	Δp_p, MPa	Δp_{cav}, MPa
BPA	0.1...0.15	0.01...0.025
BPE	0.5...0.6	0.03...0.08
MFP	6...8	0.15...0.3

To carry out the calculation of the fuel system altitude performance, it is necessary to know:

- lay-out diagram of the fuel system in three projections, with the directions and lengths of pipelines and the locations of components;
- required fuel volume flow depending on the flight mode (M, H, throttling back);
- fuel properties (density, kinematic viscosity, saturated vapor pressure) depending on temperature;
- cavitation and pressure properties of pumps.

According to Airworthiness Requirements - 3, the calculations are carried out for the most adverse and heavy operating conditions:

1. *Flight at the altitude of maximum speed* (for airplanes with the ceiling

above 11 km, it is 11 km). The engine power is full throttle power or power augmentation. The load factors are the most adverse in their effect to pressure at BPE inlet (for civil aviation $n_x = -0.3...0.3$; $n_y = -0.5...3$; $n_z = 0$).

Designed fuel temperature is maximum (for subsonic airplanes it is more or equal to 45 °C; for supersonic ones it is more or equal to 100 °C).

2. *Flight at the ceiling*. The altitude is: the absolute ceiling - for non-maneuverable airplane; the zoom altitude - for maneuverable airplane. The flight speed corresponds to the ceiling. The engine power is full throttle power or power augmentation. Load factors are $n_x = 0$; $n_y = 1$; $n_z = 0$, i.e. inertial losses are absent.

3. *Flight at the mode corresponding to maximum fuel flow*. The engine power is full throttle power or power augmentation. Considered fuel is the most viscous among used in the airplane. The designing fuel temperature is minimal (-50...-60) °C. One BPA feeds two engines with the cross-feed valve opened.

Conditions of operating of the fuel system with failed BPA (inertial losses are assumed equal to zero).

4. Takeoff power. The altitude is 2000 m.

5. Cruising power. The altitude is 6000...8000 m.

Altitude performance calculation

Altitude performance calculation of a fuel system is based on definition of requirements ensuring cavitation-protected operation.

The basic value determining normal operation of the fuel system is the pump suction pressure p_{in}^{BPE}, which for prevention of a cavitation must exceed the fuel saturated vapor pressure $p_{t4/1}$ on a value of the cavitation margin Δp_{cav}^{BPE}:

$$p_{in}^{BPE} > p_{in.min}^{BPE} = p_{t4/1} + \Delta p_{cav}^{BPE}.$$

This relation is to be satisfied at all flight modes of an aircraft at all overloads and temperatures of a fuel.

Let's consider the equation for the minimal required pump inlet pressure providing pump cavitation-protected operation for two cross-sections T-T (tank) - E-E (engine):

$$p_{in}^{BPE} = p_H + \Delta p_T + \Delta p_{BPA} - \Delta p_{hyd} - \Delta p_{in} + \rho_f g \left(y_T - y_E \right) > p_{in\,min}^{BPE}.$$

The design diagram is shown in Figure 2.15.

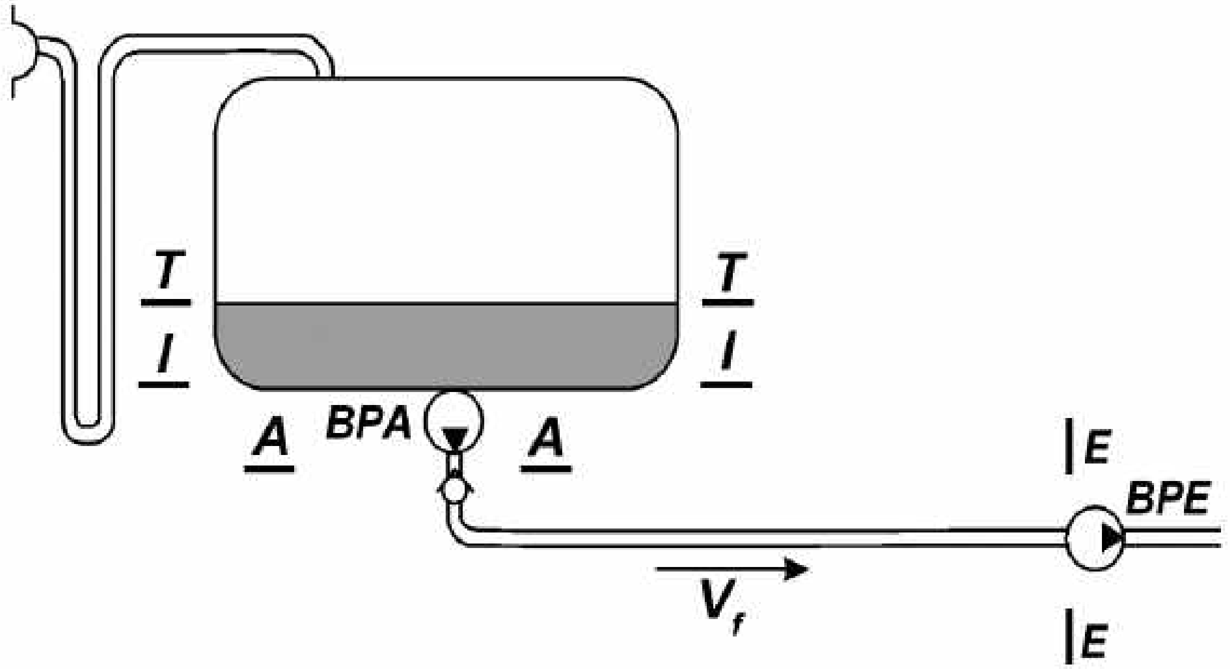


Fig. 2.15. Fuel Pump Feeding to BPE

Let's consider the values, which are included in this equation:

p_H - pressure at the specified altitude (taken from ISA).

Δp_T - overpressure created in the fuel tank by the ram pressure (opened venting) or by the pressurization system (closed venting); pressurization can be carried out by bottles with neutral gas or by the engine compressor; value of the ram pressure that is used for creation of overpressure in a fuel tank, depends on the type and dimensions of vent air intake tube; (usually for airplanes with gas-turbine engines Δp_T =0.02…0.06 MPa). For vent air intake tube (see Figure 2.10, b)

$$\Delta p_T = q\, cos 1.5(90 - \varphi),$$

where q -air ram pressure (this formula is valid for $\varphi = [30...90]^\circ$ at subsonic flight speed);

ρ_f - density of fuel;

y_i - level in the corresponding point of the supply pipeline;

g - acceleration of gravity.

p_{hyd} - hydraulic losses into the pipeline segment. They summed up of friction losses p_{fr} and form losses p_{form}; pressure losses caused by friction may be approximately determined by the formula

$$p_{fr} = \lambda \frac{l}{d} \frac{\rho_f V_f^2}{2},$$

where λ - friction drag coefficient;

l - length of the pipeline;

d - average diameter of the pipeline;

V_f - average fuel speed in the section of the pipeline (if volumetric flow Q of fuel is known, the speed is determined by the formula $V_f = 4Q / \pi d^2$).

The friction drag coefficient λ depends on the fuel flow mode determined by the Reynolds' number

$$Re = \frac{V_f d}{\nu} = \frac{4Q}{\pi d \nu},$$

where ν - factor of kinematic viscosity.

For the laminar fuel flow mode, when $Re \le 2300$, the friction drag coefficient $\lambda = 64 / Re$.

For the turbulent flow mode, when $3000 < Re \le 10^5$, the friction drag coefficient $\lambda = 0.3164 / \sqrt[4]{Re}$; when $10^5 < Re \le 5\,10^6$, the friction drag coefficient $\lambda = 0.09 / \sqrt[7]{Re}$.

For flexible hoses the friction drag coefficient must be increased by 30 %: $\lambda_{f.h} = 1.3\lambda$.

Form losses appear when changing the cross-section or direction of the stream that promotes vortex generation. Form pressure losses are determined by formula

$$\Delta p_{form} = \Sigma \xi_{form} \frac{\rho_f V_f^2}{2},$$

where ξ_{form} - factors of form losses into the pipeline segment;

V_i - the greater fuel speed value in the location of form losses.

Values of the factors of form losses are taken from handbooks or methodical textbooks.

Inertial pressure losses are caused by inertial forces in fuel pipelines. These forces appear at motion of aircraft with acceleration. They are determined by the formula

$$\Delta p_{in} = \rho_f g \left[n_x l_x + \left(n_y - 1 \right) l_y \right],$$

where n_i - load factor along the i axis;

l_i - projection of the segment of the supply line $T - E$ on the i axis, taking into account the sign ($l_x = x_E - x_T$, $l_y = y_E - y_T$).

Considered above equations are used for checking calculation by the conditions of altitude performance of BPE.

To increase the altitude performance of the fuel system, we can do the following:

1. Applying the fuel with the minimal saturated vapor pressure.
2. Applying pumps with good cavitation characteristics. That is with the small cavitation margin.
3. Protecting fuel from heating:
   - heat-insulating fuel tanks, applying in flight cooling system;
   - feeding fuel first of all from the most heated fuel tanks;
   - fuelling the aircraft with cooled fuel.
4. Reducing length of pipelines (by rational arrangement).
5. Reducing the hydraulic form losses.
6. Using the closed vent system (pressurization from the compressor or from the neutral gas system).
7. Degassing the fuel before filling.

2.8 Fuel tanks

Fuel tanks must meet the following requirements:

- strength, tightness;
- small mass;
- corrosion stability.

Usually the fuel tanks include:

- shell;
- bulkheads for stiffness (diaphragm);
- attachment fittings;
- protective self-seal;
- fuel tank equipment:
  - filler neck;
  - outlet connection;
  - recuperators (in supply fuel tank);
  - vent or pressurization line connection;
  - drain valve (Figure 2.16);
  - dumping connection;

    - fuel quantity gauges;
    - pumps;
- electrical bonding.

The diaphragms are designed to:

- maintain strength and stiffness of the fuel tanks;
- soften the hydraulic shocks during changes of aircraft attitude;
- quiet the surface of fuel, that reduces evaporation.

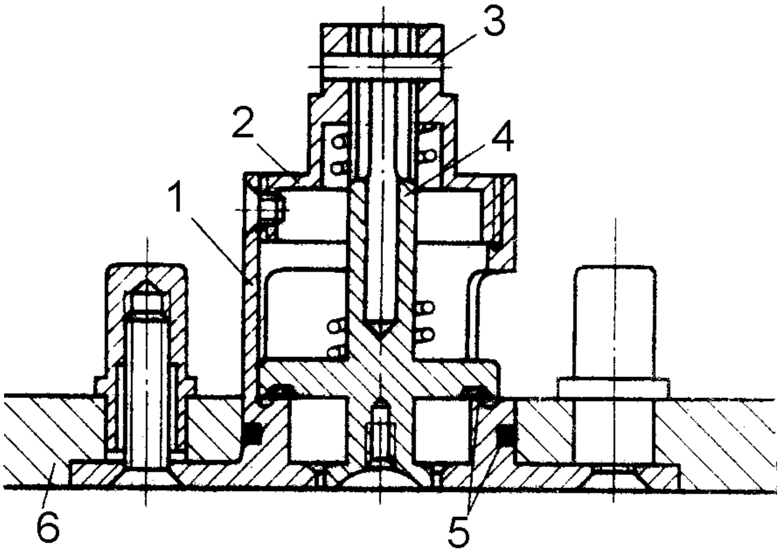


Figure 2.16 - Drain valve:
1 - casing; 2 - cover; 3 - rod; 4 - valve; 5 - sealing; 6 - bottom wing skin

The outlet connection is usually arranged at some distance from the fuel tank bottom. It prevents hitting of condensate into the engine. If the fuel tank is flat, the outlet connection is placed sideways, Figure 2.17.

To provide a reliable feeding of the engine with fuel during changes of aircraft attitude, two outlet connections are installed or special recuperators are applied. In the simplest case, such recuperator is a supply section of supply fuel tank equipped with a set of check valves. Such type of recuperator is used at non-maneuverable aircraft. At acrobatic maneuverable airplanes, whole supply fuel can be made as a recuperator.

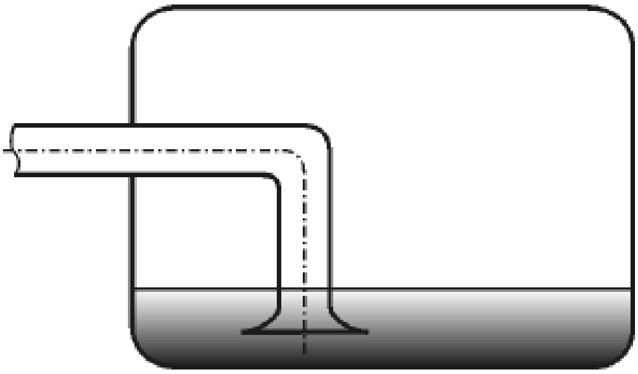


Figure 2.17 - Versions of outlet connection arrangement

At combat maneuverable aircraft, fuel pumps with recuperators and fuel accumulators are usually used.

Fuel tanks can be: internal (rigid, bledder, integral) and external (under-wing, ventral, laid on and conformal). Internal fuel tanks can be placed into a fuselage, a wing or a stabilizer.

Fuselage fuel tanks have the shape convenient for fuel use; have smaller mass, in comparing to wing fuel tanks (because of strength). But they take a payload volume in the fuselage.

Wing fuel tanks unload the wing in flight; free payload volume in the fuselage from fuel. But they complicate fuel use (because the fuel tank is flat) and have more vulnerable area.

Rigid fuel tanks have the stiffness independent of the airframe. But they require big cut-outs to install and remove them from airplanes; do not completely use the allowable volume of the airframe; can be damaged by vibrations and have big mass.

Now rigid fuel tanks are applied on light airplanes with piston engines. The rigid fuel tanks are made of sheets of aluminum alloys such as АМг and АМц. These alloys allow deep draw-forming, embossing, they are corrosion-resistant and well welded. Recently composite materials are also used for manufacturing rigid fuel tanks.

By its design the casing of rigid fuel tanks usually consists of a shell and two welded bottoms. Welding provides tight connection. The fuel tank is welded from outside on special flanging separated by embossing. It eliminates hitting of flux and a fire scale inside of the fuel tank and reduces residual stresses after welding.

Bulkheads are usually produced of duralumin. As duralumin is bad welded, bulkheads are attached to the shell with rivets. The head of rivets can be welded for tightness. The other way of diaphragm attachment is spot welding (not requiring tightening), that considerable simplifies manufacturing process.

Installation of stiffen fuel tank is usually carried out with special support assemblies, to which fuel tank is held down with attaching straps.

After manufacturing, all fuel tanks are tested for tightness and vibration strength.

In military airplanes, the fuel tanks are usually covered with a self-seal which is capable to tighten shell-holes in the fuel tank.

Bladder-type fuel tanks:

- are installed and removed through cut-outs of small sizes;
- are stable to vibrations;
- have good survivability.

But they:

- lose elasticity at low and high temperatures, hence appearance of cracks is possible;
- have mass greater than integral fuel tanks;
- require presence of container inside the airframe.

The shell of flexible fuel tanks usually consists of several layers. There is a layer of fuel resistant rubber inside. The following layer is usually the self-seal tightening shell-holes. Then there is a layer of vulcanized rubber. The external layer is the protective cord (strong rubber cloth).

The fuel tank equipment is vulcanized to walls of the fuel tank, besides it is fastened to the container.

Integral fuel tanks represent the closed pressurized section of an airframe. Integral fuel tanks:

- use the allowable volume completely;
- have minimal mass;
- do not require big cut-outs for maintenance.

But they:

- are subjected to aerodynamic, vibrational, thermal effects;
- require special measures to provide full fuel use;
- require tightening; tightening process is complicated, detrimental to health, not always reliable.

External (under-wing, ventral, laid on and conformal) fuel tanks represent rigid fuel tanks, extruded directly to ram airflow. Just like the integral fuel tank, it is subject to aerodynamic, vibrational, thermal effects. Besides, the shape of such fuel tanks must provide the minimal external drag at the specified volume. The shape of fuel tanks must not cause stalls, disturbance of stability and controllability of the aircraft.

On maneuverable airplanes external fuel tanks are usually designed droppable. It allows to get rid fast from superfluous mass and to improve maneuverability of the airplane if necessary. As the result there are no pumps inside them. A fuel pump is very expensive. Therefore fuel feeding from external fuel tanks is usually provided by forcing out. Thus tanks pressurization with overpressure increases strength of fuel tanks.

Laid on fuel tanks differ from under-wing or ventral only in arrangement. And usually they are not droppable. Conformal fuel tanks represent external fuel tanks, attached to the airplane without clearances. Thus total aerodynamic drag of the system (the airplane plus the fuel tank) can even be decreased. The external weapon-pylon bases can be attached to such conformal fuel tank.

The list of self-check questions

1. What is called the fuel system?
2. List the basic requirements for the fuel system.
3. What is the fuel for aircraft engines?
4. What is the mass and volumetric calorific value? What are the units of these values measuring?
5. How fuel density varies with temperature rise? What does this result in an airplane?
6. What is the saturated vapor pressure of fuel? How and why it is denoted?
7. How does the saturated vapor pressure of fuel change with increase in temperature?

8. How the coefficient of kinematic viscosity changes with fuel temperature increasing?
9. What causes the presence of water and mechanical impurities in the fuel? How to fight them?
10. Please describe the composition of the fuel system.
11. Name and describe three ways of outflow of fuel from the tank.
12. What is a two-stage pumping scheme? Why is it so widespread used?
13. What are the functions of the check valve in the fuel pipe lines?
14. What are the functions of the fuel accumulator?
15. List the advantages and disadvantages of parallel and serial connections tanks to the groups.
16. What is the altitude performance of the fuel system?
17. What determines the altitude performance of the fuel system?
18. Write down the main condition in the fuel system altitude performance calculation.
19. What is the positive suction head (cavitation margin)?
20. What is the overpressure in the tank? How is it created?
21. What types of total pressure losses do you know?
22. How the Reynolds number for the pipeline of circular cross section is determined?
23. What methods are used to improve the altitude performance of the fuel system?
24. What is the purpose of venting and pressurization of the fuel system?
25. What methods of fueling do you know?
26. List the types of the fuel pump drives. Characterize briefly each of them.
27. What kinds of fuel tanks do you know?
28. Why outlet connection is typically located at some distance from the bottom of the tank?

3 FUEL SUPPLY SYSTEMS OF ENGINES

GTE fuel systems are designed for fuel supply:

- into the main combustion chamber and afterburner in accordance with predetermined operation of the engine, altitude and flight speed of the aircraft;
- in compressor mechanization control hydraulic cylinders and adjustable jet nozzle;
- in devices that cool oil and electronic systems.

3.1 General information about GTE fuel supply systems

Fuel supply system must operate reliably with various fuels at different temperatures and its moderate reactivity, toxicity, purification from mechanical impurities and water. The fuel system must provide also:

- possibility of manual control and automatic regulation of fuel supply in order to change or maintain desired operating mode of the engine;
- good atomization of fuel for better combustion;
- possibility of a complete fuel cut-off at the engine's shut-down;
- required fuel supply in the pilot burner nozzle and combustion chamber when the engine is started and throughout the operating range of the engine;
- predetermined altitude performance.

In modern GTE fuels produced by direct distillation of the natural petrol are used. The most common of them are kerosene T-1, TC-1, T-2, T-5, T-6, T-7, T-10, PT, Jet A, Jet A-1, Jet B, JP-5, JP-8 which are characterized by relatively high values of density, specific heat of combustion and thermal stability.

The value of required fuel supply to the combustion chamber of the engine depends on engine operating mode, altitude and flight velocity of the aircraft and it is from 300...400 up to 10000...30000 kg /hr. Fuel pressure required to achieve the required fuel flow through the injectors and high-quality spray is 3...15 MPa.

3.2 Composition of GTE fuel supply systems

The fuel supply system of an aircraft power plant consists of the fuel system of the aircraft (from the fuel tanks of the aircraft to the engine booster pump) and the GTE fuel supply system.

In general the GTE fuel supply system may include the main, starting and afterburning subsystems.

Figure 3.1 shows a diagram of afterburning turbofan engine's fuel supply system. Fuel fire protection valve (FPV), engine centrifugal boost pump (boost pump of engine BPE), filter (F) with relief valve (RV) and differential pressure sensor (DPS) are located at the inlet of it.

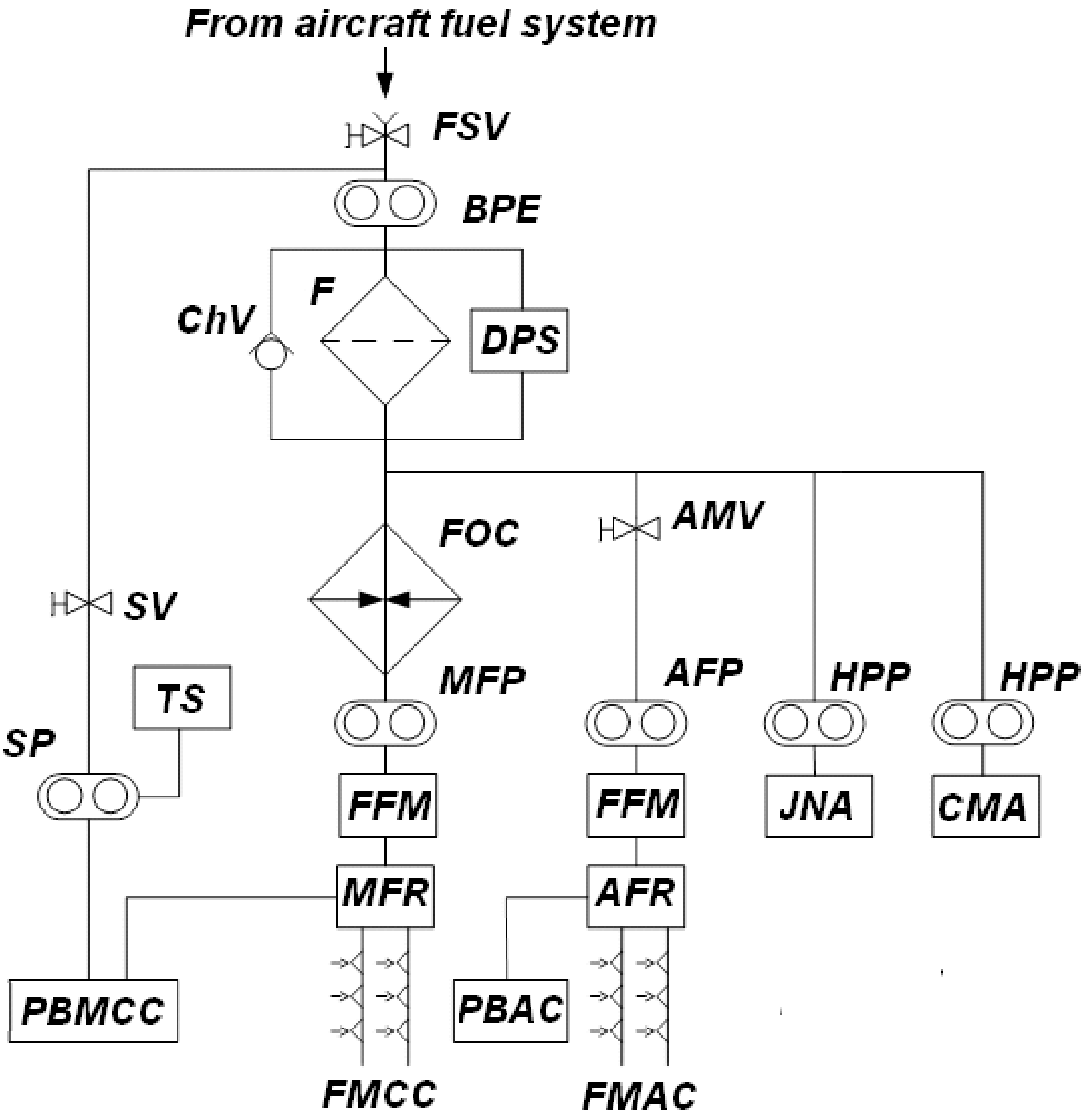


Figure 3.1 - Schematic diagram of the turbofans fuel system

The ***basic subsystem*** provides fuel supply into the main combustion chamber (MCC) during engine operation. It consists of the fuel-oil cooler (FOC) in which the fuel cools the oil that flows from supports and drives, the main fuel pump (MFP), fuel flow meter (FFM), the main fuel flow regulator (MFR) and fuel manifolds of main combustion chamber (FMCC) with nozzles.

The ***afterburner subsystem*** supplies fuel to the afterburner combustion chamber when the engine operates at the afterburning mode. It includes afterburning mode valve (AMV), afterburner fuel pump (AFP), fuel flow meter (FFM), afterburner fuel flow regulator (AFR) and afterburner chamber fuel manifolds (FMAC).

The ***main fuel starting subsystem*** (*of main combustion chamber*) provides the fuel supply to the pilot burner of main combustion chamber (PBMCC) when the engine starts up. Fuel flows through the start-up valve (SV) and the starting pump (SP), which can have independent drive from turbo starter (TS). When you startup at flight, pilot fuel supply into PBMCC can be performed through the MFP and the main fuel flow regulator, as MFP is driven by freewheeling rotor and the pressure from the pump is sufficient to run the MCC.

The ***afterburner fuel starting system*** supplies fuel to the pilot burner of an afterburner combustion chamber (PBAC) when the afterburner starts up.

To improve the reliability of fuel ignition and the engine or the afterburner startup at high altitudes and in winter conditions oxygen replenishment of MCC and afterburner chamber (AC) pilot burners is applied.

In addition to its direct functions fuel performs functions of the working fluid in compressor mechanization and nozzle flaps hydraulic actuators. For this purpose, the system includes special high pressure fuel pumps (HPP) supplying fuel to a jet nozzle actuator (JNA) and compressor mechanization actuator (CMA). JNA changes position of nozzle flaps; CMA changes position of guide vanes and compressor bypass valves. Power components of actuators are hydraulic cylinders. Fuel is returned from hydraulic cylinders to the fuel system and further enters into the combustion chamber.

For aircraft flying at speeds of $\boldsymbol{M_f} > \mathbf{2}$ it is possible to include in the fuel system a special air - fuel cooler for air cooling. Air is supplied to such heat-exchangers from aircraft environment control system.

3.3 Units of fuel system

The fuel system units include booster and main fuel pumps, filters, fuel governors, fuel manifolds and fuel spray nozzles (injectors).

Booster fuel pumps

The boost pump of engine (BPE) (Figure 3.2) creates the fuel pressure required to overcome the hydraulic resistance in pipes and components of the engine fuel system located upstream the main fuel pump, and prevents cavitation at the inlet to the main fuel pump. Application of booster pump increases the altitude performance of the fuel system.

Centrifugal pumps can be used as engine boost ones, at least - lobe rotary or rotary gear pumps. The engine boost pump is driven by the engine rotor through the gearbox.

The pumping unit is the impeller, which pumps out fuel from the suction line and supplies it with high pressure and velocity to the diffuser where the dynamic head is converted to static pressure.

Rotational speed limit of the pump rotor is chosen as a minimum of three conditions:

- cavitation-free mode;
- strength of the impeller;
- limited drive possibilities.

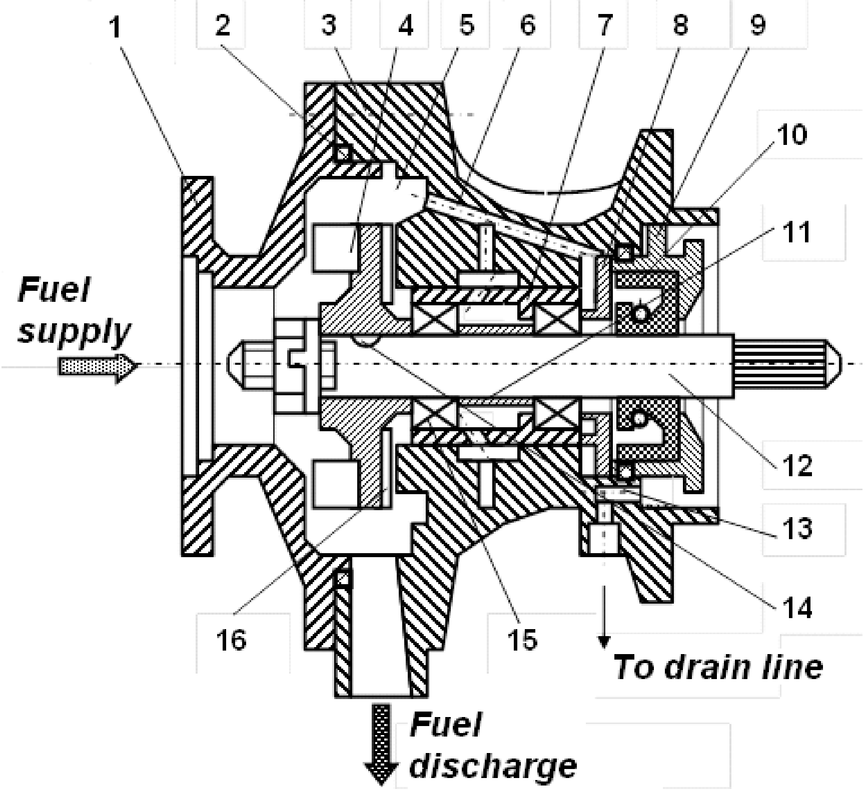


Figure 3.2 - Turbojet AL-21F-3 booster centrifugal pump DCN-70:
1 - cover of housing; 2 - O-ring; 3 - pump housing; 4 - impeller; 5 - high pressure chamber;
6 - channel for supplying fuel to the bearings lubricating; 7 - housing of bearings;
8, 11 - bushings; 9 - cover gasket; 10 - cuff; 12 - shaft;
13 - drainage channel; 14 - key; 15 - bearing; 16 - impeller

Taking into account the impeller cavitation qualities the number of blades is selected in the range from 6 to 14. Blades are bent to the course of the impeller rotation at angle of 110...150° to increase the pressure, or upstream of the impeller at angle of 18...40° to ensure high efficiency of the pump.

The main disadvantages of centrifugal pumps are the sharp decreasing of pressure head with impeller speed decreasing and essential fuel heating at off-design operating modes.

High-pressure pumps of the main and afterburner fuel supply

The main and afterburner fuel high-pressure pumps (MFP and AFP) supply fuel to the fuel injectors under pressure that ensure high spray atomization quality at all modes of operation. The plunger, gear and centrifugal pumps are used as MFP and AFT.

Plunger pumps can be used in the GTE fuel-supply systems with a fuel flow up to 5000...10000 kg/h.

The plunger pumps have perfect sealing of pumping unit and high strength of its parts, so these pumps are capable of developing high and ultra-high pressure (up to 20...25 MPa).

Furthermore, using devices of a relatively simple design, the plunger pumps capacity can be controlled at a constant rotational speed of a drive shaft without bypass and throttling which reduces heating of the fuel pump.

The disadvantages of this type of pumps include:

- complexity of design;
- sensitivity to corrosion and mechanical impurities in the fuel;
- limited performance;
- low level of fuel temperature, which provides a reliable operation of the pump (up to 370...390 K).

Additionally, these pumps require large NPSH (net positive suction head, cavitation margin) at the inlet (not less than 0.15...0.35 MPa).

By design the plunger pumps can be made with radial or axial arrangement of plungers. In most GTE fuel systems pumps with axial plungers positioned at angle to the axis of rotation are used (Figure 3.3).

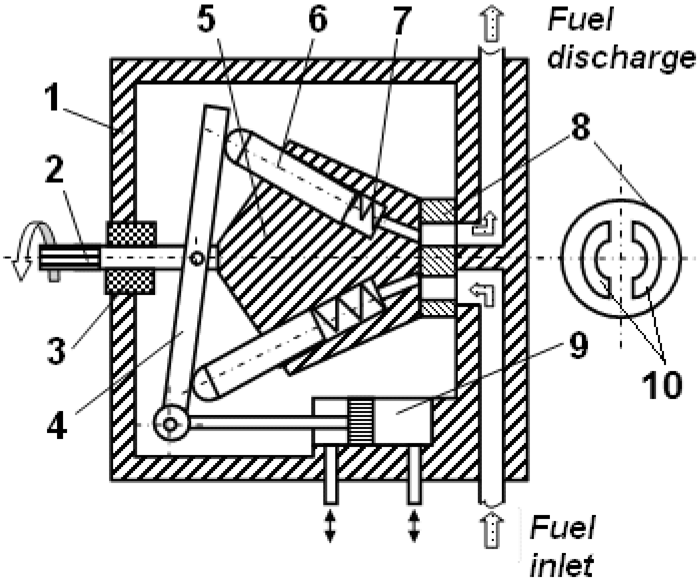


Figure 3.3 - Plunger fuel pump scheme:
1 - housing; 2 - spline shaft drive;
3 - sealing gasket; 4 - swash plate;
5 - rotor; 6 - plunger; 7 - spring; 8 - slide valve;
9 - servomotor; 10 - distributive windows

Plungers alternately suck and pump fuel through the distributive holes of the slide valve when reciprocating in the cylinders along the axis of the rotating rotor.

Volumetric capacity of the plunger pump consists of individual plungers delivering:

$$Q = z \frac{\pi d_p^2}{4} s_{max} n \eta_v ,$$

where z - the number of plungers (normally 5…11);

d_p - plunger diameter (10...20 mm);

s_{max} - plunger stroke from the top dead center to the bottom center point for a half revolution of the rotor (15...30 mm);

n - rotational speed of the pump rotor, about 70…85 r/s (4000...5000 rpm; at higher speeds the inertial loads and wear of the pump are increased);

η_v - volumetric efficiency ($\eta_v = \mathbf{0.95...0.96}$ when the fuel pressure at the pump inlet is 0.15...0.5 MPa and outlet pressure is 9…10 MPa).

In order to reduce fuel pulsation at the pump outlet the number of plungers is always chosen odd. Start of feeding by one plunger at even number of plungers will coincide with the end of feeding the other, opposite plunger. At odd number of plungers fuel pulsations are smoothed because of the phase offset between suction and discharge cycles (Figure 3.4).

Capacity control of the plunger is achieved by changing pump plunger stroke by controlling the installation angle of the swash plate (see Figure 3.3) using a servomotor. Maximum angle of the swash plate is 13...15 °.

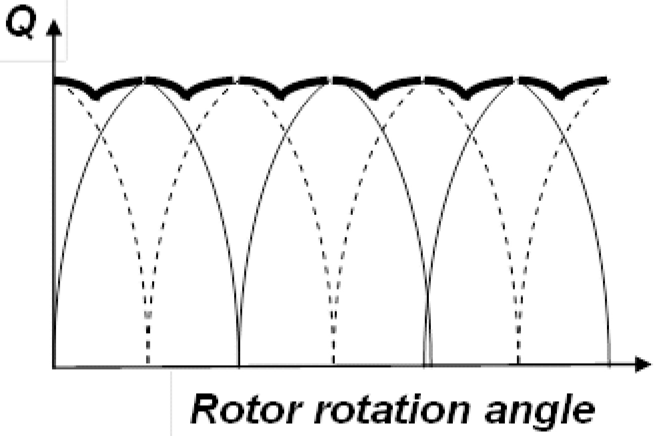


Figure 3.4 - Capacity of plunger pump against the rotor rotation angle

Plungers are made of hardened steel 12ХН3Ф, ХВГ; drum rotor - of antimony bronze or steel (with bronze cylinder liners for plungers), pump housing - of cast aluminum alloys АЛ-4, АЛ-5, АЛ-9.

Gear fuel pumps have a number of advantages comparing with the plunger pumps:

- design simplicity, compactness;
- capacity above 1.5...2 times as with identical dimensions and mass;
- capacity increasing of a gear pump through the use several pumping sections;
- lower sensitivity to the purity and grade of fuel.

The main disadvantages of gear fuel pumps are:

- difficulty of a high fuel pressure ensuring due to significant leakage through the radial and face clearances (modern gear pumps using booster centrifugal pump provides fuel pressure at the outlet not more than 8...12 MPa);
- increase of the required power to drive the pump and circulating fuel auxiliary heating because of the change of pump performance by changing the bypass fuel;
- low volumetric efficiency (0.75...0.82).

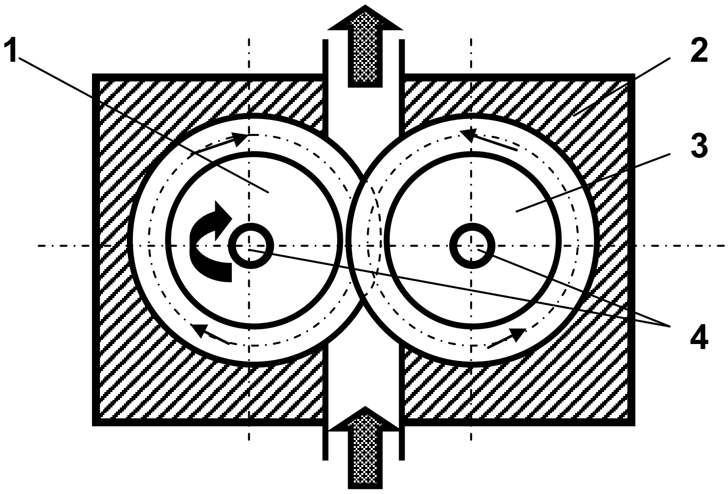


Figure 3.5 - Scheme of the gear pump:
1 - drive gear; 2 - housing; 3 - driven gear; 4 - gear shafts with bearings

The main elements of the gear fuel pump (Figure 3.5) are: drive gear driven from the engine rotor; driven gear, driven in rotation by the driving gear; housing; gear shafts, bearings, face seals.

To reduce fuel pulsation, gears have a sufficiently large number of teeth (10...18), despite the fact that it increases the pump size.

Gears rotational speed is

limited by maximum peripheral speed on heads of teeth (not more than 10...17 m/s with a booster pump) due to ensuring fuel filling cavities between teeth. When fuel is supplied to the ends of gear the circumferential speed of teeth on the heads can be increased to 50 m/s.

The fuel velocity at the pump inlet is limited to 4...5 m/s which is connected with the possibility of cavitation as in the pump itself as in the inlet and outlet pipes.

The most loaded elements of the fuel gear pump are gear supports. They are loaded by lateral force of pressure difference between the fuel inlet and outlet, fluctuating loadings, torque reaction force. To support the fuel pump gear there roller and needle bearings are mounted which are lubricated and cooled by fuel.

Gears are made of cemented or nitralloy steels 12ХН3Ф, 18ХНВА, ЭИ247, housing is casted from steel or cast aluminum alloy ribbed for cooling surface increasing.

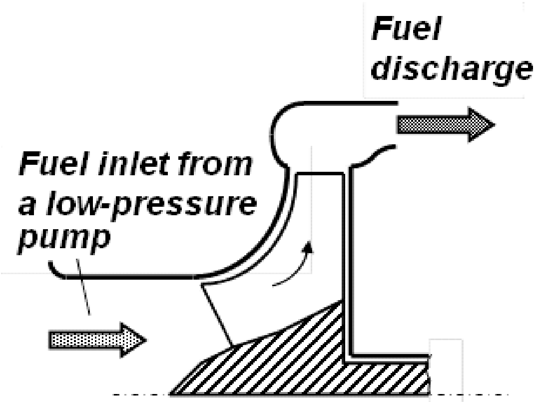


Figure 3.6 - Scheme of centrifugal high pressure fuel pump with open impeller

Centrifugal fuel pumps are widely used not only as a booster but also as the main and afterburner high-pressure pumps. With a relatively small size, they provide capacity up to 35,000...40,000 kg/h at outlet pressure to 8...9 MPa at inlet pressure 0.2...0.6 MPa. An open type impellers are usually used in the high-pressure fuel pumps (Figure 3.6). Opened impellers are easy in manufacturing; they can withstand high centrifugal loads but have increased hydraulic losses due to leakage at the faces.

Fuel flow control units

The main and afterburner fuel flow control units are the components of fuel systems as well as engine control automatic system.

In engines with a fully hydro-mechanical automatic control system flow control units contain all devices providing automatic control of a fuel flow into the main combustion chamber and afterburner.

In engines with electronic automatic control system fuel flow control units include actuators for fuel metering as well as the backup devices for automatic control of the engine.

Composition of actuators for the fuel metering includes metering unit (plunger pump swash plate or metering pin in case of a gear pump), metering unit servo drive and stabilization system of pressure drop across the metering unit, solenoid-operated automatic stop valve and manual stop valve.

Composition of devices for automatic control is determined by tasks of the engine control by hydro-mechanical system.

At basic operating conditions, fuel supply to the main and afterburning combustion chambers is controlled by electronic control unit (ECU); hydromechanics fuel governor executes commands of ECU to change fuel flow.

In the case of failure of the main and backup ECU circuits the engine control is transferred to backup system which carries out function of fuel flow control unit. The realized in it control tasks are usually much easier comparing with electronic control; they ensure successful completion of flight only.

Fuel nozzles

Fuel is supplied into the main combustion chamber and afterburner by the fuel nozzles (injectors). To obtain combustion efficiency, stable combustion and reliable starting one can have the following requirements to fuel nozzles design:

1. Quality atomization (fineness) of fuel at all engine operating modes (mean droplet diameter must be 30...100 mm). Spray fineness is affected by fuel pressure difference at the nozzle. Minimum pressure difference of fuel which ensures good atomization is 3...6 MPa.
2. Uniformity of fuel supply and distribution by volume of combustion zone, which provides combustion efficiency, uniform temperature field at turbine inlet and specified ecological characteristics of combustion chamber. Non-uniformity of fuel supply by separate nozzles of one set at maximum capacity must not exceed 2...3 % and at idle – 10...20 %. Peripheral non-uniformity within each spray cone relative to the axis of atomization - not more than 20...30 %.
3. The required value of a nozzle spray cone angle: at engine startup mode when fuel is ignited, nozzle spray angle must be 60...70 °, at idle - 110...120 °, at the main engine operating modes - 80...90 °. When engine is started, good conditions for ignition are created due to the required fuel concentration in a relatively small volume, the idle spray angle increasing allows to cover and to heat the maximum value of a liner, at maximal mode fuel flows out of nozzles at high pressure and must not fall on a flame tube wall so as not to cause its burnout (but if to reduce the angle of the nozzle spray angle greatly, the fuel will burn out in a turbine).
4. The nozzles leakproofness, wear resistance, preventing carbonization.
5. Low weight and compact dimensions, simple structure.

Conditions of fuel injectors operation in GTE are very hard and characterized by the following factors:

- non-uniform temperature of nozzle parts (outer part is streamlined by the high-temperature gas and the inner part is washed by the fuel);
- increased vibration as nozzles are fixed to elastic foundation (to a thin-walled shell of the combustion chamber or the relatively non-rigid fuel manifold);

- danger of cavitation, caused by the warmed fuel flowing in the channels of nozzles at high speed;
- fuel nozzle can be used as one of supports of a liner.

These factors must be taken into account at designing of nozzles and their arrangement on the engine.

The ***fuel nozzles*** according to supply process are divided into two types: atomizing and evaporative.

The ***evaporative nozzles (injectors)*** supply fuel as the gas-vapor mixture which is formed during preheating, evaporation and partial thermal cracking of liquid fuel. They are simple in design, provide high combustion efficiency but are difficult to operating development and control, explosive at evaporating tubes burnouts therefore are not widely used. The evaporative injectors are installed, for example, on the APU TA-6A of Il-76 aircrafts and on turbo shaft engine T700-GE-700 of General Electric Company.

The ***atomizing nozzles*** supply fuel in the form of finely atomized droplets. Two types are used: jet and centrifugal.

The ***Jet nozzles*** are simple in design but do not provide good atomization of the fuel and its distribution over specified volume of combustion chamber. They have been used in afterburner combustion chambers. They are rarely used in main combustion chambers (turbo shaft engine GTD-3F of Ka-25 helicopter, turboprops Walter M-601, M-602 for passenger aircraft L-410, and small-sized engines for small-sized unmanned aircraft).

The ***swirl nozzles*** can be adjustable or fixed. Fixed swirl nozzles are used in starting systems and afterburners, adjustable - in main combustion chambers where it is necessary to change the fuel flow over a wide range depending on operating modes of the engine and the aircraft flight.

Fuel flows tangentially into the swirl chamber of the swirl nozzle. In swirl chamber of the nozzle fuel flows to the blast orifice from the periphery to the center (Figure 3.7). At the same time the tangential velocity of fuel increases and pressure decreases up to the air pressure value in combustion chamber. Flowing out of the orifice, the fuel particles form a hollow cone with an apex angle $\mathbf{2}\alpha$.

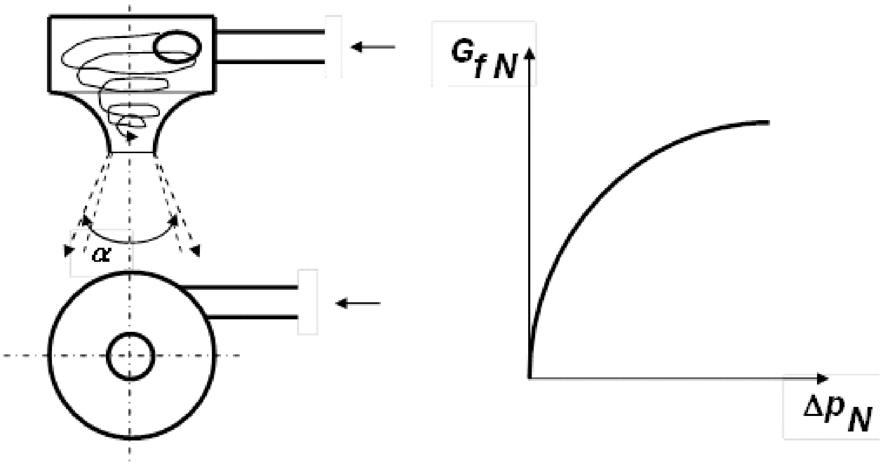


Figure 3.7 - Operating principle of the swirler

Fuel flow through all types of fuel nozzles is defined as

$$G_{f\,N} = \mu F_N \sqrt{2\rho_f \Delta p_N},$$

where μ - fuel flow coefficient of the orifice (for swirl-type nozzle $\mu = \mathbf{0.3...0.4}$);

F_N - orifice exit area;
ρ_f - fuel density;
$\Delta p_N = p_{in} - p_g$ - pressure drop across the nozzle;
p_{in} - fuel nozzle inlet pressure;
p_g - gas pressure in combustion chamber.

Fuel flow control in a simplex single-orifice burner is accomplished by changing a pressure difference that provides flow ratio to a minimum or maximum mode $\frac{G_{f\,N\,max}}{G_{f\,N\,min}} = 4...6$. ***Simplex injectors*** are used in auxiliary GTE combustion chambers, turbo-starters (TS-19, TS-21, S-3), afterburners combined with jet nozzles (R-29, AI-21) and in main chamber of the engines with a small range of fuel rate variation by modes (D-36, D-136).

The required ratio of fuel rate to the maneuverable aircrafts (fighters, attacks, attack helicopters) is $\frac{G_{f\,N\,max}}{G_{f\,N\,min}} = 40...50$ and cannot be achieved by the pressure drop changing. For fuel flow changing in wide ranges the control by area F_N changing and orifice flow coefficient μ changing while changing pressure difference Δp_N is used.

The ***two-orifice*** (Figure 3.8) or ***three-orifice nozzles*** are controlled by changing the area of the orifice.

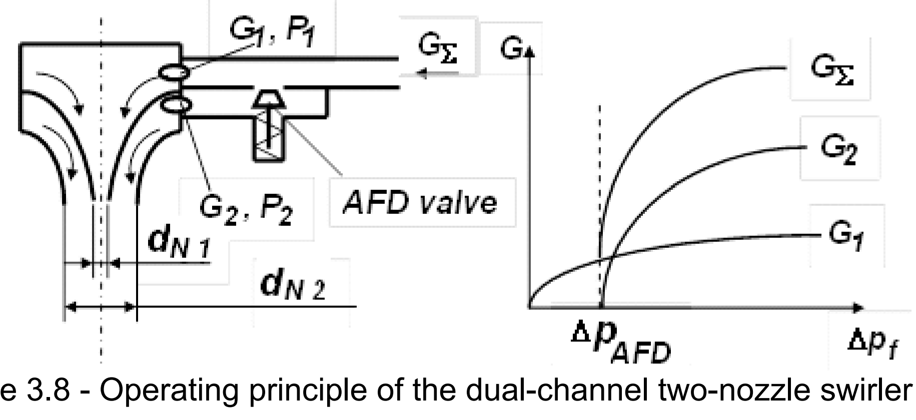


Figure 3.8 - Operating principle of the dual-channel two-nozzle swirler

At low pressures, automatic fuel distribution (AFD) valve is closed, the fuel flow is determined by a single orifice d_{o1} (flow G_1). When the fuel pressure reaches 1.0...1.8 MPa AFD opens and second orifice d_{o2} with a flow G_2 starts operation then the total fuel flow is equal $G_{\Sigma} = G_1 + G_2$.

Disadvantages of these nozzles are:

– unsatisfactory fuel atomization at the time of valve opening, since the flow from the nozzle at this point occurs at a small overpressure;

– unevenness of fuel flow through the nozzles situated at upper and lower parts of the fuel manifold at the moment when the AFD starts due to the impact of the fuel column pressure in manifold.

Fuel control by the flow coefficient changing can be carried out in two-stage (Figure 3.9) or three-stage plunger nozzles and in nozzles with fuel bypassing.

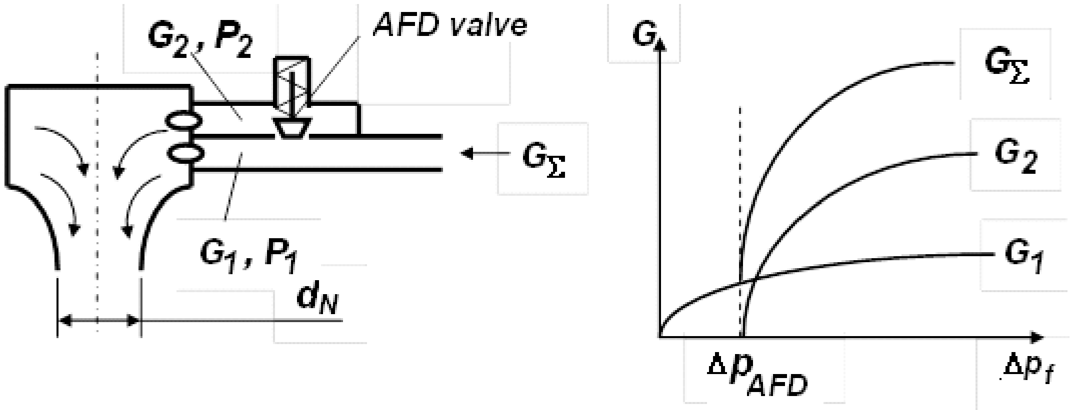


Figure 3.9 - Operating principle of the two-stage single-chamber centrifugal fuel injector

In ***plunger nozzle*** (Figure 3.10) when fuel pressure increases then plunger slides to left (upstream) thus opening tangential holes increasing the flow coefficient and fuel flow.

The disadvantage of single-chamber and plunger nozzles is non-uniform fuel flow of different nozzles that supply fuel from same fuel manifold. It is explained by different hydraulic resistance of inlets and different rigidity of springs that support valves and plungers.

These disadvantages are less inherent to the ***bypass fuel nozzle*** (Figure 3.11). In such a nozzle swirl chamber is served all total fuel flow, and its excess returns to the inlet to the pump via drain line. The amount of the drained fuel is reduced with

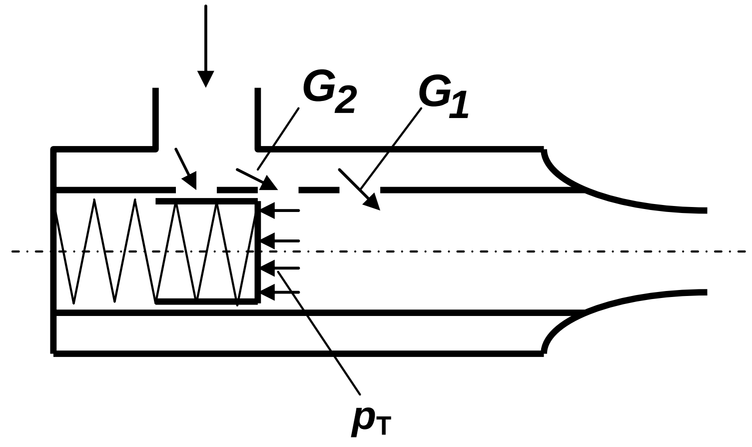


Figure 3.10 - Plunger nozzle

increasing pressure.

Disadvantages of bypass fuel injectors are excessive pump loading at modes with low fuel flow, a constant spray cone angle and bypass fuel heating.

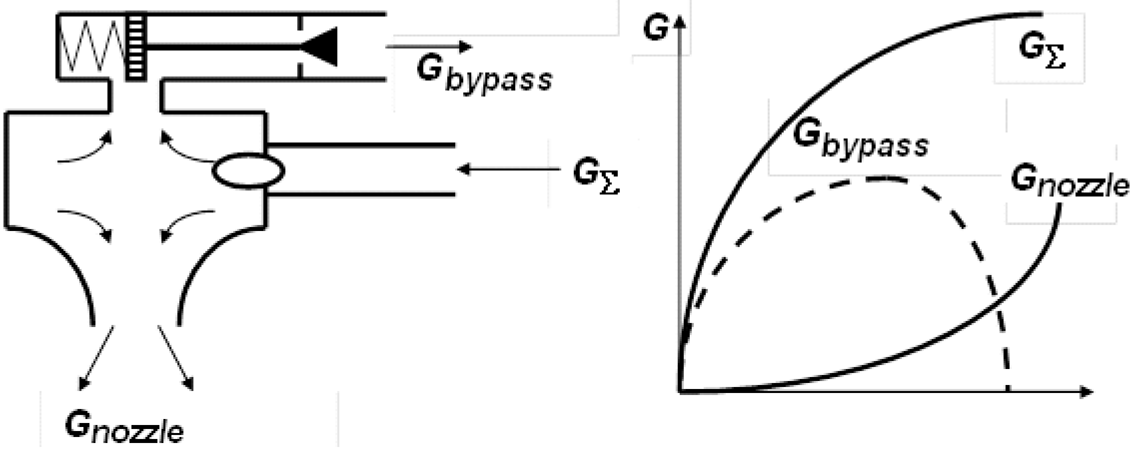


Figure 3.11 - Operating principle of fuel injector with bypassing

Disadvantages of above considered nozzles are not inherent to ***two-stage two-chamber nozzle*** (Figure 3.12). In such nozzles, partition wall reduces influence of pressure difference in chambers on uniformity of flow as leakage of fuel decreases from one cavity to another.

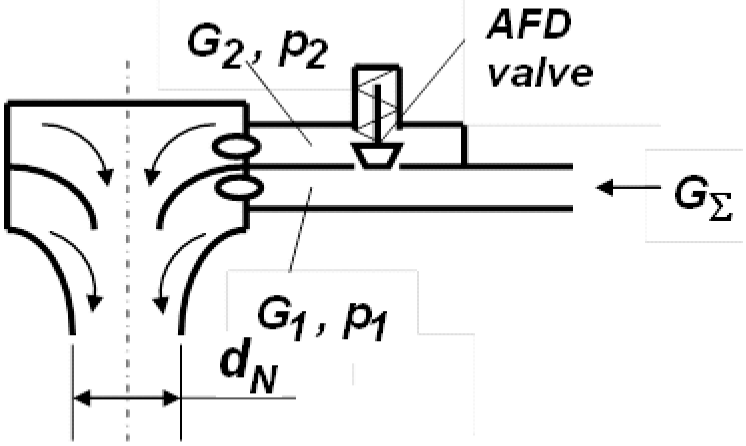


Figure 3.12 - Operating principle of two-stage two-chamber centrifugal fuel injector

Fuel flow metering units

Fuel flow rate is an important parameter that is necessary for solving problems of the engine control and diagnostics.

There three ways are most widely applied to determine fuel rate:

- on a metering element position;
- by determining the fuel volumetric flow rate and density;
- with a twin-turbo meter.

The fuel rate is determined by the position x of the metering element by the formula

$$G = \mu F\left(x\right)\sqrt{\frac{\Delta p_{ME}}{\rho_f}},$$

where $F\left(x\right)$ - cross-sectional area of the metering element;

μ - flow coefficient depending on the shape of the metering element;

Δp_{ME} - differential pressure across the metering element;

ρ_f - fuel density.

The simplest method to determine fuel flow is based on ***measuring the metering element position***. Typically, calibration characteristics that associate x with a fuel flow at constant pressure drop on the metering element and calculated value of a density is introduced into electronic system. Since the composition of the fuel controller includes a device that ensures constant pressure drop, the numerator of the formula radicand for determining the flow rate is constant. The fuel density usually is corrected using its dependence on temperature

$$\rho_f = \rho_0 + c\left(T_c - T_0\right),$$

where T_c - current temperature which is measured;

T_0 - reference temperature;

ρ_0 - density at reference temperature;

c - temperature correction factor of density.

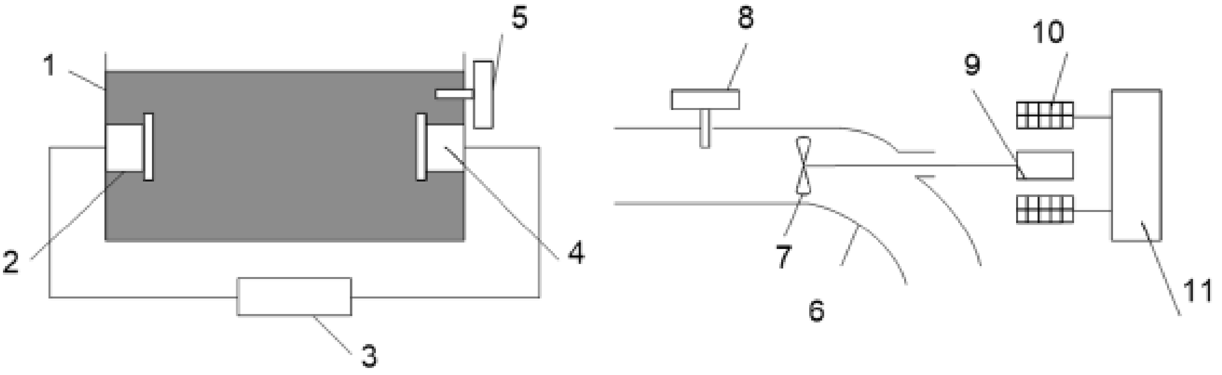
Disadvantage of this method is low precision due to the fact that it does not takes into account individual characteristics of the metering elements and their geometric changes in maintenance due to thermal deformation and wearing. This method is based on the assumption of constant pressure drop and also ignores the fact that different types of fuels have different densities in reference conditions ρ_0 and temperature correction factor of density c.

Determination of the fuel mass flow rate using the volumetric flow rate and density allows you to increase significantly the accuracy. Set of corresponding devices is called the ***fuel consumption measuring system*** (FMS) and is used, for example, in engines D-36, D-18T etc.

The FCMS diagram is shown in Figure 3.13. In the pipeline of fuel supplying to the controller, the impeller is installed. Its rotational speed is fixed by the inductive sensor that includes an anchor, coil and the frequency meter. This rotational speed is proportional to the volumetric flow rate of fuel.

However, it is necessary to determine the mass flow associated with the volumetric flow rate by the ratio

$$G_f = \rho_f Q_f .$$



a b

Figure 3.13 - System for fuel consumption measuring:
a - the device disposed in the fuel tank; b - the device disposed in the pipeline;
1 - supply fuel tank; 2 - generator; 3 - vibrating fuel densitometer; 4 - receiver;
5, 8 - resistance thermometers

To determine the density, the above formula is used, but instead preset constant density ρ_0 the current density in the fuel tank $\rho_{f\,T}$ is substituted into it:

$$\rho_f = \rho_{fT} + c\left(T_f - T_N\right).$$

Temperature T_f is measured using a resistance thermometer 8 and the temperature T_N - by the resistance thermometer 5. The density of fuel in tank is determined with the device FVD (fuel vibrating densitometer) which operating principle is based on the fact that the density of fluid depends on the wave propagation velocity in it (velocity of sound). The device includes the variable frequency pulse generator 2, the receiver 4, and the control device 3. The distance between surfaces of generator and receiver is known with high accuracy. This device automatically changes frequency of pulse so as to determine the resonant frequency. It is known that the resonance conditions in the area between generator and receiver are an integer number of half wavelengths. This allows determining the speed of sound and the density of fuel in tank.

The disadvantage of the FCMS is high cost and weight, as well as the necessity to distribute parts of the system between the aircraft and engine.

Determination of fuel flow through the twin-turbo flow meter is based on the fact that the torque that acts the impeller disposed in the stream of fluid is proportional to the mass flow.

The ***twin-turbo flow-meter*** (Figure 3.14) consists of two impellers (small turbines) mounted on shafts. Impellers have significantly different profiles of blades. Therefore when there is no mechanical connection between them, they will rotate with different rotational speeds. Since the impellers are connected by the spring, their rotational speed is the same; but under the action of torque which is transmitted through the spring they have the angular offset. This angular displacement is proportional to the torque and hence to the fuel mass flow rate. The inducers are mounted above the impellers to determine the angular displacement. The inductor signals received by the phase measuring device according to the phase shift of electrical signals determine the angular displacement of impellers and therefore fuel flow rate.

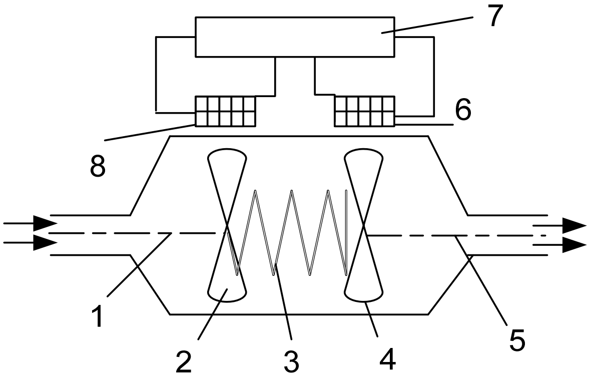


Figure 3.14 - Twin-turbo meter:
1, 5 - shafts; 2, 4 - impellers; 3 - spring;6, 8 - inductors;
7 - phase measuring device

Fuel Filters

Presence of impurities in fuel leads to intensive pump wearing, plunger and slide valves seizing, nozzles and fuel jets blocking. Therefore fuel is filtered many times when supplying to the engine. Aircraft fuel filters must retain particles with a diameter of more than 16...20 microns, and engine fuel filters - up to 3 ... 4 microns.

The filters are installed as upstream the main fuel pump (low pressure filters), as downstream the main pump (high pressure filters).

The ***mesh filters*** twill weave is made of brass, bronze or nickel wire. They are simple, durable, have low hydraulic resistance. Filter fineness is 16...20 microns.

The ***porous filters*** are used in channels with relatively low fuel flow (in components of automatic systems). They are produced by sintering copper or bronze grains (90...95 %) with tin (5...10 %), the fine pores are formed between the grains.

The slit filters are threaded frame in which wire wound around coil to a coil so that the gaps are formed between turns through which the fuel passes. Such filters are installed directly into the fuel injectors.

In early GTE designs fabric (felt, silk, and nylon) and paper filters were used. They provide a high degree of fuel filtration but have a short life and absorb the water present in fuel which may cause frosting of the filter at low temperatures.

In the case of the filter clogging its design contains a special valve for bypassing raw fuel to the outlet fitting.

Flushing of filter in maintenance is performed with the gasoline at ultrasonic installations.

Pipelines of fuel systems

Aviation GTE fuel supply system includes suction, discharge and drain lines. Hard steel pipes which are made of steel 20A or X18H10T with anticorrosive coating are most applicable.

Pipelines have technological and mounting fittings. The pipeline fittings must ensure tightness at all operating conditions. Pipelines are connected with themselves and components through the nipple, compression fittings or flange connections.

The elements of sleeve connection are pipes, nipple, union nut and cone (Figure 3.15).

Seal connection is performed by a tight contact between the nipple inner cone and the conical or spherical mating surface.

Nut thread is covered with the technical silver to improve anti-friction properties of the screw pair.

Elements of socket pipe connection are sealed with a rubber sealing ring (Figure 3.16).

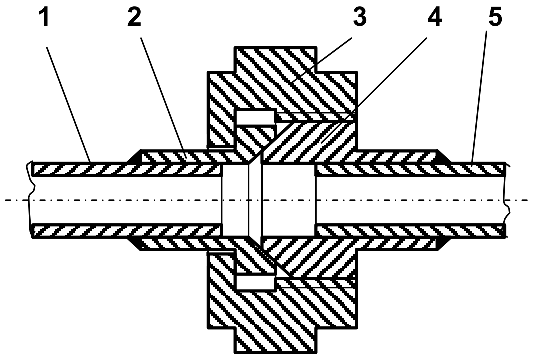


Figure 3.15 - Plug-in connection:
1, 5 - connecting tubes; 2 - nipple;
3 - nut; 4 - cone

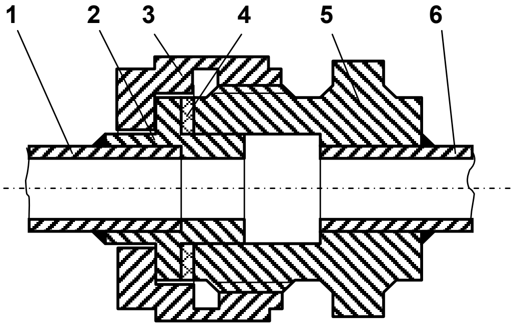


Figure 3.16. Couplings:
1, 6 - connecting tubes; 2, 5 - parts of the reinforcement; 3 - nut; 4 - laying

Flanged pipe connections with components are sealed with rubber rings.

Some pipelines have a telescopic connection. Telescopic connections are used to compensate for mounting stress and thermal expansion resulting from the uneven heating of engine parts and small pipes skewing.

Destructions of pipelines are usually fatigue and occur in places of welding or soldering nipple or fitting parts; under mounting pipe clamps to the motor housing as well as in the places of maximum curvature.

To reduce vibrations, the pipeline sections are rebuilt from resonances by pipeline rigidity increasing or the mounting method improving. Dumpers of vibrations (wired, rubber or PTFE) are mounted under fixing pads. To decrease rigidity of pipelines, rigid pipes are joined by flexible rubber-fabric pipes with reinforcing metal braid.

The list of self-check questions

1. What fuels are used in gas turbine engines?
2. What are the functions of fuel in gas turbine engines?
3. What is the purpose of a booster fuel pump?
4. What types of pumps are used as booster?
5. What types of pumps are used as the main ones?
6. What does determine the fuel pressure value which the main high pressure fuel pump must provide?
7. What does determine the value of pressure which afterburner fuel pump must provide?
8. What does determine the values of pressure and flow rate which must provide pumps that supply fuel to the actuators?
9. Explain the principle of a centrifugal pump operation.
10. Explain the principle of a plunger pump operation.
11. Explain the principle of a gear pump operation.
12. How does the fuel consumption changes when plunger or gear pumps are used?
13. What are the reasons of choosing the number of plungers in plunger pump?
14. What is the difference in the functions of fuel governor in hydro-mechanical or electronic automatic control systems?
15. List the requirements for fuel injectors.
16. What is the difference between evaporating and spray nozzles?
17. Explain scheme and operating principle of jet injectors.
18. Explain scheme and operating principle of centrifugal nozzle.
19. How to provide a wide operating range of fuel consumption in the design of centrifugal atomizers?
20. How to determine the fuel mass flow?
21. The operating principle of fuel consumption measuring system FCMS.
22. The operating principle of twin-turbo meter.
23. How to seal connections in fuel lines?

4 LUBRICATION SYSTEMS

4.1 Purpose of lubrication systems and requirements

Lubrication (oil) system represents a set of units intended for lubrication of the engine, heat rejection from engine parts and also the removal of solid particles which are formed between surfaces subjected to friction at all aircraft operating conditions.

Even short-term breaks in oil feeding result in the engine overheating, destruction of its bearings, wedging of a rotor and as a result the engine failure.

Oil is also used as working fluid in various devices on power plants (such as a propeller pitch control mechanism, fuel control units, rotor speed governor, hydraulic actuators, etc.).

The oil system consists of two sections: external and internal. The external section is a component of the aircraft power plant. The internal section is a component of the engine.

The most of gas turbine engines are equipped with self-contained oil system that has not external section.

Requirements to oil systems:

1. Reliable oil supplying to the engine at the temperature and pressure due to specifications, at any aircraft operating conditions.
2. Minimum power consumption during heated oil cooling.
3. Reliable oil filtering from mechanical impurities and gases.
4. Fast oil heating to reduce the heating-up time of the engine.
5. Preventing oil ejection through venting and overflowing of the engine at all engine operating conditions.
6. Preventing oil tank overflowing when engine is not running.
7. Minimum mass of the system.
8. Sufficient strength, vibration strength, leak tightness and minimum hydraulic pressure losses in the system elements.
9. Fire safety.
10. Maintainability (convenient access to the oil system for maintenance and repairing).
11. Each engine of multi-engine aircraft must have an independent oil system.
12. Pipelines and units of oil systems must be of brown color.

4.2 Aviation Oils

Properties of the oil determine the reliable and continuous operation of an oil system. Operating conditions for oils are complicated and various therefore oil specifications are characterized by strict requirements to their physical and chemical properties.

Viscosity is one of the major properties of oil. If oil viscosity is insufficient, the liquid layer of the oil cannot stay in clearances and is extruded at heavy loadings. As the result, dry friction emerges which increase wear of parts.

If oil viscosity is too high, then:

- friction forces increase which causes power losses;
- oil does not get to units with small clearances;
- increased pressure in oil system is required for pumping oil;
- engine start-up is complicated.

The value of oil viscosity is measured by the factors of viscosity. Just as with fuel, there are two factors of oil viscosity: kinematic and dynamic ones. The factor of kinematic viscosity of aviation oils is 2.5…25 mm^2/s.

The viscosity of oil drops when temperature increases. Most aviation oils in the past were made from natural petrol, by acid (MK) or selective (MC) clearing. The viscosity of such oils drops sharply with temperature increase. High temperature in oil system results in the evaporation and oxidation of these oils. The resulting deterioration of physical and chemical properties worsens operation of the oil system. Now in heat-stressed engines, synthetic oils are widely used. They are formed on the basis of esters. The viscosity-temperature relation for such oils is weaker. Besides these oils have a broad range of operating temperatures.

The density of aviation oils makes 850...950 kg/m^3.

The thermal-oxidative durability of oil is characterized by maximum temperature at which the oil can be used. When this temperature is exceeded, oil is coked, i. e. oil sediment appears and a film is formed on the greased parts. The type of oil to be used is determined by the engine type.

4.3 General characteristics of oil systems

Oil systems for piston engines

Oil systems for piston engines are the most complicated and loaded ones. Piston engines have a large friction area. There is high pressure $(> 25\ \text{MPa})$ on these surfaces which increases the heat transfer into oil $(3400...6800\ \text{J}/(\text{kW min}))$. Hence high oil flow rate through engine $\left(2.7...5.4\ \text{dm}^3/(\text{hour kW})\right)$ is required.

Second feature of oil system of piston engines is that oil directly contacts with a combustion zone that causes high oil consumption $\left(C_p = 8...16 \text{g}/(\text{hour kW})\right)$.

To provide oil system operation in these conditions oils with viscosity 20...25 sSt at 100 °C are required, for example MC-20, MK-22 (the number in the marking designates viscosity in sSt at 100 °C). Less viscous oils are applied in winter conditions.

The recommended oil temperature makes 65...75 °C at the engine inlet, and 105...125 °C at the engine outlet. Delivery oil pressure is in the range of 0.5...0.8 MPa.

Oil systems of turbojets and turbofans

The principal type of friction in these engines is rolling friction. Therefore the power consumption required to overcome the friction forces and the amount of the transferring heat are insignificant (8.5...17 J/(N min)). Oil flow through the engine makes 3...5 dm^3/min per bearing. The oil consumption basically comes from the losses through the breather system and makes ~ 0.1 g/(N hour).

Under these conditions oils with low viscosity (MK-6, MK-8, and also synthetic oils) are applied.

The allowable inlet oil temperature makes 25...80 °C, and the outlet ones 100...130 °C. The oil delivery pressure for turbojets is 0.1…0.4 MPa.

Oil systems of turboprops

Due to the complexity and the loadings of the turboprops oil systems, they are intermediate between the oil systems of piston engines and turbojets. The difference between these systems consists in employing the propeller gear to transmit the high power. The pinions of this propeller gear require flood lubrication.

The turboprop heat-to-oil transfer (680... 1400 J/(kW min)) is higher than turbojets', but is lower than piston engines'. So the oil flow (0.65...0.98 dm^3/(kW hour)) is intermediate too.

It is not desirable to apply here oils with high viscosity since the rate of the propeller blade angle change drops, and engine start-up is complicated. A mixture of oils with high and low viscosity (e.g. 75 % of MC-20 and 25 % of MK-8) is usually used to lubricate turboprops.

4.4 Schemes of oil systems. Air from oil separation methods

There are two types of oil systems: closed (circulating) and open, the latter is applied to the products of single utilization. The closed-type systems are widely used in aviation.

4.4.1 Direct scheme of oil system

The simplest scheme of oil system is the direct scheme (Figure 4.1). In this case oil circulates through the following path: oil tank - engine - cooler - oil tank.

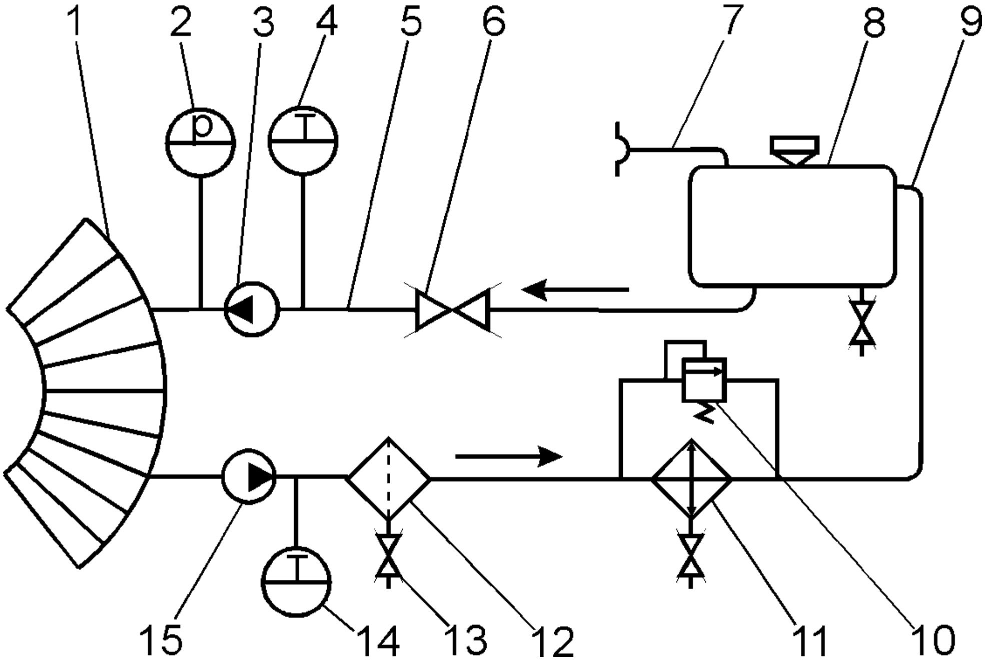


Figure 4.1 - Direct scheme of oil system:
1 - engine; 2 - manometer; 3 - pressure pump; 4 - thermometer of oil at engine inlet;
5 - suction pipeline; 6 - shut-off valve; 7 - venting; 8 - oil tank; 9 - scavenge pipeline;
10 - bypass valve; 11 – cooler; 12 - filter; 13 - drain valve;
14 - thermometer of oil at engine outlet; 15 - scavenge pump

The section of oil system from oil pressure pump to scavenge pump (including them) is an internal pipeline of the engine 1. The external oil system includes: oil tank 8, cooler 11, suction (tank - engine) 5 and scavenge (engine - cooler - tank) 9 pipeline sections, venting pipeline 7, drain pipes and valves 13, instruments for measurement of oil pressure 2, temperature 4, 14 and level in tank.

The suction pipeline must be straight, short and have a big diameter. To improve operating conditions of the pressure pump 3, it is possible to install the oil tank above the pump.

The shut-off valve 6 is sometimes installed in the suction section to prevent the oil overflow from the tank into the inoperative engine through the switched-off pump. In this case it is necessary to interconnect valve with the engine starting system.

For protection of oil system against chips, calx, dust and flux coming from the oil tank it would be expedient to install the filter in the “tank – engine” pipeline section. But thus there will be high pressure losses in the suction pipeline. Thus altitude performance of oil system will decrease. Therefore filters 12 are installed in the scavenge section. If metal chips emerge on the filter surface that is the first indicator of violation of normal engine operation. Additional filter grids are installed in the filler necks and in the tank outlet connections.

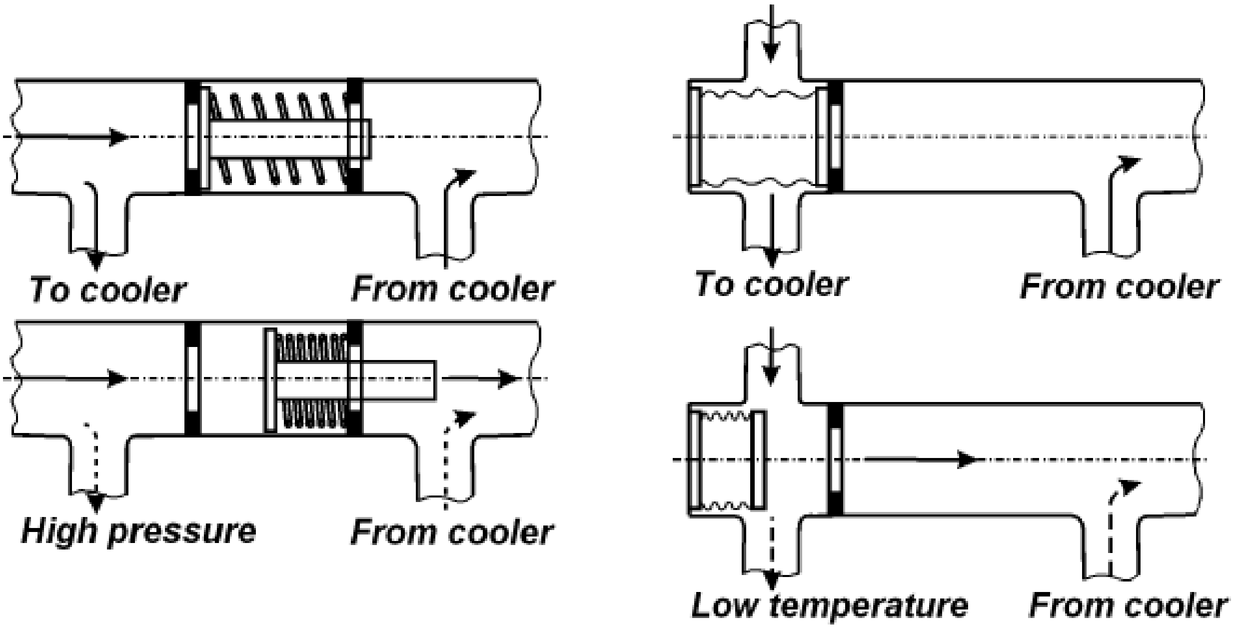
To prevent the oil and its emulsion from accumulation in the engine casing the scavenge pumps 15 must have 2...3 times more volumetric flow, than pressure pumps have. As the pumps except for the emulsion, pump out big quantity of air it results in additional saturation of oil by air.

The cooler 11 is equipped with the bypass valve 10 designed to prevent the cooler core rupture at low oil temperatures and provide the fast oil heating-up. As at the open valve oil circulates, omitting the core. When oil is heated and the pressure drops the valve closes and brings the cooler into operation.

The spring-loaded valves (Figure 4.2, a) are the simplest in design and the most reliable. Their essential disadvantages consist in the capability of passing of cold oil through the cooler at the low engine power. Thus oil flow is small and resistance of cooler is small too. It increases heating-up time of oil and in flight (for example, at gliding) causes it super-cooling. It can cause the oil solidification and breaking of oil flow.

For this reason, the thermostatic valves (Figure 4.2, b) are preferable. Such valves react to the oil temperature variation due to the bellows that is filled with low-boiling fluid. With heating of oil the bellows extends, and the valve closes. Thus oil will flow only through cooler core.

It is necessary to note the difference between the purpose of the fuel tank and oil tank venting systems. In fuel tanks the air feed is required to provide specified overpressure in the fuel tank. In oil tanks the air discharge is required because of the air comes in plenty from the engine together with air-oil emulsion.



a b

Figure 4.2 - Schemes of bypass valves

It is recommended to direct venting connections of oil tank downwards in order to prevent the oil accumulation, solidification in them and as the result, breaking of the oil tank. For the same reason, venting must be directed to a warm place, such as a cooler tunnel situated behind the oil cooler.

Venting of oil system can be open or closed (through breather system).

When designing the oil system, it is necessary to provide full, fast and reliable draining of oil from the oil tank, cooler, filter sediment trap and pipelines. Convenient access to drain valves must be provided. It is necessary to prevent hot oil from hitting onto hands of ground maintenance personnel, electrical wiring, exhaust pipes, and wheel tires.

Operation of oil system is inspected by oil pressure and temperature at engine inlet and by oil level meter.

4.4.2 Air-from-oil separation

When passing through the engine the oil is saturated with air, gases and, in piston engines, with fuel vapors. During lubrication of various units bubbles of air are in addition shattered. As the result the air-oil emulsion is formed, this emulsion is pumped out by scavenge pumps. Thus there is additional oil saturation by air. Downstream the cooler, pressure of oil drops and additional air educes from it. Thus oil in which there are bubbles of various sizes gets in the oil tank. Size of these bubbles changes from molecular ones up to 10...20 mm in diameter.

Large bubbles rapidly float and separate from oil. The less sizes of bubbles, the less its speed of floating, and it is more difficult to separate them from oil.

The speed of floating is directly proportional to the squared float diameter and inversely proportional to the oil viscosity:

$$\boldsymbol{V} \approx \boldsymbol{D}^2 / \nu(\boldsymbol{t}).$$

Thus the more time the oil in the tank is available the less air comes to suction pipeline the higher the oil temperature and the lower the oil viscosity becomes, the less time it takes for the bubble to get the surface.

The following measures are assumed to reduce the contents of air in oil:

- reducing hydraulic pressure losses in oil scavenge pipeline;
- minimum required difference between oil flows of scavenge and pressure pumps must be chosen;
- installation of special de-aerators in the oil tank; they use a principle of coagulation - enlargement of gas particles in two-phase medium;
- centrifugal de-aerators have the wide application now. They provide the complete air-from-oil separation and better altitude performance of oil system; however they require a lot of power.

Let's note the disadvantages of the direct scheme of oil system:

- high back pressure owing to presence of the cooler in a scavenge pipeline;
- low temperature in the oil tank causing the high oil viscosity and the low speed of the air bubbles floating;

– altitude performance of the direct scheme oil system makes 7...8 km.

Owing to these disadvantages other schemes of oil system are widely used.

4.4.3 Reverse scheme of oil system

The oil circulates according to the scheme (Figure 4.3): oil tank 11 - cooler 5 - engine 1 - oil tank.

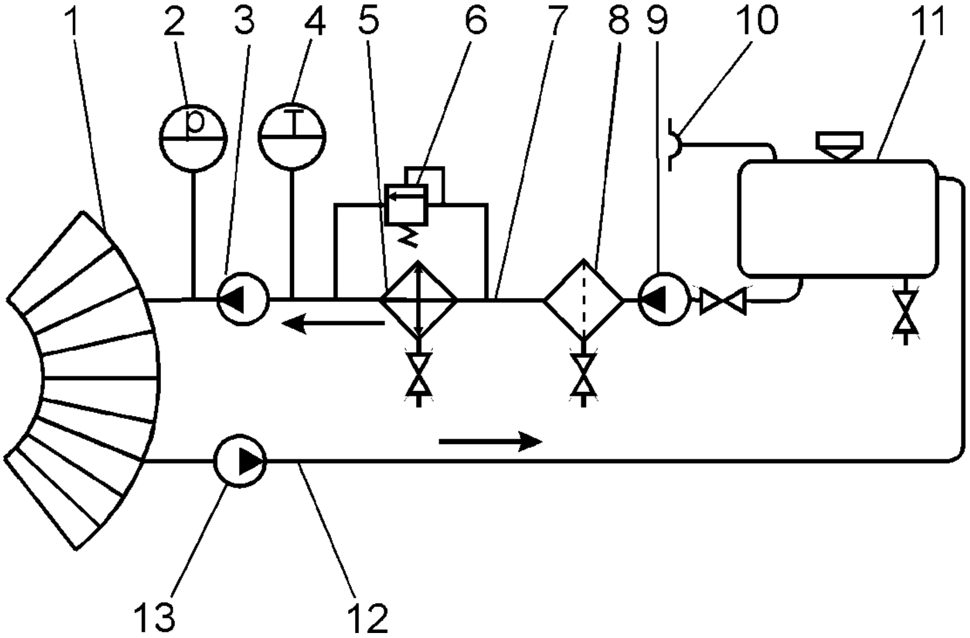


Figure 4.3 - Reverse scheme of oil system:
1 - engine; 2 - manometer; 3 - pressure pump; 4 - thermometer of oil at engine inlet; 5 - cooler; 6 - bypass valve; 7 V suction pipeline; 8 - filter; 9 - transfer pump; 10 - venting; 11 - oil tank; 12 - scavenge pipeline; 13 - scavenge pump

Hot oil, without cooling in the cooler gets directly to the oil tank; oil viscosity considerably decreases. The speed of air separation proportionally increases. Besides, through absence of cooler, the air bubbles are not shattered and keep the relatively big diameter; that also promotes fast air separation.

When the oil cleared from air flows through the cooler its heat rejection increases. Since the oil from the cooler passes directly to the pressure pump, the system reacts faster to the regulating of cooling.

But the pressure pump cannot provide the oil pumping through a cooler. Therefore the additional pump 9 in the segment «oil tank - cooler - engine» must be installed in the reverse scheme of oil system. It is a disadvantage of the reverse scheme.

The altitude performance of the reverse scheme oil system makes 10...12 km.

4.4.4 Single-circuit scheme with centrifugal de-aerator

The altitude performance of the direct scheme can be increased if to install the centrifugal de-aerator 9 in the oil scavenge pipeline (Figure 4.4).

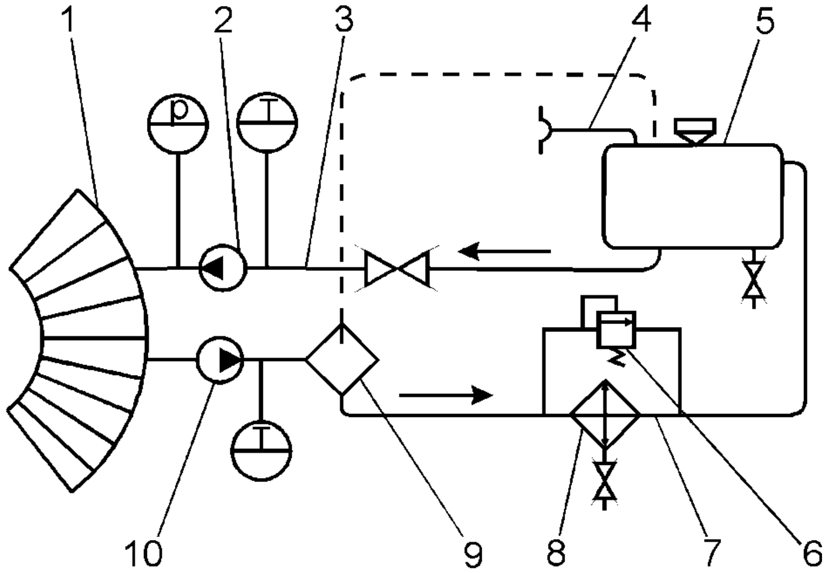


Figure 4.4 - Scheme of oil system with centrifugal de-aerator:
1 - engine; 2 - pressure pump; 3 - suction pipeline; 4 - venting; 5 - oil tank;
6 - bypass valve; 7 - scavenge pipeline; 8 – cooler; 9 - centrifugal de-aerator;
10 - scavenge pump

The centrifugal de-aerator (Figure 4.5) is installed before the cooler, thus making the process of air separation far easier (as the oil is hot).

Besides heat rejection in the cooler also increases as oil is cleared from air. This scheme is the most used on up-to-date turbojet airplanes.

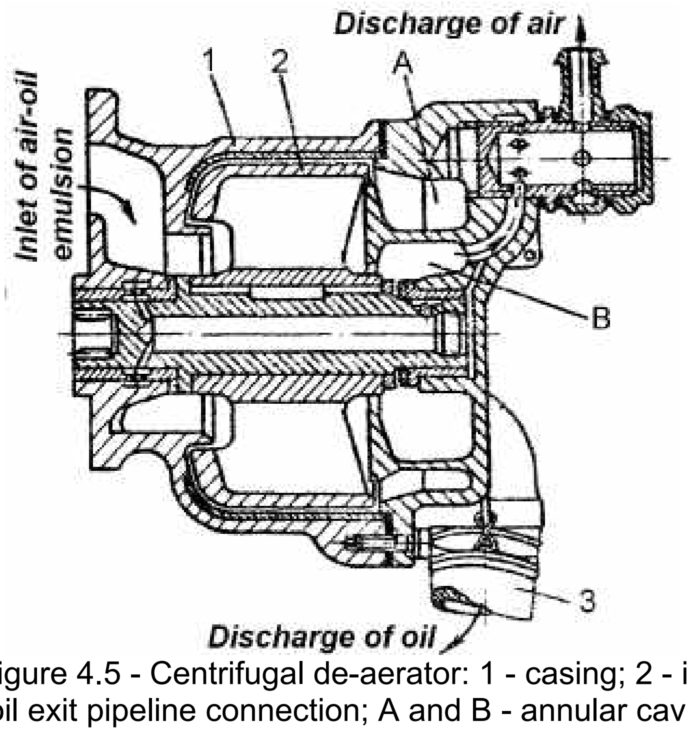


Figure 4.5 - Centrifugal de-aerator: 1 - casing; 2 - impeller;
3 - oil exit pipeline connection; A and B - annular cavities

4.4.5 Shorted schemes

As the centrifugal de-aerator is capable to clean the oil from air, there is no need for oil circulation through the oil tank. This fact has resulted in the development of the shorted oil system (Figures 4.6, 4.7).

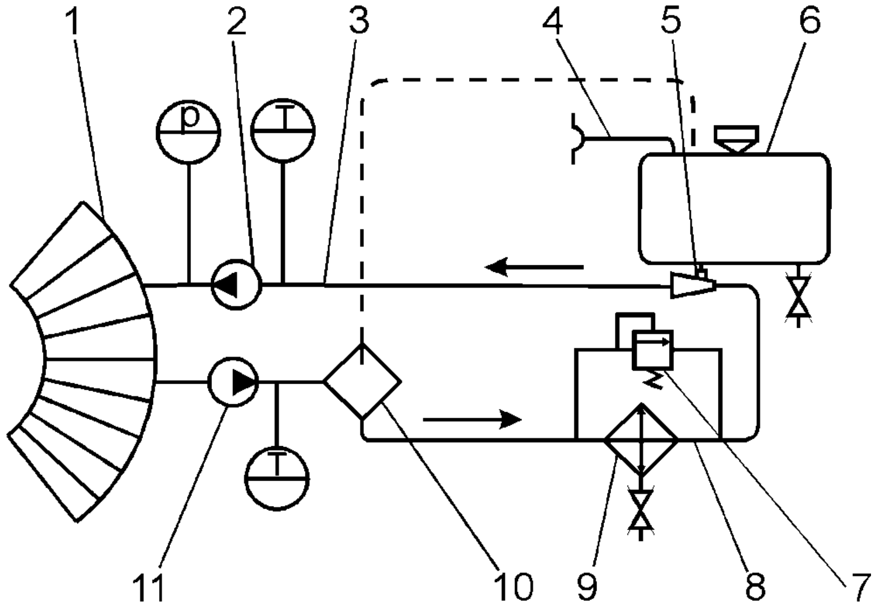


Figure 4.6 - Shorted scheme oil system with ejector:
1 – engine; 2 - pressure pump; 3 - suction pipeline; 4 - venting; 5 - ejector;
6 - oil tank; 7 - bypass valve; 8 - scavenge pipeline; 9 - cooler;
10 - centrifugal de-aerator; 11 - scavenge pump

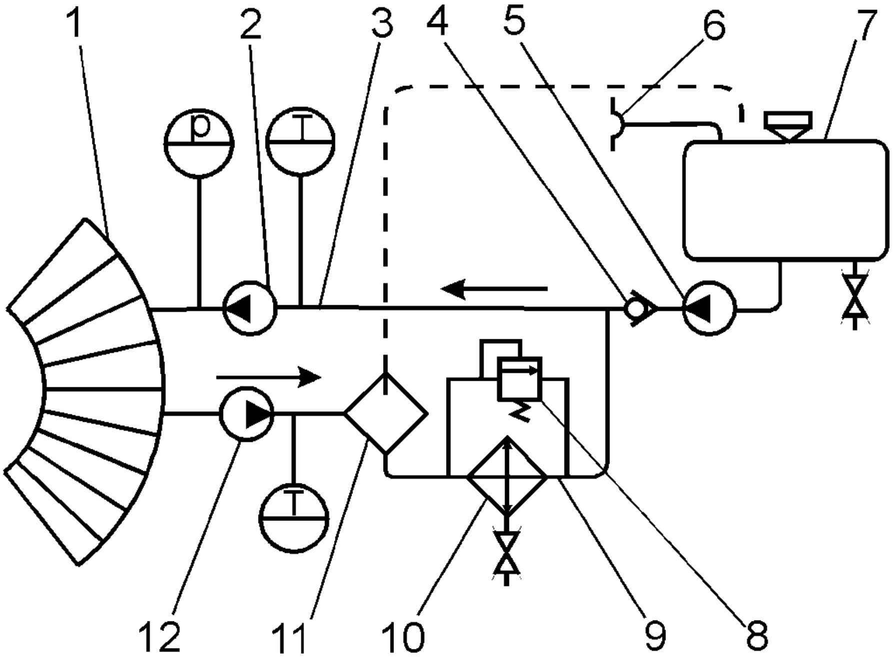


Figure 4.7 - Shorted scheme oil system with pump:
1 - engine; 2 - pressure pump; 3 - suction pipeline; 4 - check valve; 5 - transfer pump;
6 - venting; 7 - oil tank; 8 - bypass valve; 9 - scavenge pipeline; 10 - cooler;
11 - centrifugal de-aerator; 12 - scavenge pump

According to this scheme (see Figure 4.6), the oil circulates within the contour “engine - scavenge pump 11 - de-aerator 10 - cooler 9 - pressure pump 2 - engine”. The ejector 5 serves for compensation of the oil consumption only.

The scheme provides:

- fast oil preheating (as only the oil circulating within the contour is preheated);
- good altitude performance (due to the capability of creation backup in the main pump inlet, see Figure 4.7);
- small capacity (hence mass) of the oil tank; the oil tank contains only the store of oil consumed in flight.

The disadvantage of this scheme is that as the tank is not used for cooling oil, the cooling surface of cooler (hence mass) must be increased.

The shorted schemes of oil system are used for short-medium range turboprop airplanes (An-24, An-140, ATR-42, ATR-72).

4.4.6 Double-circuit scheme of oil system

Double-circuit scheme of oil system (Figure 4.8) has the boost pump 5 and two contours of oil flow: main and additional.

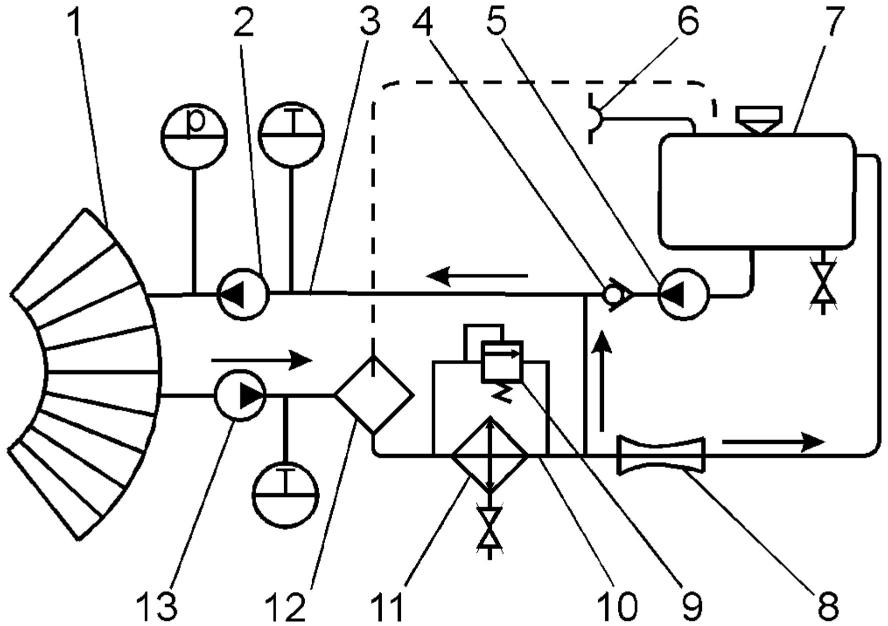


Figure 4.8 - Double-circuit scheme oil system: 1 - engine; 2 - pressure pump; 3 - suction pipeline; 4 - check valve; 5 - transfer pump; 6 - venting; 7 - oil tank; 8 - orifice; 9 - bypass valve; 10 - scavenge pipeline; 11 - cooler; 12 - centrifugal de-aerator; 13 - scavenge pump

The main contour includes: pressure pump 2 - engine - scavenge pump 13 - centrifugal de-aerator 12 - cooler 11 - pressure pump. Approximately 90 % of oil circulates in this contour. The residual oil passes in the oil tank for preheating through the additional circuit (cooler - oil tank 7 - boost pump). The diameter of orifice 8 in the additional circuit is selected by condition of passing of the oil optimal quantity (approximately 10 %) through it.

The double-circuit scheme has the same advantages as the shorted scheme. It is applied in power plants of long-range airplanes, such as Il-62.

4.5 Calculation of oil system parameters

4.5.1 Determining of oil tank required capacity

The oil tank capacity is calculated on condition of filling up the tank with maximum amount of oil and providing the reserve volume for the oil expansion and foaming.

The oil tank capacity is determined as a sum of the following volumes:

1) The volume V_1 required for consumed oil capacity

$$V_1 = K \frac{c_o N_e \tau}{\rho_o},$$

where c_o - specific oil consumption;

N_e - engine power;

τ - maximum possible engine operating time without oil servicing;

ρ_o - oil density;

K - safety factor which takes into account random oil emission, complete filling up, etc.; $K = 1.15...1.2$.

2) The volume V_2 that is the amount of oil left in the oil tank at the end of flight. This volume is required to supply the oil system with oil in the case when the acceleration of engine at balked landing is required.

Value V_2 is usually determined by the engine manufacturer and is specified in maintenance manual.

3) The volume V_3 required for a oil system filling up.

Thus, the oil capacity, which is filled in the system, is determined as

$$V_{LS} = V_1 + V_2 + V_3.$$

The total oil tank capacity is $V_T = K_1 V_{LS}$, where K_1 - the tank capacity safety factor at the oil-into-foam expansion; $K_1 = 1.15...1.25$.

4.5.2 Calculation of altitude performance of oil system

Altitude performance of oil system is the maximum flight altitude up to which the pressure pump provides the required oil flow at minimum allowable pressure.

Diameter of suction pipeline is determined as a result of the calculation. Parameters of the pressure pump, the maximum pressure valve in the tank etc. are also checked. The scavenge line usually is not calculated. Diameter of the scavenge pipeline is assumed as $d_s = (0.8...1)d_p$.

Condition of oil system calculation is the required oil flow through the engine. Oil pressure in the pressure pump inlet is accordingly determined.

Calculation of oil pressure at the pressure pump inlet is carried out similarly to the calculation of fuel system. The oil pressure at pump suction p_{in} is

$$p_{in} = p_H + \Delta p_T + \rho_o g\left(y_T - y_{in}\right) - \Delta p_{hyd} - \Delta p_{in} > p_{in\,min},$$

where p_H - atmospheric pressure at the altitude;

Δp_T - overpressure in the tank;

$\left(y_T - y_{in}\right)$ - relative height of the tank over the pump inlet level;

Δp_{in} - inertial pressure losses;

Δp_{hyd} - hydraulic pressure losses at the oil motion;

$p_{in\,min}$ - minimum allowable oil pressure at the pump inlet.

The hydraulic losses are determined by the known formula

$$p_{hyd} = \left(\lambda \frac{l}{d} + \Sigma \xi_{form}\right) \frac{\rho_o V_o^2}{2}.$$

However the flow mode is assumed as laminar, i.e. $\lambda = K\,64/Re$. The factor K takes into account the increase of the friction losses because of oil cooling (according to the viscosity increase) near the pipeline surface. $K = 1.1$ - for heated pipelines; $K = 1.3$ - for non-heated ones.

One more difference is that the overpressure in the oil tank is created not by external sources but due to allocation of air from the air-oil emulsion. This overpressure is determined by the formula which is analogous to one while calculating the fuel system venting:

$$p_T = \left(\lambda \frac{l_v}{d_v} + \Sigma \xi_{form\,v}\right) \frac{\rho_{air} V_v^2}{2},$$

where λ, l_V, d_V, $\xi_{form\ V}$, ρ_{air}, V_V - friction drag coefficient, length, diameter of the pipeline, its factors of form loses, density and speed of air in the vent system respectively.

Overpressure in the oil tank is usually maintained constant by the installation of the proportional valve in the oil tank outlet to the venting pipeline. This pressure must be minimally required, as it increases mass of the oil tank. It is approximately $\Delta p_T = 10...25$ **kPa**.

The minimum allowable pump inlet pressure $p_{in\,min}$ is determined by cavitation pump characteristics (Figure 4.9). To calculate this pressure we must do the following:

1) Determine required oil flow through the engine by the condition of rejection of required heat quantity.
2) Lay off the value of this flow on the ordinate axis (point *a*).
3) Draw a horizontal (*ab*) up to an intersection with the cavitation pump characteristic corresponding to the assumed contents of air in oil.
4) Drop a perpendicular from the obtained intersection point (point *b*) to the abscissa axis (point *c*).

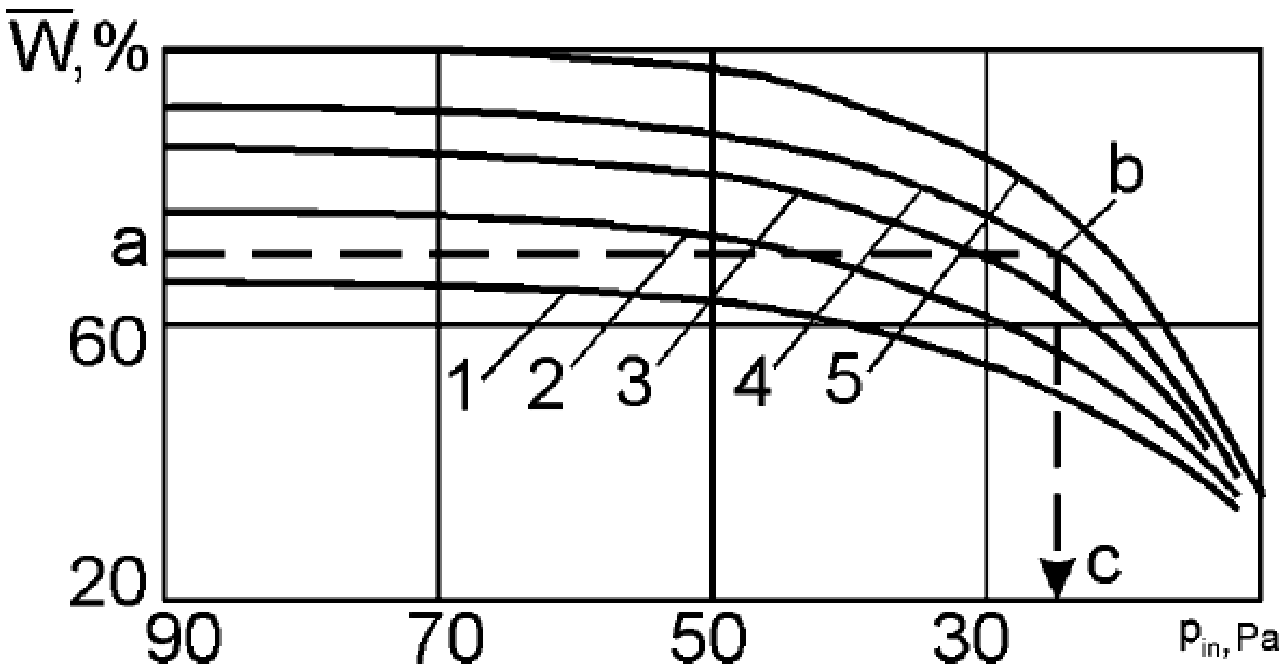


Figure 4.9 – Finding minimum allowable pump inlet pressure:
1, 2, 3, 4, 5 – lines corresponding to the different air content in oil

If altitude performance of the oil system is not provided, the following measures can be used: increasing of overpressure in the oil tank, the booster pump installation, increasing of pipeline diameter or using another oil system scheme.

4.6 Units of oil systems

4.6.1 Oil pumps

To ensure the reliable oil circulation in GTE gear and gear-centrifugal pumps are most widely used as the pressure and scavenge pumps. Gear pumps are simple in design, reliable, have a small size and weight, their volumetric efficiency is 0.75...0.85. Sometimes ejector, plate and scoop pumps can be used. Feed pump capacity at the bench mode must exceed the needed oil pumping through the engine 1.2...2 times.

Figure 4.10 shows the diagram of oil pressure gear pump installing into the pipeline with bypass and check valves. The bypass valve is used to adjust the oil pressure at the engine inlet. The adjustment is made by tightening the spring by the special adjusting screw. The check valve prevents flow of oil from the tank to the engine in the aircraft parking space. It opens only when the pressure pump operates with excess oil pressure 0.04...0.06 MPa.

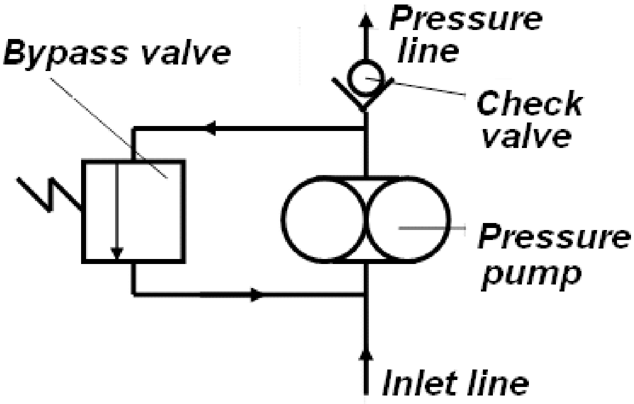


Figure 4.10 – Oil pressure pump equipped with bypass and check valves

Number of scavenge oil pumps is selected depending on the type of engine, number of supports, number of outputs. Usually for each output its own scavenge oil pump is provided.

Total capacity of scavenge pumps must exceed 2-3 times the capacity of pressure pump as a scavenge pump is supplied with foamed oil at large volumetric content of air.

The pressure pump is mounted below the oil tank to use hydrostatic pressure of the column of oil at the pump inlet.

Pressure and scavenge pumps are often collected into a single assembly called an oil unit. Fine filter, oil check and bypass valves, sensors of temperature and oil pressure at the engine inlet are placed in the same unit.

4.6.2 Oil filters

Oil filters purify oils from various impurities - mechanical impurities that enter the system from outside, oil coking products, products of parts wearing and corrosion. Impurities contained in the oil getting into the gaps between the friction parts working surfaces (bearings, gears), have an abrasive effect, impair of cooling friction surfaces, and may cause jamming of parts, clogging nozzles and throttle channels.

Filters of GTE oil systems are installed in feeding pipeline downstream the pressure pump (fine filters), and upstream the pressure pump, upstream the oil nozzles, in the scavenge pipeline (strainers).

Modern GTE oil systems are equipped with mesh and slotted strainers.

The oil mesh strainer (Figure 4.11) is a package of individual filter elements composed on hollow rod. Filter elements packet is mounted between the disks and fixed in the filter cover by spring ring. Assembled package is installed in the housing boring of the filter and fixed by cover screw flywheel on a pin.

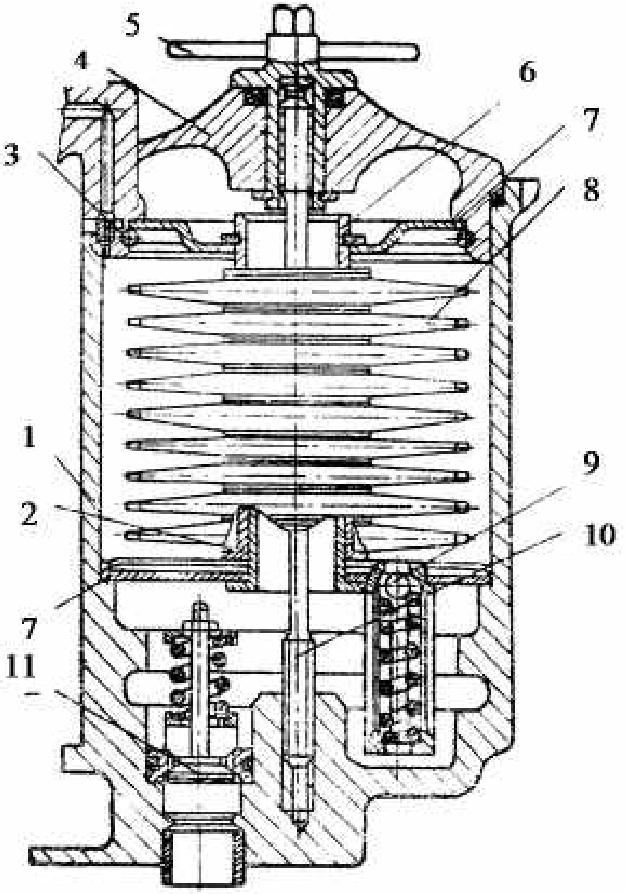


Figure 4.11 - Oil filter:
1 - housing; 2 - frame; 3 - spring ring; 4 – cover; 5 - flywheel cover; 6 - hollow rod; 7 - disc; 8 - filter element; 9 - relief valve; 10 - pin; 11 - check valve

When the engine operates oil through a side channel enters the filter housing boring, passes through the mesh filter into the inner cavity of the rod and then - into the feed line.

Relief valves and check valves are placed in the filter housing. The relief valve opens in case of clogging of the filter element (at a pressure drop of 0.13...0.16 MPa) thus bypassing unfiltered oil to the oil injectors. The check valve prevents flow of oil from tank to supports when the engine is off.

Each of the filter elements (Figure 4.12) has a disk shape and consists of a corrugated diaphragm, wireframe mesh, mesh filter and holder. The mesh filter is made of stainless steel or brass wire with the number of cells on 225...5000 per 1 cm^2 for strainers and up to 12,000 cells per 1 cm^2 for fine filter. The wireframe mesh has 30...40 cells per 1 cm^2.

Slotted filter is a hollow frame with threaded surface. In the thread hollows wire is wounded turn to turn in such a way that gaps remain between the turns of 0.03...0.08 mm in which the oil passes. Filtering surface of the filter is small. These filters are set upstream the nozzles or orifices.

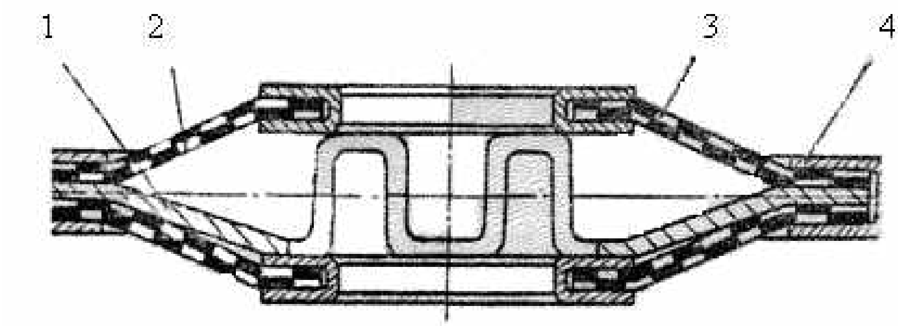


Figure 4.12 - Oil filter with mesh filter element:
1 - corrugated diaphragm; 2 - wireframe mesh; 3 - mesh filter; 4 - holder

4.6.3 De-aerator

One possible cause of a malfunction of the GTE oil system is oil saturation with air and gases penetrating into the oil cavities when the engine operates. Foamy oil reduces altitude performances of pressure pump and oil system, reduces cooling of friction parts and oil cooling in the cooler.

Most complete removal of air and gases from the oil is carried by a special ***centrifugal de-aerator*** which is placed downstream scavenge pumps. The centrifugal de-aerator is the unit which impeller is driven by the running engine rotor through the drives box. Scheme and the operating principle of centrifugal de-aerator are shown in Figure 4.13 while an example of embodiment - in Figure 4.5.

The principle of operation of the centrifugal de-aerator is based on the fact that the oil-gas emulsion flowing into the rotor in the field of centrifugal force is divided into two fractions: a heavy oil travels towards the periphery by centrifugal force, and further through the gap and outlet channel enters radiator for cooling while the light fraction (air containing a small amount of oil vapor) through the hollow shaft enters venting system.

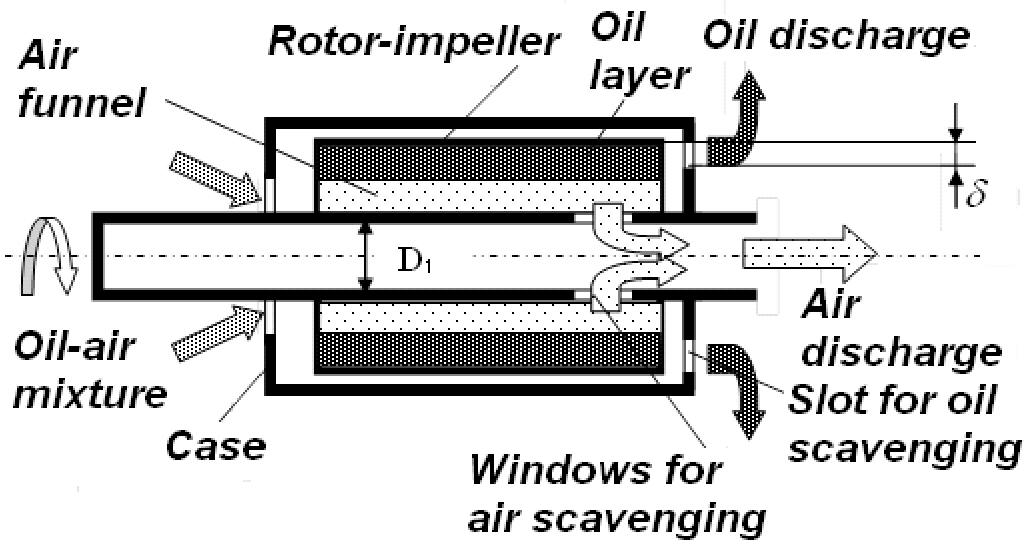


Figure 4.13 - Driven centrifugal de-aerator scheme

The centrifugal de-aerator efficiency substantially depends on the rotor rotational speed. Therefore at lower engine operational modes oil can flow into a venting cavity (drives box) through the hollow shaft. To prevent this phenomenon the centrifugal valve is mounted within the hollow shaft which opens an outlet to air venting system only when the rotor speed is not less than 0.35...0.5 of the maximum.

To reduce foaming and to remove air from the oil the oil system is equipped with special devices. Examples of these devices are defoaming nets in the sump, horizontal baffles in the oil tank on which foam oil spreads, special grids and static de-aerators separating the air from the oil that enters the tank.

4.6.4 Air-breathers

Air-breathers are designed for air and gas discharging from oil cavities of the engine into the atmosphere, to separate oil particles from the air and gas flow and to maintain a predetermined overpressure in the breathed cavities.

The ***centrifugal air-breathers*** (Figure 4.14) are most widely used.

The centrifugal air-breather contains rotating at a high speed impeller that is located within the housing. When the engine operates the air containing a small amount of vapor and fine droplets of oil enters the impeller cavity. Centrifugal force directs oil particles to the wall of housing where accumulated oil through the special grooves drains into the crankcase. This reduces the deadweight oil losses. The air cleaned from oil is discharged into the atmosphere through the hollow shaft of the impeller.

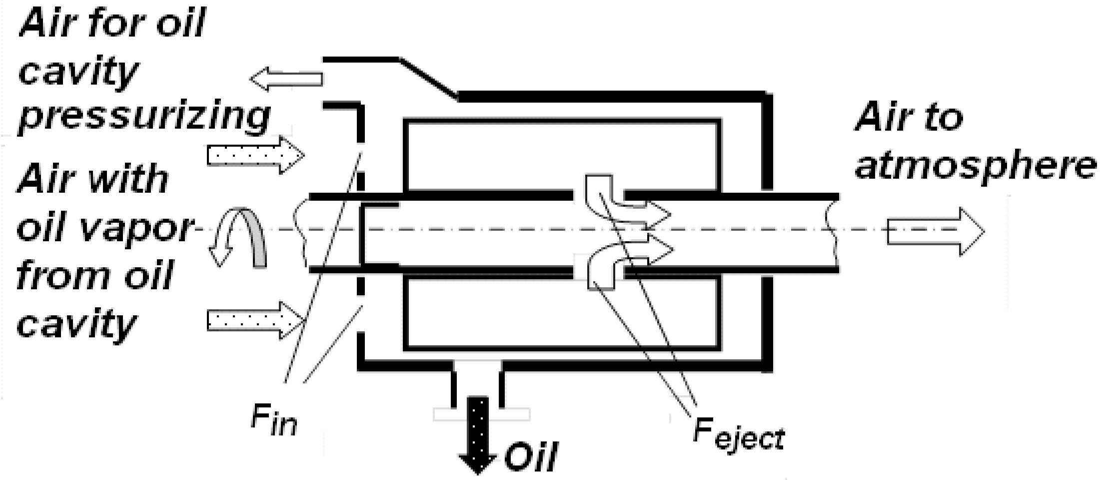


Figure 4.14 - Scheme of centrifugal air-breather

Oil Cooling

Coolers are devices designed for transferring heat from the cooled medium to the cooling one. Coolers are named by the medium (cooling-cooled): air-oil, fuel-oil, water-oil coolers.

Air-oil coolers are usually applied in airplanes with piston or turbo-prop engines. In this case, fuel-oil coolers are not used, as far as the heat flow into the oil is considerable, but fuel consumption is low. Thus fuel cannot cool oil down to acceptable temperature. These coolers can be used in jet engines as first pre-cooling stage of cooling process, decreasing size of fuel-oil cooler.

Fuel-oil coolers are usually used in airplanes with turbo-jets and turbofans. Their functions are:

– elimination of power consumption for overcoming the external drag of the cooler installation;

– preheating of fuel before supplying it to the engine;

– automatic regulation of oil temperature while changing the engine power, i.e. the fuel consumption.

Besides the air stagnation temperature on the surfaces of supersonic airplanes can exceed the oil temperature thus preventing the cooling process. Therefore for such airplanes only fuel-oil coolers may be used.

According to the design we can distinguish two types of coolers: honeycomb, finned and tubular.

Honeycomb coolers (Figure 4.15) consist of a set of copper or brass pipes of 250...300 mm long, with the wall thickness of 0.1...0.2 mm and the 4...5 mm in diameter, concluded in a steel casing.

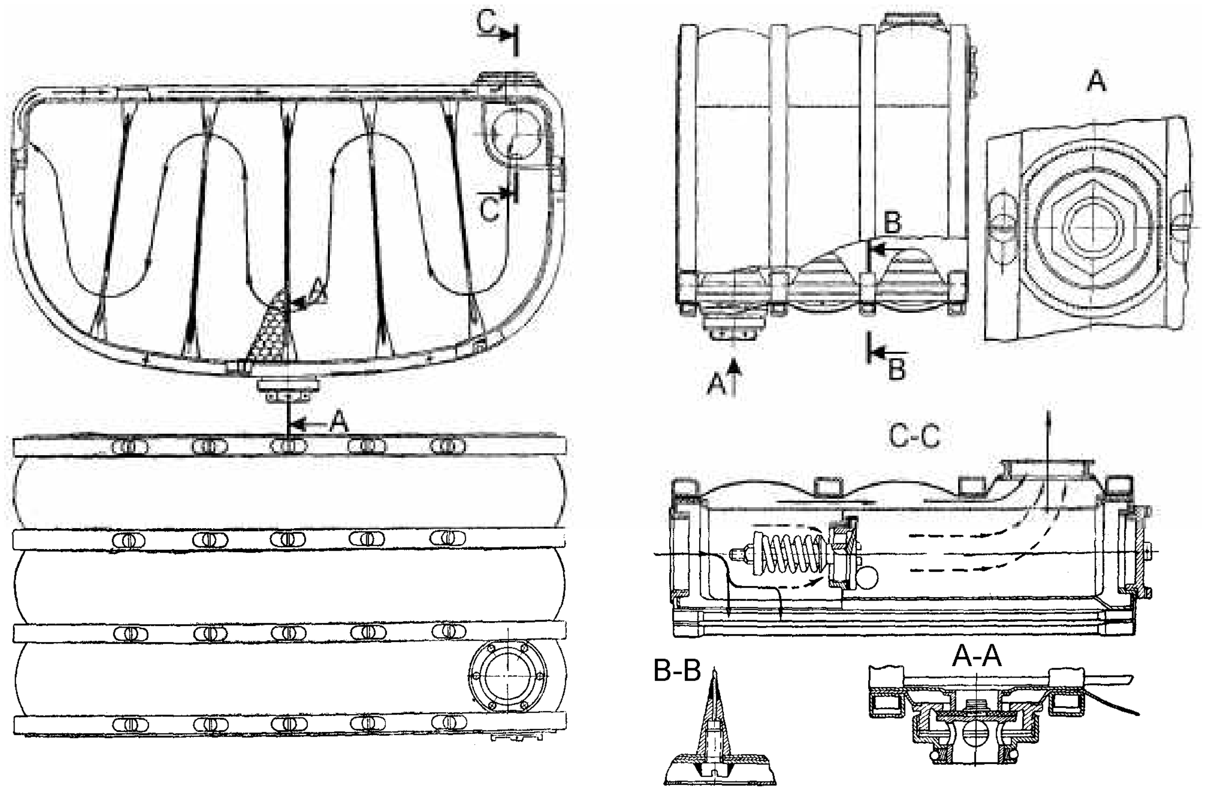


Figure 4.15 - Design of honeycomb air-oil cooler

The pipe tails at the $\boldsymbol{l} = (\mathbf{2...3})\boldsymbol{d}$ segment are flared to a hexahedron and hermetically soldered. Thus there are slots among the pipes through which the hot oil passes. The cooling medium flows inside the pipes. To increase the oil path and to decrease the cooler sizes bulkheads are installed in the cooler. Besides, these bulkheads provide strength and stiffness of the cooler structure.

The honeycomb coolers are convenient in service. In the case of tube' leakage, it is possible to unsolder it and replace or solder both ends.

The shape of coolers should provide minimal drag and is selected in compliance with arrangement in the airplane: round, oval, horse-shoe.

The other type of coolers is ***finned coolers*** (Figure 4.16). They consist of a set of streamlined pipes, made of aluminum alloys and welded to the perforated plates. The oil flows inside these pipes, and the air passes in the space among the pipes.

Finned coolers have approximately 25 % smaller mass; they are stronger than honeycomb ones. Their tightness does not depend on quality of welding. The finned coolers have stable heat conduction characteristics. Their only disadvantage is that it is impossible to repair a finned cooler in field conditions.

The coolers are attached by steel attaching straps with damping rubber plates, analogously to the rigid fuel tanks attaching or by brackets.

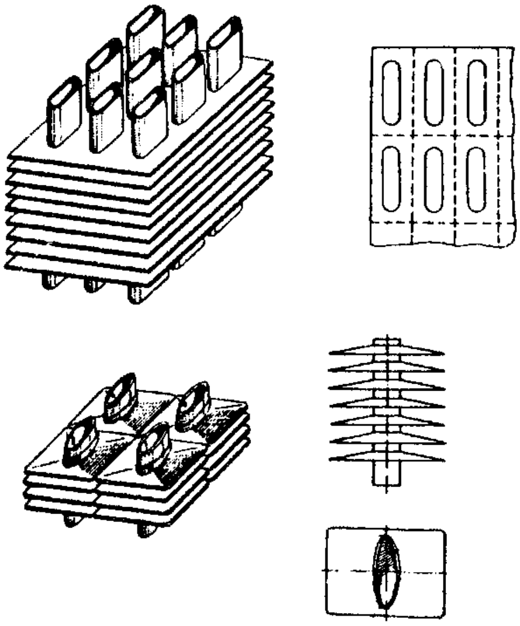


Figure 4.16 - Design of finned air-oil cooler

Structure of oil tank

The structure of oil tanks (Figure 4.17) is very similar to that of rigid fuel tanks. Now the rigid oil tanks are usually used. They are made of aluminum-magnesium or aluminum-manganese alloys. The main difference between oil and fuel tanks consists in the installation of the air separation devices and the pipe connection for return the oil to oil tank.

There are various types of de-aerators. For instance let us consider the pan de-aerator and the centrifugal de-aerator-well.

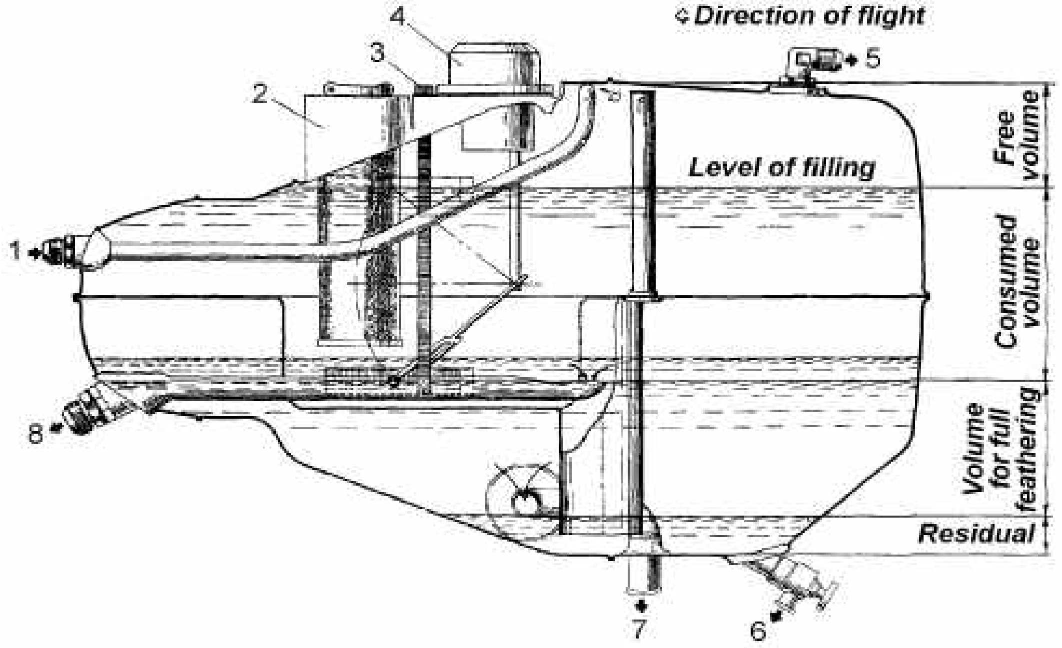


Figure 4.17 - Oil tank structure of turboprop airplane:
1 - air-oil emulsion input from engine; 2 filler neck; 3 – measuring bar;
4 – oil-metering sensor; 5 - venting; 6 - drain; 7 - oil outlet for propeller feathering;
8 - oil outlet to engine

A principle of sediment is used in the ***pan de-aerator*** (Figure 4.18). After entering into the oil tank, the oil stream is directed to the inclined face-pan that extends to the bottom. Sometimes a grid is installed instead of a pan. The oil freely drains through such grid but the surface tension prevents air bubbles from passing through it. Such de-aerators are all used in flat tanks up to 350...400 mm height.

If the oil tank is high, the ***centrifugal de-aerator-well*** is usually used (Figure 4.19). Oil gets into the de-aerator tangentially to the well and leaves it in the same way or along the axis of the well. In the first case, the oil is pressed to the well wall by the centrifugal force. In the second case, the straightening cross is installed below in places of the oil exit. The separated air leaves the de-aerator through special openings above.

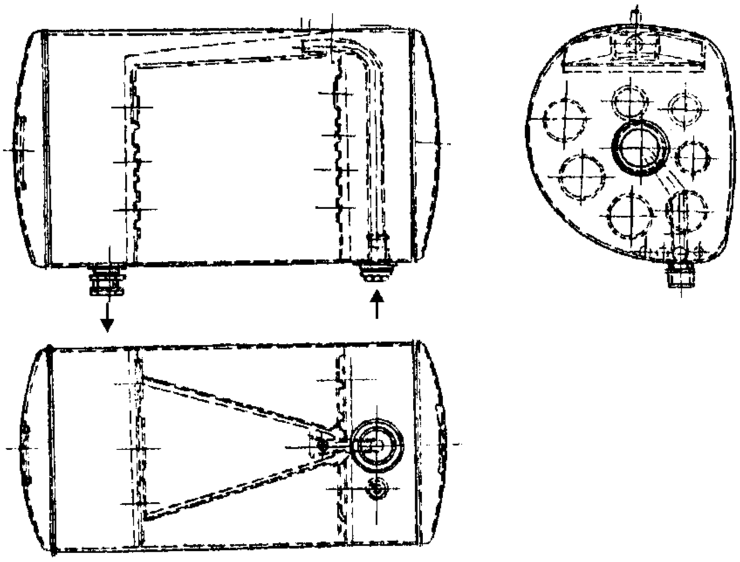


Figure 4.18 - Pan de-aerator

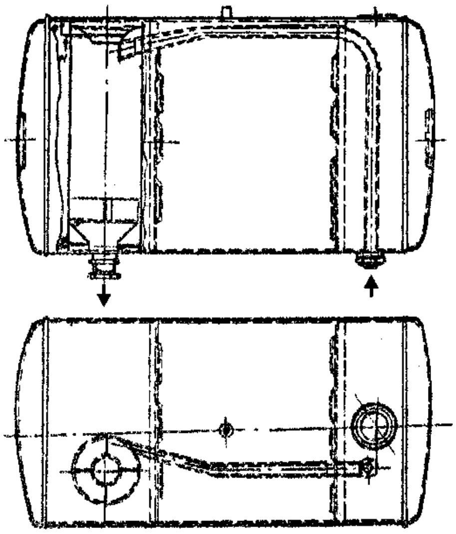


Figure 4.19 - Centrifugal de-aerator-well

The pipe connection for the oil return must be installed in the top of the oil tank. Thus duration of oil availability in the oil tank increases and oil in full capacity is circulated. The venting connection is disposed in the top of the oil tank. If the oil tanks are wide or long, it is recommended to use two venting connections. To provide reliable operation of oil system at acrobatic and maneuverable aircraft under decelerations and negative overloads special devices are installed inside the oil tanks.

The list of self-check questions

1 Which problems does the engine oil system solve?
2 What are the requirements to the oil system of aircraft engine?
3 What are the defining properties of oils for aircraft engines?
4 What is the difference between oil systems for TJE (TFE) and TPE?

5 Perform a comparative analysis of direct and reverse schemes of oil system.

6 What are the advantages of two- and short-circuits oil systems?

7 What are the measures taken to reduce the consumption of air in the oil?

8 How to identify the needed capacity of the oil tank?

9 What is the altitude performance of the oil systems? How is it provided?

10 Why is the scavenge pumps capacity several times higher than pressure pump capacity?

11 What are the oil filter filtering elements made of?

12 Explain the principle of centrifugal de-aerator and centrifugal breather operation.

13 How is the oil pumped out from the engine cooled?

14 What are the elements of the oil tank?

5 TURBINE ENGINE STARTING SYSTEMS

Start-up is a process of the engine transition from the off state to idle power.

One can distinguish ground startup and start in flight (relighting). In the first case engine starts from the off state, and in the second - from the state of autorotation.

Let's consider ground startup. As it is known from the above thermodynamic analysis of engine workflow, a positive work of the thermodynamic cycle cannot be obtained without prior compression of the working fluid (air). Therefore for the beginning of the startup process an external source of mechanical energy is allowed to turn the rotor and provide the required minimum pressure ratio of the compressor.

A device that provides the initial turning of the rotor is called a starter.

In addition to pre-compression of air, there are other reasons that need spin up of rotor before initiating combustion in the combustion chamber (CC):

- all fuel and oil pumps are rotated by the engine shaft, so to ensure a reliable supply of fuel and oil at a set pressure spin up of plunger and gear pumps is needed;
- stable fuel ignition is possible only in a limited range of the excess air–fuel ratio and rotation of compressor is necessary to ensure proper air flow.

Ground startup can be divided into three stages (Figure 5.1). The first stage is the initial rotor acceleration by a starter. After completion of this phase ignition in a combustion chamber is produced and the second stage begins – the rotor acceleration under the action of starter and turbine. Then the starter is disconnected and at the third stage the rotor is rotated by the turbine only.

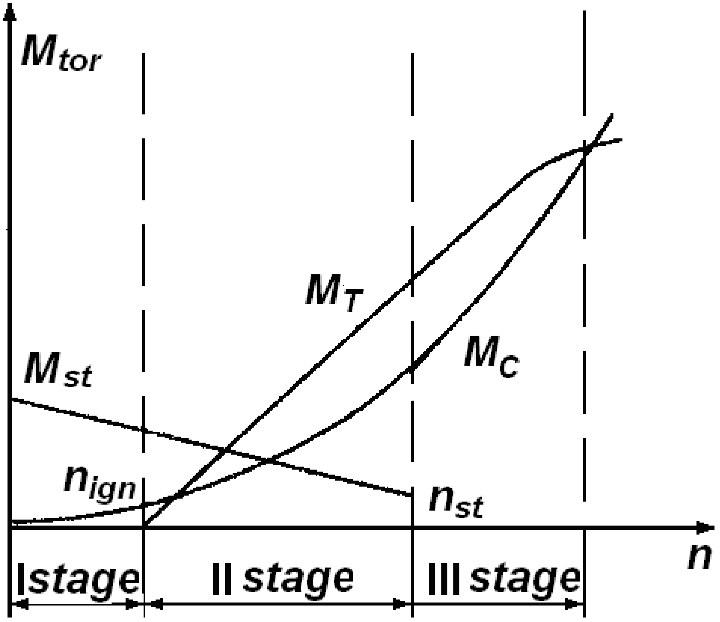


Figure 5.1 - Moments acting the rotor at startup:
M_{st} - starter torque; M_T - turbine torque; M_C - torque of compressor;
n_{ign} - combustion chamber ignition; n_{st} - starter switch-off

5.1 Classification of starting systems

By basing site, there are differed autonomous and ground power starting systems. The system which all devices and energy sources are located on the aircraft board is called as autonomous.

By the type of energy sources used, the following types of starting systems are distinguished:

- electric power;
- air;
- gas;
- direct feed with compressed air or gas;
- turbocharging;
- hydraulic.

5.1.1 Electric starting systems

Electric starting system (Figure 5.2) is a system in which motor or a motor-generator is used as a starter. The electric starter is usually a direct current motor connected to the engine through the gearbox and clutch which automatically releases the connection when the engine's rotor reaches set rotational speed.

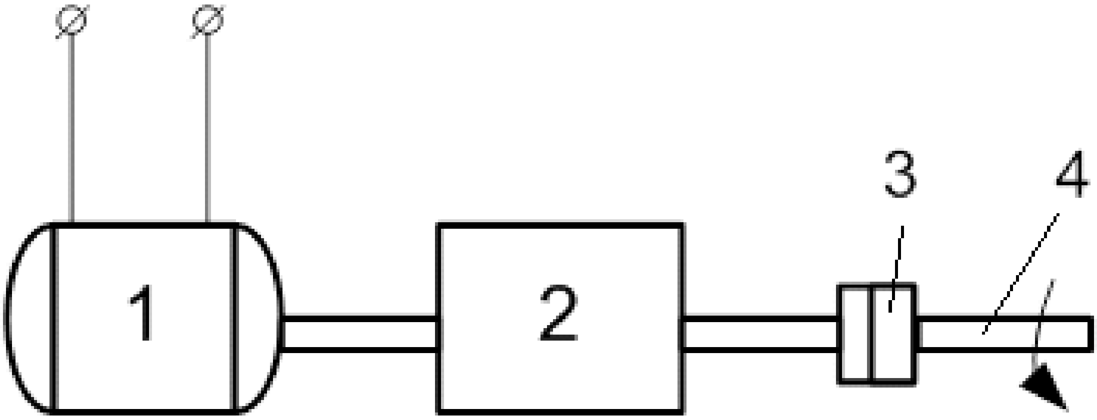


Figure 5.2 - Electric starting system:
1 - electric starter; 2 - gearbox; 3 - clutch; 4 - engine rotor

5.1.2 Air (pneumatic) starting systems

Air starting systems are used for most commercial engines and for many military engines. They have many advantages over other starting systems and have a relatively low weight, are simple and economical in operation.

The air starter (Figure 5.3) is a turbine which transmits power through the gearbox and clutch to the engine’s rotor.

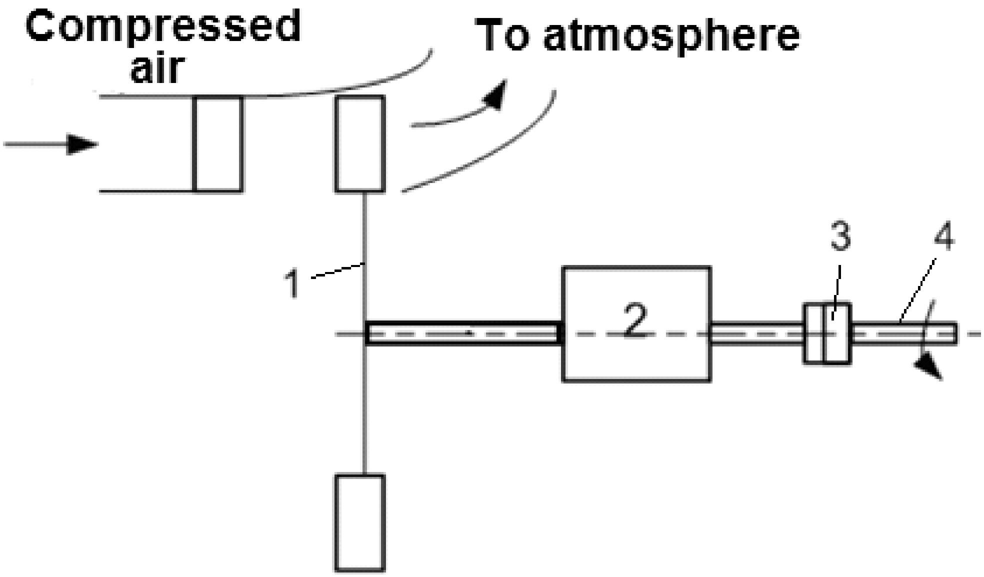


Figure 5.3 - Air starter:
1 – turbine; 2 – gearbox; 3 – clutch; 4 – engine rotor

One of the advantages of an air starting system is the ability to use different sources of compressed air. It can be taken away from the auxiliary power unit (APU), running engine, on-board pneumatic accumulator or ground air system.

The air supply to the starter is controlled by electrically operated control valve and pressure reducing valve. Metering valve opens when engine is started and closes automatically at a predetermined starter speed.

The clutch automatically disconnects starter shaft with engine rotor after the engine rotor reaches idle speed. Therefore the starter rotation ceases.

The air pressure in the low pressure starting systems is 250...400 kPa, the specific mass of the system - 0.13...0.25 kg/kW.

The main advantage of the high pressure air starting system comparing to the low-pressure system is smaller hydraulic losses as in the high-pressure air flow is less than required to produce the same power. That is why in modern aircraft starting systems APU with high pressure compressor are used. This pressure can reach 600 kPa or more.

5.1.3 Gas starting systems

The gas starting systems are based on the same principles as the air ones. The difference is in the fact that gas is used instead of air. As a method of gas generating they are distinguished:

- systems with combustion chamber;
- solid propellant systems (high-temperature and low-temperature);
- liquid monopropellant systems.

Starter with combustion chamber is usually a supplement to the air starter and used if the external source of air is not available. Starting device has a small auxiliary combustion chamber into which a high pressure air is supplied from the onboard pneumatic accumulator as well as the fuel from the engine's system. The fuel pressure required to keep it stable spray pattern is generated in the hydraulic accumulator by supply of compressed air to it. The value of this pressure is controlled by a valve. When the valve opens the ignition system is activated. Fuel mixture in the combustion chamber is ignited and the resulting combustion gas flows into the turbine starter.

Special electric device terminates air and fuel supplying into the auxiliary combustion chamber and switches off the ignition system after the engine has started.

Starting systems with solid propellants are used for startup engines of aircrafts which are based on unequipped airfields or being expendable.

The main advantage of these systems is accelerated (5...20 s) autonomous startup.

The starting device is an air-gunpowder turbo starter. Its impulse turbine operates on gases formed during combustion of solid propellant charge in the cartridge. Compressed air can be used instead of gunpowder gases if there is airfield source of compressed air.

The turbine is connected with the rotor of engine through gearbox and clutch, as it is done in the air starting system (see Figure 5.3). An electrically fired detonator ignites the cartridge charge.

Regular high-temperature gunpowder (e.g. cordite) is used in high-temperature systems. Such systems have high specific energy, are small in mass and size. However their disadvantage is short life time due to high temperature and chemical activity of propellant gases.

The low temperature solid charge systems which have high life time are also known.

A common disadvantage of this type of starting systems is the inability to terminate burning of charge and the necessity to replace the charge when you restart, or to equip starter with multi-breech cartridge.

Starting systems with liquid monopropellant are used for engines of the same class as the systems with solid propellants.

The propellants used are:

- hydrogen peroxide $\mathbf{H_2O_2}$;
- isopropyl nitrate $\mathbf{(CH_3)_2CHONO_2}$;
- hydrazine $\mathbf{N_2H_4}$.

The isopropyl nitrate has widest application having low toxicity and other positive operational qualities.

These propellants at elevated (*increased)* temperatures begin to decompose; decomposition products are gaseous which allows their use as a working fluid to drive a turbine. Decomposition takes place within a special chamber into which fuel is supplied by a pump or by the expulsion gas pressure system.

To initialize isopropyl nitrate decomposition in the initial period an air is supplied into the chamber and the resulting mixture is ignited by an electric spark. As the temperature increases the spontaneous decomposition begins.

Electrical system controls supply of fuel and air, ignition and shutdown.

5.1.4 Starting systems with compressed air supply directly onto the turbine blades

Starting with the compressed air impingement on the engine turbine rotor blades is used in small GTE, auxiliary power units and lifting GTE.

The working fluid (compressed gas or air) is supplied through a check valve onto the rotor blades of a centrifugal compressor or the turbine rotor blades (for GTEs with axial compressor) (Figure 5.4).

To startup lift engines of STOL airplanes, the compressed air is taken from the compressor of running thrust engine.

The main advantage of impingement starting system is essential reduction in weight, size and cost of the engine due to the exclusion of complex and heavy equipment.

The main disadvantage is the reduction of turbine's efficiency.

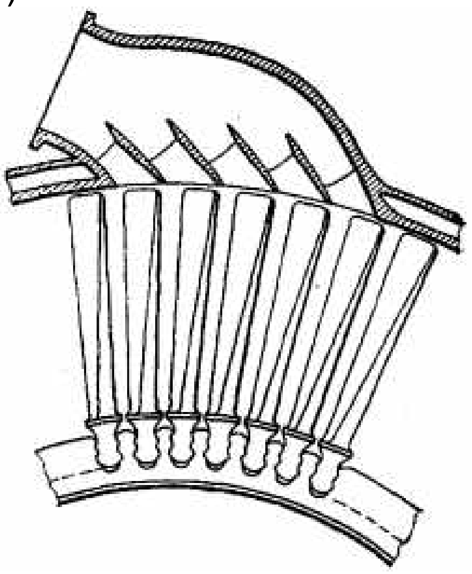


Figure 5.4 - Starting system with compressed air supply directly onto the turbine blades

5.1.5 Gas turbine starting systems

In GTE gas turbine starting systems, the starting device is the gas turbine starter.

The gas turbine starter (GTS) is a compact GTE with limited operating period (90...120 s) at starting mode and a capacity of 50...200 kW. Free turbine of GTS is connected through a reduction gear and automatic clutch to the engine's rotor.

This GTS is completely autonomous. It has its own fuel, lubrication and starting (electric or hydraulic) systems. Autonomy and ability to provide high startup power caused widespread use of gas turbine starting systems.

5.1.6 Hydraulic starting systems

The starting device of the hydraulic starting system is a hydraulic motor.

Presence of high pressure hydraulic systems on aircraft provides favorable conditions for use of hydraulic starting systems. The power of known hydraulic starters reaches 140 kW.

In most cases one of the engine mounted hydraulic pumps is utilized and is known as a pump/starter although other applications may use a separate hydraulic motor. Herewith the hydraulic displacement machines property of reversibility is used. Typical scheme of torque transmitting to the engine rotor includes gearbox and connecting clutch.

Transition of hydraulic starter to the normal pumping mode after the startup completion is provided by electrically operated hydraulic valves.

5.2 Ignition sources

As it known, an external source of energy is needed to ignite the fuel/air mixture.

All of GTE starting systems are equipped with duplicated igniting devices. Each device has an igniter which is connected with its own ignition module. Ignition modules are placed at a considerable angular distance one from another.

Ignition device needs considerable energy. It is powered by low voltage current circuit of starting system.

Electrical energy is stored in the unit until, at the predetermined value, the energy is dissipated as a high voltage, high amperage electrical discharge across the sparking plug.

Discharge energy can vary. Powerful discharge (about 12 J) is required to restart the engine at high altitudes and sometimes during ground startup. Discharge of low power (3...6 J) is used in continuous operation at special atmospheric conditions: icing or taking-off in a strong downpour or snowfall. Such a discharge automatically ensures relight. Ignition device electrical power may be provided by AC or DC. Both systems contain a capacitor for energy storing.

There are two types of sparking plugs:

- the constricted or constrained (air gap) type;
- the shunted surface discharge type.

High-voltage spark (Figure 5.5) is similar to the sparks used in reciprocating internal combustion engines but has a large air gap between the electrode and the body for the formation of sparks. Potential difference required to ionize the air in the gap and spark formation, up to 25,000 V so it requires a powerful electrical insulation.

Surface discharge spark (Figure 5.6) has a central and lateral (hollow cylindrical) electrodes. Annulus in between them is filled with ceramic insulator. Current is applied to the central electrode and the lateral electrode is connected to ground. End surface of the insulator is a semiconductor. The end surfaces of electrodes can be sprayed with layer of tungsten.

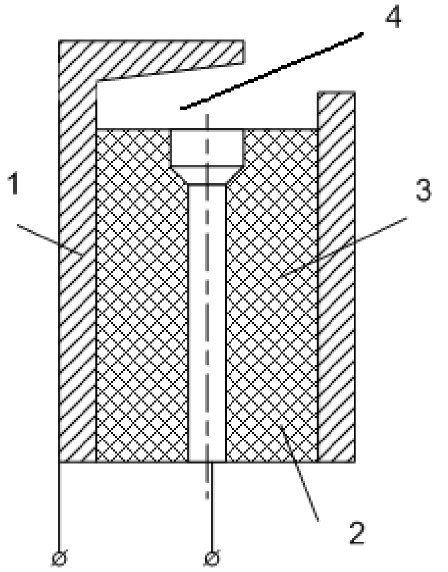


Figure 5.5 - High-voltage constrained plug:
1 – steel body; 2 – iron-nickel electrode;
3 – ceramic insulator;
4 – air gap

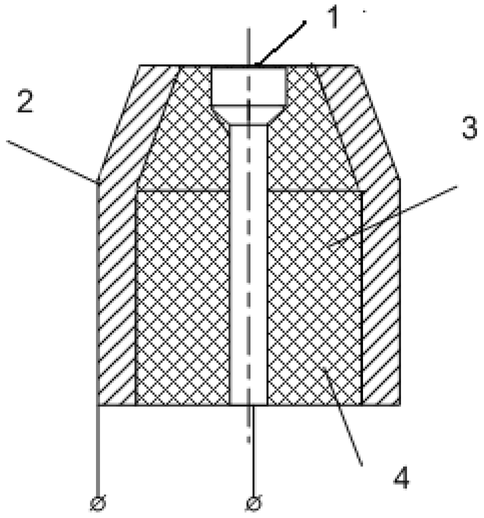


Figure 5.6 - Surface discharge plug:
1 – inner electrode; 2 – lateral electrode;
3 – semi-conductor (silicon carbide);
4 – ceramic insulator

When electrical voltage is applied to the central electrode, the airspace around it's end is ionized and semi-conductor surface is a source of power and sustained electric spark across all of the end surface with a relatively small voltage (1200...1500 V).

The list of self-check questions

1. What is the difference between ground and in-flight startup?
2. What is the reason of preliminary rotor acceleration at startup?
3. Explain character in which moments are varied during engine startup.
4. Which kind of rotor is preferable to be accelerated in multi-shaft engine startup and why?
5. Name the types of starting systems.
6. Name the advantages of air starting system.
7. What kind of starting systems has the least mass?
8. How is the combustion chamber ignited? Why the external source of energy is required?
9. Draw the constructive scheme of high-voltage constrained sparking plug. How much voltage it needs?
10. Draw the constructive scheme of a surface discharge sparking plug. What are its advantages comparing with the high-voltage constrained sparking plug?

6 TURBINE ENGINE PROTECTION SYSTEMS

6.1 Anti-icing system

Icing of the engine and the elements located in the air suction system may occur when flying in clouds containing super cooled water droplets or when working on the ground in frosty mist. Protection against ice formation is needed because the icing can significantly reduce the air flow in the engine resulting in reduced thrust (power).

In addition the ice can damage the acoustic cover of the air suction system and pieces of ice when separated from the walls fall in the flow and damage the compressor blades.

Therefore engines are equipped with anti-icing system which must reliably prevent ice formation throughout the entire range of operating conditions. This system must also have a low weight, high performance and must not have a significant effect on engine performance. Figure 6.1 summarizes the zone of turbofan that is normally protected against the formation of ice.

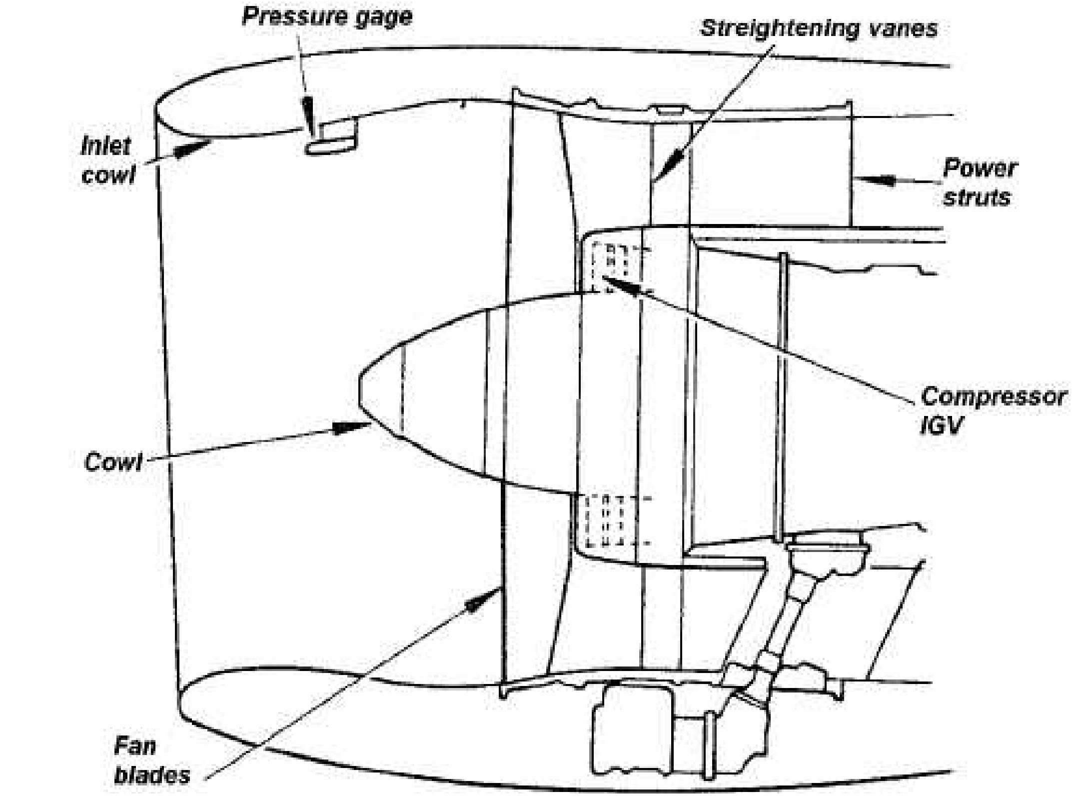


Figure 6.1 - Engine zones where it is necessary to provide protection against of ice formation

Freeze-up protection is provided by heating of the corresponding parts. Three methods of heating are used in engines: hot air; electric current and oil.

The air heating system is most widely used. Some TPE and TShE use electrical systems, and in low power GTE heating of the air suction system may be made with oil.

6.1.1 Hot air system

Air system provides heating of engine parts preventing formation of ice. Protection of rotor blades of the fan or compressor usually is not required because the resulting ice is removed from them by the centrifugal forces. Rotating spinner of propeller (fan) can also be not heated, if its form, design and speed provide the dropping ice (examples are engines D-18, AI-222).

Hot air for anti-icing system is generally taken from the high pressure compressor. Shut-device and the valve regulating the flow are installed in line supplying air to the heated part. Also dispenser is mounted wherein the air flows bleed from different sections of the compressor are mixed. Thus the temperature of air supplied to the heater is regulated.

After passing through the channels in heated parts this air returns back into the flow at the compressor inlet.

Bleed valves are opened and closed by commands of the automatic engine control. The icing sensor mounted in the air suction system or on aircraft can serve as the source of information about the necessity of opening (closing) of the valve. In the absence of such sensor commands are generated by the outdoor temperature (e.g., at the temperatures ranging from - 8 ° C to +5 ° C, the valve is open).

Switch gear mixes hot bleed air from the compressor with cooler air that is taken from one of the intermediate stages of the compressor. It maintains the constant temperature of the air supplied to the heating thus saving hot air flow and corresponding fuel consumption.

As an example Figure 6.2 shows a diagram of the anti-icing system of the AI-25 engine. The hot bleed air from high pressure compressor is used for heating the inlet guide vanes (IGV) of fan and cowling and also for heating the stagnation pressure gage. The air consumption for IGV heating is set by thermostat.

The stagnation pressure gage is heated continuously. The blades and LPC IGV cowl heating switches on only in icing conditions by opening the valve using electric mechanism.

The hot air flows from the annular cavity above the cone of the combustion chamber through the rack and gets into the pipeline. Part of the air from the pipeline through a tube of small diameter is used for the heating of stagnation pressure gage. The rest air flows through the heating valve with damper and thermostat into the annular cavity formed by the outer ring and the housing of inlet guide vanes. This air supply provides more uniform distribution of heat between the vanes. The air from the annular cavity enters vanes, passes through channels between deflector and edges of blades and enters the cavity within cowling. From here through the central hole in the deflector of cowling the air passes into slit channel between cowling and deflector, heats cowling and flows out into the gas path through the slots.

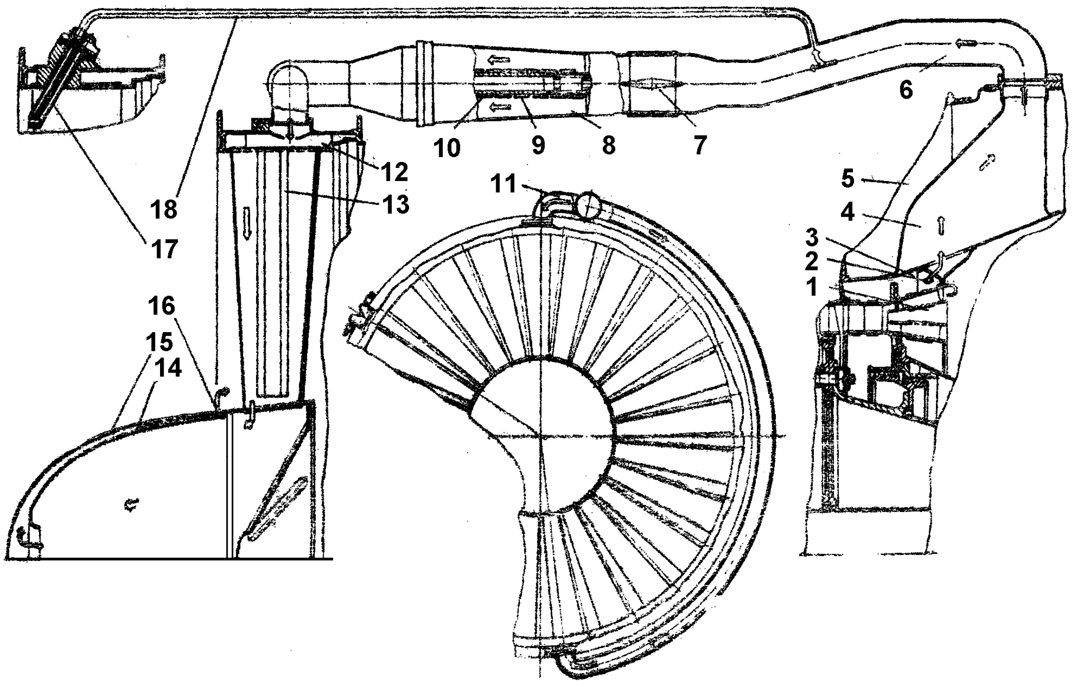


Figure 6.2 - Scheme of the engine AI-25 anti-icing system :
1 - diffuser; 2 - air passage hole; 3 - annular cavity; 4 front housing of the combustion chamber; 5 - secondary duct; 6 - pipeline; 7 - throttle; 8 – IGV heating thermostat; 9 - bimetallic spring; 10 - movable element of throttle; 11 - manifold; 12 – cavity of IGV outer ring; 13 - baffle; 14 - deflector of spinner; 15 - spinner; 16 - air vents to the gas path; 17 - stagnation pressure gage; 18 - air supply pipe for heating the stagnation pressure gage

Heating thermostat has a bimetal plate that covers the orifice and reduces supply of hot air when temperature in the pipeline increases (e.g., due to higher engine operating mode). Thus the relative flow of hot air decreases when operating mode or ambient air temperature increases. This reduces fuel consumption at these operating conditions.

6.1.2 Electric system

Electric anti-icing system is used for heating propeller blades in turboprops. In any type of turbine engine this system can also be used to heat the leading edge of the air intake, spinner and the input of the air duct of oil cooler.

Plates with electrically heated elements (Figure 6.3) are attached to the outer surface of the cowlings. They consist of conductive strips stacked between the layers of neoprene or glass coating and impregnated with epoxy adhesive. To protect against erosive impact of raindrops plates are covered with a special paint based on polyurethane. When anti-icing system operates, some areas are heated continuously to prevent the formation of ice. Other areas are heated by intermittent supply of electric current to provide delamination and destruction of the resulting thin layer of ice.

The electric current is formed with generator. To reduce the required power and weight of generator, voltage pulses are fed to the heating elements (blades, input device, spinner, etc.) sequentially.

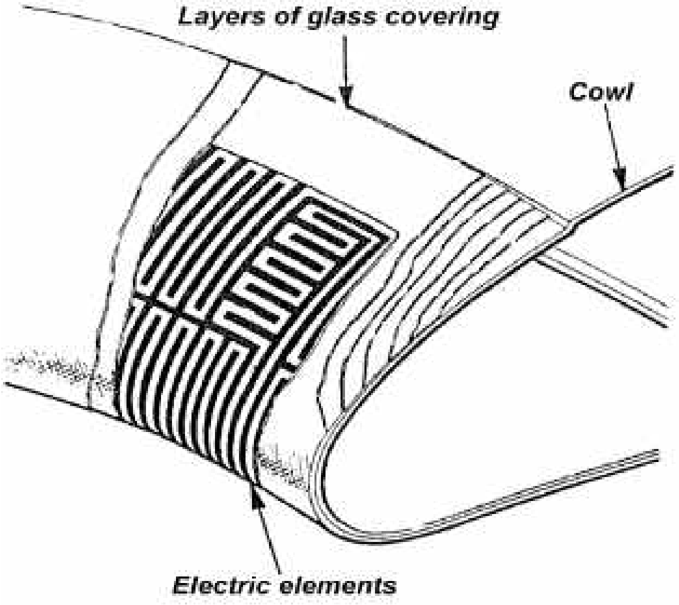


Figure 6.3 - Electrically heated elements

Test questions on ice-protection system

1 At which flight conditions there is a risk of engine icing?
2 What elements of the engine must be protected from icing?
3 What types of anti-icing systems do you know? Name their advantages and disadvantages.
4 What is the purpose of the thermostat in anti-icing system?
5 How to protect propeller blades against icing?

6.2 Fire suppression system

All gas turbine engines and auxiliary power units are designed to reduce the risk of fire. However this does not diminish the relevance of the rapid detection and elimination of fire and prevent its spreading if it occurs. In most cases ignition occurs if there are double failures. Detection and elimination of fire must have high reliability and low weight.

6.2.1 Prevention of fire

Pipelines with flammable liquids usually are isolated from the "hot" part of the engine. Components and pipelines of fuel and oil systems are located on the compressor housing at the "cold" zone and are separated by the firewall from the "hot" zone, which contains the combustor, turbine and exhaust system. Engine under cowling space is ventilated by an air system to prevent the accumulation of inflammable vapors.

All pipelines are designed in accordance with the requirements of fire safety, and electrical equipment and connections - in accordance with the requirements of explosion protection. Sparking due to static electricity is prevented by connecting of all units of the aircraft and engine by electrical conducting elements.

Pipelines with flammable liquids located in the "hot" area in some engines are double-walled. Therefore the liquid accumulates inside the pipe and do not flow outwardly at the destruction of the inner wall (core).

The power plant cowling is equipped with a drainage system for the removal of flammable liquids outside of the nacelle, compartment or reservoir, and all leaks through the units seals are drained overboard in the place from which they cannot go back into the fluid manifold and cause a fire.

When flying at high Mach numbers danger of spontaneous combustion can be minimized by creating a protective layer around the engine of the bleed air from the air intake. However in the case of ignition it is necessary to block air flow as it will enhance the combustion rate and reduce the efficiency of fire suppression system.

6.2.2 External cooling and venting

Engine compartment is typically cooled and vented by the atmospheric air that flows around the engine and is exhausted overboard (Figure 6.4).

Convective cooling during on-ground operation can be provided by using the effect of ejecting a cooling air flow of gas coming out of the engine. An important function of the ventilation air is the removal of flammable vapors from the engine compartment. Herewith this air flow must be the minimum necessary to reduce the drag force of the power plant.

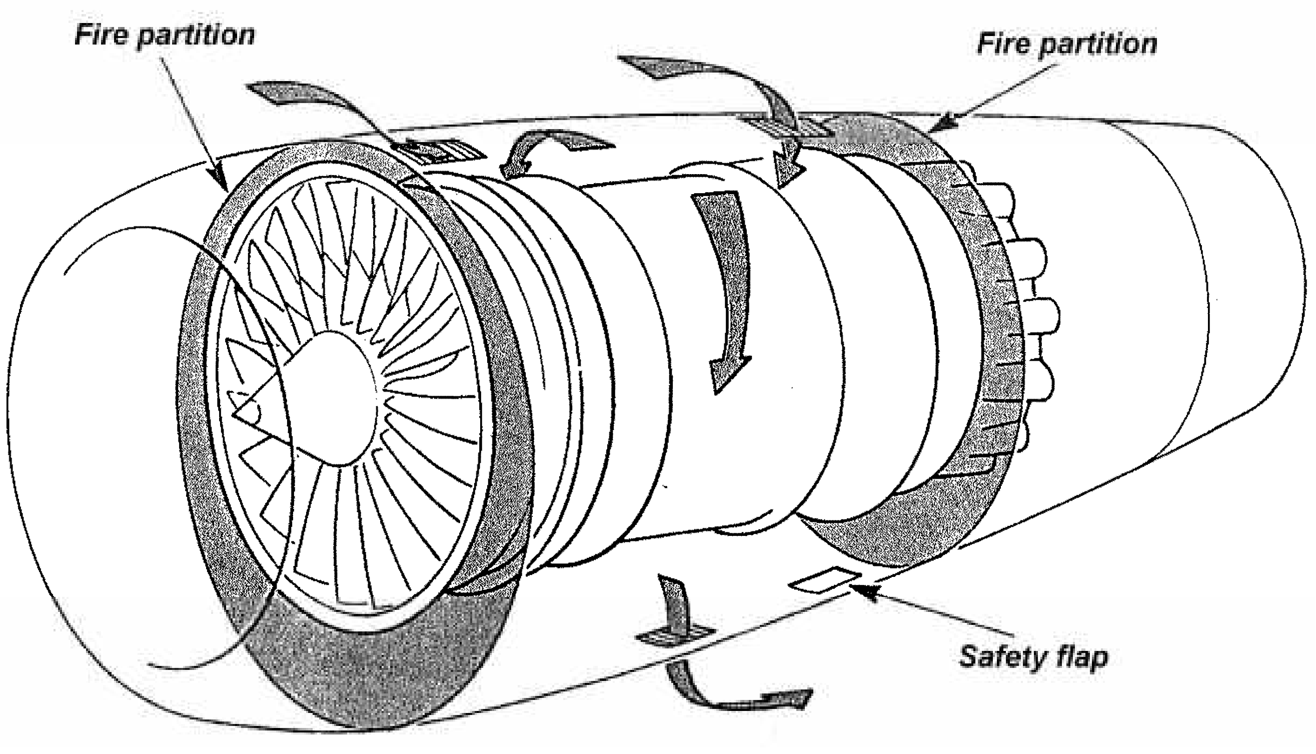


Figure 6.4 - Typical engine compartment cooling and venting system

In some cases for separation of the "cold" and "hot" zones the fire partitions between them are set. Herewith in the "cold" zone fuel and oil systems accessories units are mounted and this zone is pressurized to prevent ingress of flame from the "hot" area in the case of fire.

Figure 6.5 shows a more complex turbofan system of cooling and venting. Air is bled from the air intake system as well as from the fan downstream and fed to the several cooling zones. Each zone has a calibrated flow rate of the cooling air.

6.2.3 Fire detection

In order to successfully switch off the engine and effective firefighting it is necessary to ensure early detection of fire. At the same time it is important that the system does not give false signals about the fire.

The system will consist of a number of sensors the location of which is pre-justified or has one extended sensor (gas-filled or electric) of a given shape attached to the pipeline. The sensing element can be pulled through the vent zone outlet to provide early detection of fire.

In an electrical detecting system the presence of fire is determined to change the characteristics of the circuit. These characteristics depend on a type of the sensor, which may be a thermistor, thermocouple or resistive temperature detector (RTD). In these cases the generated temperature change signal is transmitted via an amplifier to the indicator.

Thermocouple generates electromotive force (EMF) when junction is heated and signals about a change in temperature at the point where the junction is located.

A thermistor is made of semiconductor material which resistance increases with temperature. It may be fabricated as an extended sensor and in this case detects the temperature change in a particular zone.

Another type of extended sensor element is a capacitor which consists of a tube filled with dielectric material and an internal conductor. Potential difference is applied to the tube and to the conductor. With temperature increasing, the capacitance changes and the corresponding signal is generated.

Gas-filled detector has the form of stainless steel tubing which is filled with an absorbing gas material. With increasing temperature, an abrupt evolution of gas occurs; the pressure rises inside the closed tube and is fixed by the sensor.

At high flight speeds characteristic temperature level is very high which makes unsuitable conventional thermocouples and thermistors. Therefore the elements that are sensitive not only to the level but also to the temperature gradient may be more efficient.

Alternative to the above sensors are radiation flame detectors perceiving its light emission. They can be made so that they are sensitive only to ultraviolet and infrared radiation generated by combustion of kerosene.

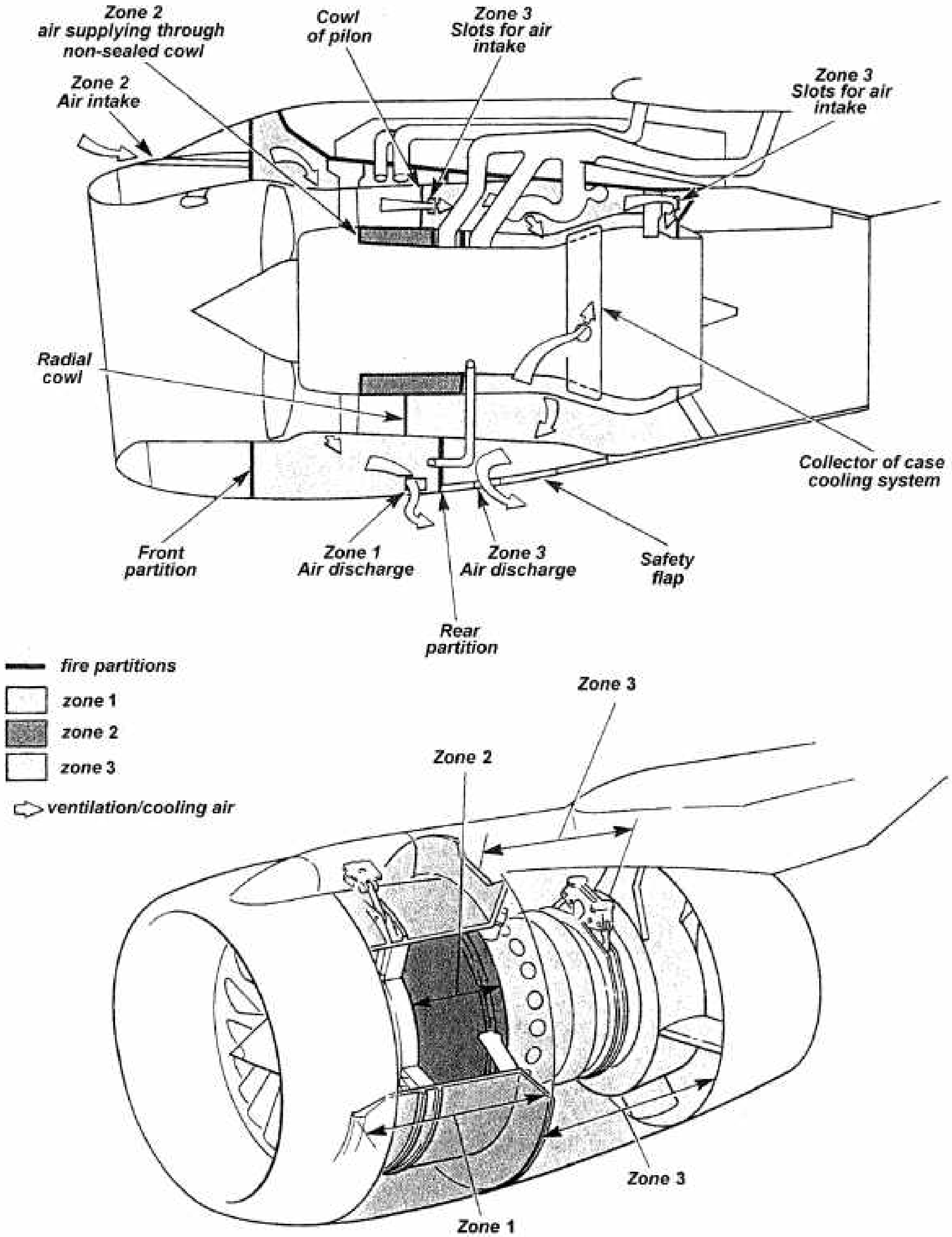


Figure 6.5 - TFE compartment cooling and venting system

6.2.4 Localization of fire

Engine fire must be located within the power plant and must not spread to other parts of the aircraft. Cowlings of the engine compartment or nacelle are usually made of aluminum alloys, so they are not able to limit the spread of flame, when the aircraft is not moving. In flight, the airflow cools the housing, improving its fire resistance. Firewalls and uncooled casings, as well as structural elements in the area of the channels which can be a "flame stabilizers" are made of steel or titanium alloys.

6.2.5 Fire extinguishing

Before the extinguishing of the fire, it is needed to stop the engine to reduce the delivery of combustible fluids and combustion air to the inflammation zone. All valves (e.g., low pressure fuel valve) regulating the flow of flammable liquids will be located outside the "hot" areas to prevent damage if ignited.

After the fire elimination the engine must not be started, as this may lead to re-ignition. Fire extinguishing will be impossible, as the fire extinguishing system is already inoperable.

Freon mixtures are used as the fire-extinguishing liquid. They are contained in the high-pressure cylinders placed outside the fire zone. When you manually turn the system on the fire-extinguishing composition follows from the tanks through the rows of perforated tubes or spray nozzles in the fire zone (Figure 6.6).

The flow must be sufficient to provide the desired concentration of extinguishing composition for the time of 0.5 ... 2 seconds. Usually the system is a single one, but it uses two independent capacities to enforce two attempts firefighting.

6.2.6 Identification of engine overheating

Overheating of turbines does not pose a serious fire hazard. However, information about overheating is necessary to stop the engine and prevent mechanical damage.

Overheating detection system may be similar to a fire detection system, or based on the use of thermocouples that measure the temperature of the turbine cooling air. Temperature alarms installed in the engine compartment blower ducts of the engine may also be used as additional indicators.

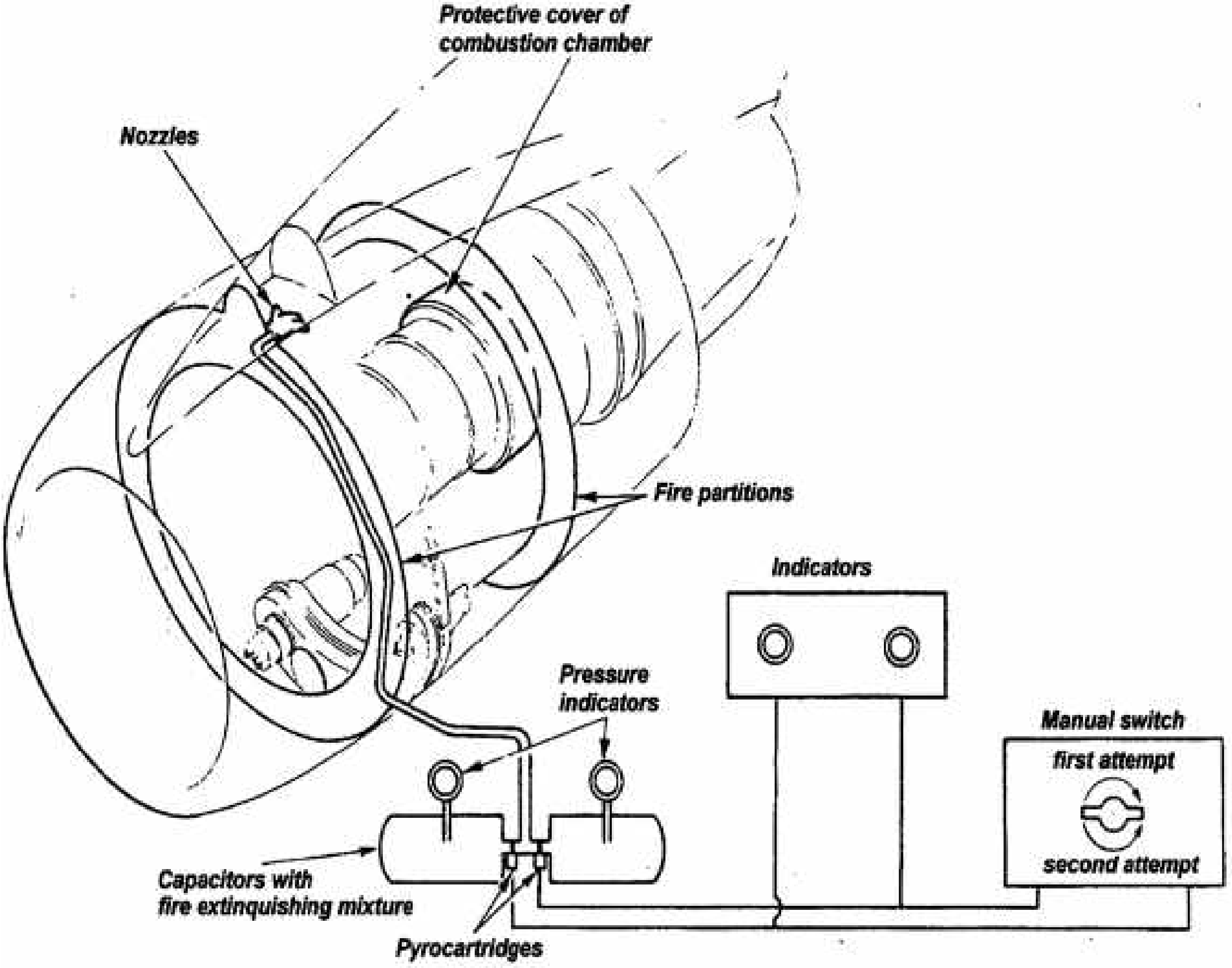


Figure 6.6 - Fire suppression system diagram

The list of self-check questions

1. Which design measures reduce the probability of engine fire?
2. Why is the engine compartment vented?
3. What is the purpose of fire partitions? Where are they placed?
4. How to detect the engine firing?
5. How to find the engine overheating?
6. How is the engine firefighting organized?

7 ACCESSORY GEARBOXES

Auxiliary drives provide mechanical power transmission to hydraulic, pneumatic and electrical components. Given the significant role of these elements in ensuring the engine efficiency the reliability of the drives has high demands.

Auxiliary elements drive is usually done by the engine rotor via a central drive to drives box that provides mechanical energy distribution between these elements. These transfers must be connected with the starter when you start up the rotor.

Total power drawn from the engine rotor is up to 400 kW.

7.1 Central drive

Location of the central drive in the engine housing is due to the complexity of ensuring the radial position of the shaft that outputs mechanical power out with the limited space inside the case.

This shaft crosses the gas pass. Therefore it must be located within the racks streamlined by flow. Placement of such racks close to the turbine is more difficult than to the compressor: firstly, in the area of the turbine temperature is high, which greatly reduces the strength of all drive elements and increases the need for oil to its cooling; secondly, in the multistage axial compressor there is more space for positioning the drive than in a single or two-stage turbine.

In a centrifugal compressor there is less space for the drive so the central drive can be located in a non-rotating inner cowl and for the turboprop engine - behind the propeller gear. Variants of drives are shown in Figure 7.1.

In the multi-shaft engines selection of the rotor from which power is taken is determined primarily by the terms of a starting aid. When engine starts up the rotor accelerates and necessary for that torque is transmitted from the starter via an external drive. Typically high pressure rotor accelerates first; therefore it is connected with the central drive by transmission.

Because the output shaft is located radially power take off from the engine rotor is realized through bevel gear. Axial displacement of the rotor may lead to a shift of bevel gears and gearing disruption or to additional axial force which reduces the strength of transmission elements. To reduce the axial displacement of the bevel gears one of the three design concepts shown in Figure 7.2 is used.

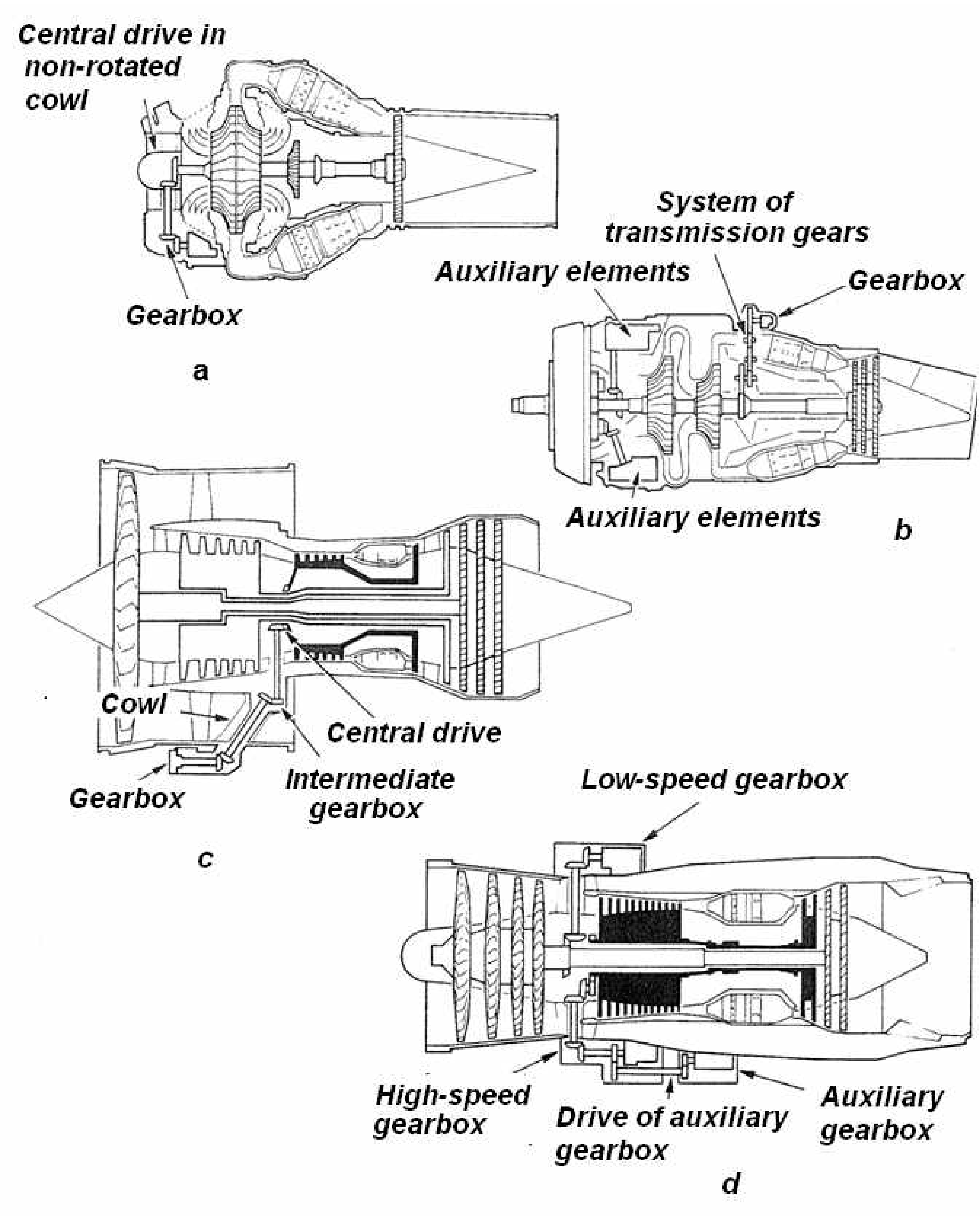


Figure 7.1 - Accessories drives:
a - placing the drive in a fixed central front cowl; b - direct units drive and gear to an external drive; c - single-drive through an intermediate gearbox;
d - drive with double-flow intermediate drives gearbox

If the drive bevel gear is located on the compressor rotor in the immediate vicinity of the thrust bearing in the structure of the central drive (Figure 7.2, a), a minimum number of parts is used. In other cases the leading bevel gear is located on the shaft having a thrust bearing. The pivot pin is connected to the compressor shaft by splines that provide freedom of movement without axial displacement of the conical gearing (Figure 7.2, b). Sometimes they also apply a more sophisticated design with the intermediate shaft (Figure 7.2, c) in which the free axial displacement occurs along the spur gearing teeth of the drive shaft to the intermediate shaft.

To reduce the load on the elements two self-drives (from the rotors of high and low pressure) are used in some engines (Figure 7.2, d). In this case placement of units on the engine housing also facilitates. Because speeds of the rotors of high and low pressure are different, in this case units are combined in a high-speed and low speed group.

Radial drive shaft is used for power transmitting from the central drive to the accessories box or drive gearbox. It is also used to transmit torque from the starter to the rotor during startup. Transmission may be direct (see Figure 7.1, a, b, d) or be with intermediate drive (see Figure 7.1, c).

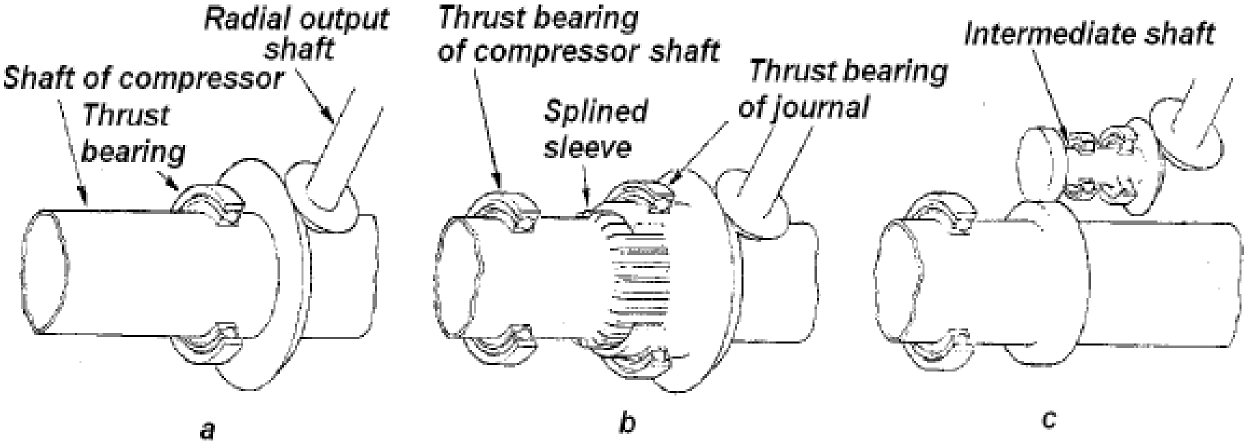


Figure 7.2 - Schemes of central drive:
a - direct drive; b - with a pin; c - countershaft

To reduce influence of the radial shaft to the hydraulic losses in the gas pass it is normally located inside the power rack connecting the outer casing of the compressor housing with internal supports. In the turbofan engine drive shaft is located in guide vanes of the fan or in hollow streamlined racks. To reduce losses the driving shaft must have the smallest possible diameter. Therefore for a given power speed of rotation must be as much as possible. However, increasing the rotational speed increases the centrifugal forces and vibrations. Increasing the ratio of the shaft length to diameter ratio leads to a reduction in its stiffness. Therefore, to ensure satisfactory frequency characteristics the additional radial bearing can be required. Thus speed and diameter of the drive shaft are chosen as a compromise solution that satisfies the requirements of minimizing the diameter at the constraints on the strength and stiffness of the transmission.

Direct transmission, the use of which is characteristic of the first generations of engines includes radial shafts, which are used to drive one or a pair of units. This arrangement alleviates the problem of accessories and decreases the load on each of the drive members but requires increasing the size of the central drive. Furthermore increasing the number of radial shafts hampers their layout and increases complexity of manufacture and repair.

In some cases the direct transmission can be used in conjunction with external drive. For example, in Figure 7.1, b a diagram of TFE is shown in which the engine units are driven by an external transmission from the compressor rotor, and propeller accessories - from the propeller gearbox.

If space allows, you can use gearing (spur gear set) behind of the compressor (see Figure 7.1, b). However, in modern designs it is not applicable due to the increased weight and a lot of parts.

7.2 Intermediate drive

Intermediate drives are used in the case where it is not possible to provide direct connection to the drive shaft with an external drive. An example is shown in Figure 7.1, c.

7.3 Accessory gearbox

Accessory gearbox is designed for the distribution of power between the units as well as for attaching them. It has elements for connecting the starter, as well as to provide manual scroll of engine rotor for maintenance. Figure 7.3 shows an example of unit placement in the drive box.

Design of the box drive depends on many factors. To minimize the drag it must be as less as possible increase of the frontal area of the propulsion system. Therefore it is usually "wrapped" around the motor housing and has the shape of a banana. Location of the gearbox in the engine should provide quick access for maintenance, so the drive box is arranged at the bottom of the aircraft engines, and in the helicopter engines – at the top.

Gear shaft driven by starter divides drives box into two sections. The first section provides drive units that consume low power and the second serves high power units. It allows the grouping in the first section gears, transmitting small power and the second - the pinion transmitting more power and thus reduces the weight and dimensions of the gearbox.

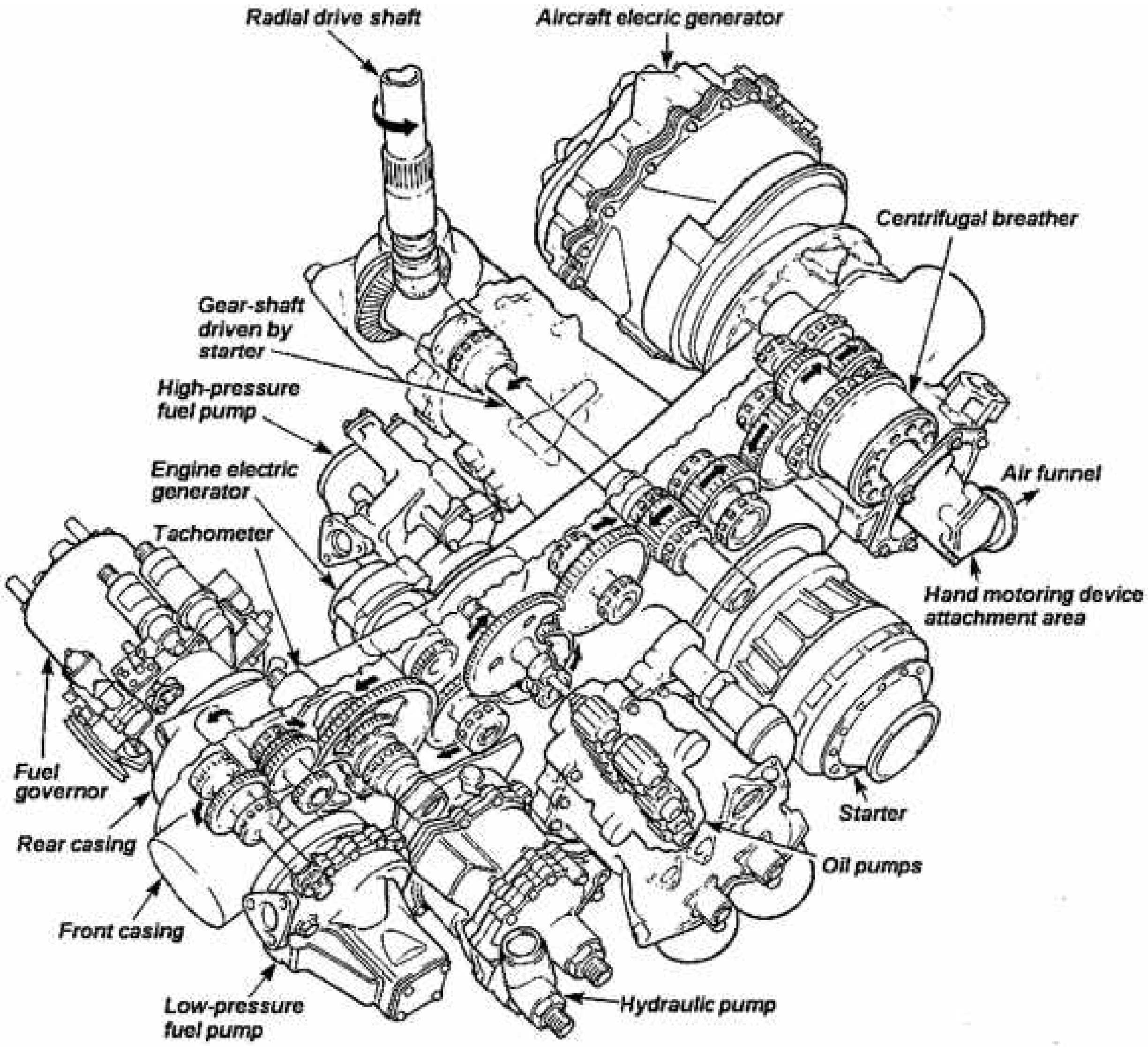


Figure 7.3 - Drive box with units

If there is failure of one of the units and it stops rotating, it can lead to shear a set of teeth in the gears. To prevent secondary faults in the design of the drive shaft "weak link" is provided. It is known as cut neck the cross section area of which is designed so that it has a minimum factor of safety and the first is destroyed in the event of overload. This link is used in the design of vital engine components such as oil pumps as their failure leads to an emergency shutdown of the engine.

Of all the gear drives the maximum torque is transmitted through the pinion shaft driven by starter, so this shaft is a basic element of gearbox design. Starter is tended to be arranged so that to reduce the length of the shaft, i.e. as close as possible to the engine body. This reduces the weight of the most loaded parts.

If the units are driven from two rotors of the engine (see Figure 7.1, d), two independent drive boxes are required. Usually they are placed on either side of the compressor and they are called high-speed and low-speed.

If the engine's case hasn’t enough space to accommodate all the drives in a single unit’s drives box, an auxiliary drive box is used. It is driven from the main box (see Figure 7.1, d).

Spur gears of the gearbox gear train are mounted between bearings supported by the front and rear casings which are bolted together (see Figure 7.3). They transmit the drive to each accessory unit which is normally 5000...6000 rpm for the accessory units and approximately 20,000 rpm for a centrifugal breather.

All gear meshes are designed with ‘hunting tooth’ ratios which ensure that each tooth of a gear does not engage between the same set of opposing teeth on each revolution. This spreads any wear evenly across all teeth.

Spiral bevel gears are used for connecting shafts whose axes are at an angle to one another but in the same plane. To improve the smoothness of rotation helical transmission is used but there are additional axial forces that influence the design of shafts supports.

Usually all the drives are lubricated and cooled by oil. To prevent it leakage shaft oil seals are required. The central drive has contactless labyrinth seals where the static casing mates with the rotating compressor shaft.

For some accessories mounted on the drives box the labyrinth seals charged by air are employed. This prevents oil from the gearbox entering the accessory unit and also prevents contamination of the gearbox and hence engine in the event of an accessory failure. Thus pressurized air inside the gearbox must be approximately 20 kPa (0.2 atm) above atmospheric pressure. To supplement a labyrinth seal oil slingers (oil thrower rings) may be used. This involves the leakage of oil running down the driving shaft and being flung outwards by a flange on the rotating shaft. The oil is then collected and returned to the gearbox.

The list of self-check questions

1 Which units need mechanical drive from the engine?
2 What determines the selection of engine rotor which drives the units?
3 What is the central drive?
4 Analyze the possible schemes of the central drive.
5 What is the drive box? How it relates to the central drive and units?
6. How is the gear ratio in accessory drive determined?
7. Why is the space inside gearbox pressurized? What is the value of excess pressure in gearbox?

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NOTES

NOTES

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(Англійською мовою)

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Зв. план, 2015
Підписано до друку 15. 06. 2015
Формат 60х84 1/16. Папір офс. № 2. Офс. друк
Ум. друк. арк. 5,6. Обл.-вид. арк. 6,25. Наклад 100 пр. Замовлення 210.
Ціна вільна

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Свідоцтво про внесення суб’єкта видавничої справи
до Державного реєстру видавців, виготовлювачів і розповсюджувачів
видавничої продукції сер. ДК № 391 від 30.03.2001