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д-р техн.наук, проф.

_______________Ю. М. Терещенко

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ДИПЛОМНА РОБОТА

(ПОЯСНЮВАЛЬНА ЗАПИСКА)

ЗДОБУВАЧА ОСВІТНЬОГО СТУПЕНЯ МАГІСТРА

ЗА ОСВІТНЬО-ПРОФЕСІЙНОЮ ПРОГРАМОЮ

«ТЕХНІЧНЕ ОБСЛУГОВУВАННЯ ТА РЕМОНТ ПОВІТРЯНИХ СУДЕН І АВІАДВИГУНІВ»

Тема: «Дослідження заходів підвищення паливної ефективності силових установок для середньомагістральних літаків»

Виконав: ____________________ Мокієнко Д.І.

Керівник: канд. техн. наук, проф. ____________________ Гвоздецький І.І.

Консультанти з окремих розділів пояснювальної записки:

Охорона праці: ____________________ Коновалова О.В.

канд. техн. наук, доц.

Охорона навколишнього середовища: ____________________ Радомська М.М.

канд. техн. наук, доц.

Нормоконтролер: ____________________

Київ 2020

MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE

NATIONAL AVIATION UNIVERSITY

AEROSPACE FACULTY

AEROENGINE DEPARTMENT

«**PERMISSION TO DEFEND**»

Head of Department

Doctor of Sciences(Engineering), prof.

_______________Y. M. Tereshchenko

« _____»__ ____________ 2020

MASTER DEGREE THESIS

(EXPLANATORY NOTE)

APPLICANT FOR ACADEMIC DEGREE OF MASTER

FOR EDUCATIONAL PROFESSIONAL PROGRAM

“MAINTENACE AND REPAIR OF AIRCRAFT AND AIRCRAFT ENGINES”

Topic: «Research of increasing fuel efficiency methods for power plants of middle-range aircrafts»

Performed by: ________ Mokiienko D.I.

Supervisor: Ph.D. (Engineering), prof. ________________Gvozdetskyi I.I.

Advisers:

Labor precaution:

Ph.D. (Engineering), assoc. prof ________ Konovalova O.V.

Environmental protection:

Ph.D. (Engineering), assoc. prof. ________ Radomska M.M.

Standards inspector: ______________

Kyiv 2020

NATIONAL AVIATION UNIVERSITY

Faculty: Aerospace faculty

Aircraft Continuing Airworthiness Department

Educational and Qualifications level: «Master Degree»
The specialty: 272 «Aviation transport»

Educational-professional Program: «Maintenance and Repair of Aircraft and Engines»

PERMISSION TO DEFEND

Head of the Department

Ph. D., assoc. Professor

__________ Y.M. Tereshchenko

«____ » ___________ 2020

GRADUATE STUDENT'S DEGREE WORK ASSIGNMENT

Denys Ihorovych Mokiienko

1. The Work topic: «**Research of increasing fuel efficiency methods for power plants of middle-range aircrafts»** approved by the Rector's order of October 08, 2020 № 1950/ст.
2. The work fulfillment terms: since October 5, 2020 until December 13, 2020 and since December 21, 2020 until December 31, 2020.
3. Initial data for the project: Turbofan engine analyzed at initial data (V=0; H=0; IST); The scientific research part: Methods for increase TFE fuel efficiency
4. The content of explanatory note (the list of problems to be considered): Introduction; Analytical part; Project part; Scientific research part; Ecology; Labour precaution; General conclusion on the work.
5. The list of mandatory graphic materials: TFE designed scheme, improved unit scheme and graphics for scientific part of graduation project.

6. Time and Work Schedule

#	Stages of Graduation Project Completion	Stage Completion Dates	Remarks
1	Analysis of modern state of turbofan engine fuel efficiency problem	05.10.20 – 12.10.20	
2	Patent search on the thesis	13.10.20 – 20.10.20	
3	Development of problem solution ways	21.10.20 – 26.10.20	
4	Thermodynamic calculation of the turbofan engine	27.10.20 – 04.11.20	
5	Gasdynamic calculation of the turbofan engine	05.11.20 – 14.11.20	
6	Development of the turbofan engine scheme	15.11.20 – 20.11.20	
7	Design of engine units	21.11.20 – 28.11.20	
8	Calculation of the turbine blade strength	29.12.20 – 03.12.20	
9	Analysis of fuel system	04.12.20 – 08.12.20	
10	Labour precaution	09.12.20 – 11.12.20	
11	Environmental protection	12.12.20 – 14.12.20	
12	Arrangement of explanatory note	15.12.20 – 16.12.20	

7. Advisers on individual sections of the work (Thesis):

Section	Adviser	Date, Signature	
		Assignment Delivered	Assignment Accepted
Environmental Protection	Radomska M. M.		
Labor precautions	Konovalova V. I.		

8. Assignment issue date "05" October 2020

Graduate Project Supervisor: ________________ Gvozdetskiy I.I.

(supervisor signature)

Assignment is accepted for performing:

Graduate student: ________________ Mokiienko D.I.

(graduate student's signature)

ABSTRACT

The explanatory note to the master's degree work: «Research of increasing fuel efficiency methods for power plants of middle-range aircrafts»:

136 pages., 11 pictures., 16 tables., 24 sources., 3 drawings

Object of research is bypass turbofan engine based on the PS-90A prototype and the fuel efficiency of the turbojet engine.

The purpose of degree work is taking into account the modern level of Ukraine's aircraft industry, design a turbofan engine with increased fuel efficiency.

Method of research is analysis of information from literary and patent search, selection of rational solutions, analytical calculations, development of a turbine rotor blade design with microcirculation cooling.

It is recommend to use the materials of the thesis in scientific research, in the educational process and in the practical activities of specialists from aviation design bureaus.

Predictive assumptions regarding the development of the research object — for a more accurate assessment of the calculated fuel efficiency from the use of microcirculation cooling, it is necessary to conduct an experimental check.

BYPASS TURBOFAN ENGINE, FUEL EFFICIENCY OF BTFE, TURBINE BLADE COOLING, MICROCIRCULATION COOLING, AIRCRAFT ENGINE EMISSION.

CONTENTS

List of abbreviations

BTFE — bypass turbofan engine

HPC — high pressure compressor

LPC — low pressure compressor

HPT — high pressure turbine

LPT — low pressure turbine

GTE — gasturbine engine

$n_{НД}$ — low pressure rotor rotation frequency

$n_{ВД}$ — high pressure rotor rotation frequency

$\eta_{Т}^{*}$ — turbine efficiency

CA — civil aviation

ATS — air turbostarter

m — bypass ratio

GPU — gas pumping unit

IGV — inlet guide vane

EHS – emission of harmful substances

TLC – take-off landing cycle

INTRODUCTION

Aviation technology is developing very rapidly all over the world. Improvement in the design of airplanes and helicopters, their engines and avionics, as well as technologies for their production provides not only wider opportunities to meet the needs of the population in air transportation, but also gives a significant acceleration of technical progress in general. This is explained by the fact that many new technological solutions used first in aviation. and engine building, after which we find application in other industries. Therefore, the aviation industry is like a driving force for many other industries. And in those countries where aircraft manufacturing is successfully developing, many other industries are improving more rapidly and more widely.

Today, the world has come to a difficult time, and improving fuel efficiency is almost the main task in civil aviation. The reserves of petroleum products on the planet are decreasing at a high rate, and in addition, about 60% of the entire operation of the aircraft is fuel. Among other things, the COVID-19 pandemic has completely reduced amount of air travel, and all airlines are suffering huge losses of money.

Therefore, there is a need to create a new aircraft and engine that can compete with Airbus and Boeing, but will be much more economical and cheaper to operate. Ukraine has experience in the creation of aircraft, therefore, in this thesis, a project of a unified turbofan engine for middle-range aircraft with a takeoff weight of 90-110 tons is being developed [4]. The development of unified engines that can be installed on 2-3, and sometimes even more, different types of aircraft is widely used in world practice. The use of unified engines reduces not only the cost and terms of engine development, but also reduces their production costs, operating costs, and the cost of training personnel for maintenance.

In the research part of the thesis, an analysis of possible ways to increase the fuel efficiency of a turbojet engine was carried out. The main way to increase fuel efficiency, as the experience of world engine-building companies shows, is to increase the parameters of the bypass turbofan engine (BTFE) working process, namely, an increase in the degree of pressure increase ($\pi^*_{\text{к}\Sigma}$), the temperature of the gases in front of the turbine ($T^*_{\text{г}}$), the degree of bypass (m) and the efficiency of engine elements [2].

However, an increase to a very high value (35-40) causes an increase in the number of compressor stages, a complication of the automatic management, etc. Significant growth requires the use of new materials and complicates the problem of providing large engine resources.

Therefore, in this thesis, the main attention is paid to one of the possible ways to increase fuel efficiency, which is to reduce air intake from the inner loop for cooling the rotor blades.

1. Selecting workflow parameters for the engine being designed

1.1. Flight performance analysis of designed aircraft

The assignment for the diploma work the class of the aircraft and its take-off weight. These data determine the requirements for the flight range of the projected aircraft, cruising speed, passenger capacity, for determine the basic operational and technical characteristics of the aircraft.

Each newly created aircraft in its main parameters must correspond to the current levels in the world aircraft industry and even take into account the future development of these parameters [1].

Therefore, the first stage in the design of a new aircraft is the data processing and primary processing of statistical data for prototype aircraft. In this thesis work, similar aircraft in takeoff weight and flight range were chosen as prototype aircraft and have proven themselves in operation in many countries: B737-800 (American Boeing), A320-200 (European Airbus), Tu-204 (Russian firm Tupolev), widely used in many countries, including Ukraine.

The processing of statistical data is necessary due to the fact, that the technical literature contains only the main characteristics of the aircraft and its scale schemes. These data are sufficient to obtain an estimate of practically all the data required when choosing design data for a new aircraft using the simplest calculations and using known dependencies.

Based on the analysis, it was concluded that for a given flight range and passenger capacity, the most successful aircraft today in terms of mass and flight performance is the Boeing-737-800. Based on the adopted prototype, the scheme of the projected aircraft. The projected aircraft will be make according to the classic design of a narrow-body aircraft with engines located under the wing on pylon.

Table 1.1 – Summarized data of the initial parameters for middle-range aircraft

№ P/P	Parameters	A320 200	B737 -800	TU-204	Project
1	2	3	4	5	6
1	Country	Eupore	USA	USSR	Ukraine
2	Number of seats	180	189	214	170
3	Number of cabin crew	2	2	2	2
4	Relative payload weight	0,26	0,26	0,23	0,25
5	Relative fuel mass at $M_{ком\ max}$	0,24	-	0,256	0,245
6	Flight range with max. payload L *макс* (км)	5550	5400	4100	4600
7	Cruising econ. speed on H *кр* V *кр* (км/ч)	840	826	850	850
8	Wing sweepback by 0,25 chord line (degrees)	25	25,02	28	29
9	Average relative Thickness (%)	-	12,9	13,1	13
10	Full area wing extension	9,39	9,18	10,46	9,5
11	Sweepback HS(degrees)	28	28,8	-	35
12	Sweepback VS(degrees)	35	44,5	-	38
13	Fuselage diameter(м)	3,95	3,76	3,80	3,9
14	Quantity of engines (TFE)	2	2	2	2
15	Thrust-to-weight ratio (H/kg)	5,00	4,70	-	4,8
16	Run length (km)	-	-	2,13	2,00
17	Landing speed (km/h)	-	-	240	231

1.2. The choice of the aircraft scheme and its brief description

The aircraft layout is determine by the relative position of the airframe parts, their number and shape. A well-chosen scheme improves the safety and regularity of flights and the economic efficiency of the aircraft.

The projected aircraft is equipped with two turbofan engines located on pylons under the wing and equipped with reversing devices.

The aircraft has a single-fin tail, made according to the classical scheme with a stabilizer controlled in flight.

The aircraft is equipped with a swept wing of a supercritical shape of a caisson type with a low position along the height of the fuselage, which has a kink and a geometric negative twist. The supercritical profile, high aspect ratio and a vertical wing-mounted tip improve the aerodynamic quality of the wing, which is especially important for medium-range aircraft [9].

The fuselage is single-deck. On the deck are placing cabin crew, passenger cabin, wardrobe, one front and two aft toilet.

Location of the wing at the bottom of the fuselage takes shock loads and simultaneously protects the passenger cabin during landing with undercarriage retracted.

The feathering is make according to the classical scheme. This results in a gain in weight and sufficient structural rigidity. The fin and stabilizer have a large sweep. This is done with the expectation that the wave crisis on the feathering occurs later than on the wing. At the same time, the shoulders of the horizontal and vertical empennages increase, which makes it possible to reduce their areas and get a gain in mass. A large narrowing of the horizontal tail allows to obtaine a large sweep while maintaining a small sweep of the elevator along the leading edge to increase their efficiency. The placement of the engines under the wing has the following advantages:

- the engine unloads the thin wing in flight from normal load;
- the tendency of the wing to flutter decreases;
- when flying in turbulence, the engines damp wing vibrations;
- the best approach to the maintenance of the power plant;
- the ability to isolate the power plant in case of fire.

On the projected aircraft, the landing gear is made according to a three-support scheme with a nose pillar. The advantages of this scheme:

- the possibility of nosing the aircraft is excluded;
- it is excluded that the aircraft does not take off when the aircraft lands.

1.3 Analysis of the main technical data of engines, similar to the projected

Table.1.2 - Technical data of engines by type and thrust which are similar to the designed

Name of engine	CFM56-5A	CFM56-7B	PS-90A	Project
County of manufactured	France-USA	France-USA	USSR	Ukraine
Bypass ratio	6	5.6	4,5	5,5
Total pressure rise	26,5	32,3	34	32,5
Fan pressure rise	1,51	1,56	1,65	1,625
Specific fuel consumption	0,032	0,0379	0,0386	0,0385
Gases temperature in front of turbine, K	1540	1569	1640	1600

Name of engine	CFM56- 5A	CFM56-7B	PS-90A	Project
County of manufactured	France-USA	France-USA	USSR	Ukraine
Ceiling , м	10700	10700	11000	11000
Number M flight	0,76	0,75	0,78	0,806
Thrust , H	23200	26810	35000	36000
Specific fuel consumption	0,592	0,650	0,595	0,511
Diameter , mm	1820	1549	1900	-
Length of engine, mm	2420	2507	4964	-

Continuation table.1.2

Proceeding from the condition of providing a given required thrust, minimum specific fuel consumption, overall dimensions and weight, as well as failure-free operation in all modes, we choose CFM56-5A, CFM56-7B, PS-90A engines as prototype engines[8].

1.4. Selection and justification of the parameters of the designed engine

Currently, in Ukraine, Airbus and Boeing occupy the majority of the market for international flights, including long-range and middle-range aircraft.

Therefore, the aviation industry of Ukraine is faced with the task of designing and ensuring the production of its own middle-range aircraft to ensure passenger transportation.

Statistical data for aircraft of this class, given in Table 1.1. These aircraft must be equipped with bypass turbojet engines. Foreign-made engines are usually very expensive. Therefore, it is clear that for installation on your own medium-range aircraft in Ukraine also need to create and mass-produce their own turbofan engines.

Considering the production volume of such engines in Ukraine, it seems reasonable to us to choose the Russian-made PS-90A engine, which has been produced in Russia for many years and is used on Tu-204 medium-range aircraft, as a prototype for the newly created engine. However, taking into account the accumulation of operating experience in its design, it is necessary to make a number of changes aimed at increasing the reliability and resource of the engine, as well as reducing its noise level.

The initial values of the parameters for the designed engine are selected in this way:

The temperature of the gases in front of the turbine is a very important parameter. An increase in gas temperature leads to an increase in specific thrust and a decrease in specific fuel consumption.

At the same time, an increase in the temperature of gases leads to the need to develop constructive measures to ensure the reliable operation of parts of the "hot" part of the engine. Operational experience shows that a significant number of defects are associated with the thermal load of the turbine and combustion chamber parts. Measures to ensure reliable operation at high temperatures are:

- effective cooling of parts of the "hot" part of the engine;
- the use of more heat-resistant materials;
- active control of radial clearances.

However, a sharp increase in the temperature of the gases in front of the turbine requires the use of new materials and technologies, which increases the cost of engines. Therefore, we choose Tg = 1600 k, which is 40 k less than that of the PS-90A prototype [6].

Increasing the degree of air pressure increase in the compressor is an effective means of increasing the gas turbine engine efficiency. To increase the efficiency of the thermodynamic cycle, a strict combination of the degree of bypass, the degree of increase in air pressure in the compressor and the temperature of the gases in front of the turbine is required.

We take into account that the designed engine has less thrust, therefore, the temperature in front of the turbine and the rate of increase in air pressure in the compressor can be slightly reduced. At the same time, in order to ensure a decrease in specific fuel consumption, we need to increase the bypass ratio [2]. However, a significant increase in the degree of bypass of the engine leads to an increase in the diameter of the fan, the loads acting on the rotor blades, and the number of stages of the fan turbine. All this leads to a significant increase in engine mass. Therefore, for the engine being designed, we take the by-pass degree, which slightly exceeds the bypass degree of the PS-90A prototype engine.

Thus, for the projected turbofan engine, we select the following values of the initial parameters of the operating cycle: the bypass ratio m = 5.5, the total degree of air pressure increase in the compressor $\pi_{k\Sigma} = 32{,}5$, the gas temperature in front of the turbine at the design mode $T_{\Gamma}^{*} = 1600$ k, the selected parameter values will be used in the thermodynamic calculation of the projected turbofan engine.

Conclusions on the analytical part

1. Statistical data on medium-range aircraft collected from literary sources made it possible to select the initial data for the mass calculation of the aircraft, which correspond to the current state of development of aircraft engineering in the world.

2. On the basis of the collected statistical data and taking into account the main task set during the design - to develop economical, reliable, not difficult to manufacture engines, the parameter values were chosen working process close to the parameters of the PS-90A engine, well-proven during operation on the middle-range Tu-204 aircraft.

2. ENGINE DESIGNING

2.1. Engine loads

During operation of the GTE, various loads act in its structural elements, applied in the form of forces and moments.

By the nature of occurrence of the load are divided into the following the conductive types:

- gas loads;
- mass (inertial) forces and moments;
- internal forces in the structural elements of the GTE, due to the limitation of temperature movements and causing thermal stresses;
- efforts caused during the mechanical of the action elements of the engine.

These forces include friction forces, contact forces in bearings, gearing, spline joints, contact forces in the joints of rotor blade shanks with disks, etc. These forces are secondary, since they result from actions of the above forces and moments.

According to the direction of the efforts BTFE divisible into the following types:

- axial forces acting along the axis of the engine (positive, directed forward along the flight of the aircraft, and negative, directed against the flight);

- circumferential forces acting along a tangent to a circle of a given radius in the direction of rotation (positive direction) or in the opposite direction (negative direction); from the center to the periphery, and for body parts the opposite effect is possible, for example, when the shell is compressed by excessive pressure);

- lateral loads perpendicular to the engine axis and not coinciding with radial, for example, the forces acting on the hull in the engine mounts to the aircraft.

In relation to engine design in general, efforts are divided into two types:

- internal (closed), which are balanced inside the engine structural elements, causing their deformation of a certain nature;

- external (free) forces and moments that are summed up in the elements of the engine structure and are transmitted through the load-bearing body to the suspension units.

The most important group of these forces is the thrust of the engine, which is a total axial force acting on the power package.

- slow-changing (low-frequency), which occur when starting, stopping the engine and its transitions from one mode to another. The frequencies of these loads are tenths or hundredths of a Hz. This type of non-stationary loads causes low-cycle fatigue damage in the parts of the turbojet engine (under low-cycle loads, the part can work until failure in the range of cycle numbers $10^4 ... 5 \cdot 10^4$);

- non-stationary high-frequency loads (with frequencies in the kilohertz range) are called dynamic. They arise as a result of the imbalance of the rotor and due to the unevenness of the parameters of the working fluid in the flow path of the turbojet engine.

Dynamic loads cause the appearance of multi-cycle fatigue damages in the materials of the turbojet engine parts (the range of the number of cycles to failure is $10^7 ... 10^8$). They are taken into account when calculating parts for high-cycle fatigue, and when working out the engine design, they are reduced to a minimum by using various measures, mainly of a structural and technological nature. The acting loads lead to the appearance of tensile (compression), bending and torsion deformations in the parts of the turbofan engine (which cause the occurrence of corresponding stresses), as well as shear and shear stresses.

2.2. Brief description of the engine

The engine under design is a turbojet two-circuit twin-shaft engine without mixing the air and gas flows of the external and internal circuits, which have separate jet nozzles and a thrust reversal device.

The engine structurally consists of fourteen modules:

- the main module;
- fan rotor module with attached steps;
- fan stator module;
- stator module of the connected steps;
- high pressure compressor rotor module;
- high pressure compressor stator module;
- combustion chamber module;
- high pressure turbine rotor module;
- high pressure turbine stator module;
- fan turbine rotor module;
- fan turbine stator module;
- nozzle module;
- unit drive box module;
- reversing device module.

All modules (except for the main one) can be replaced in operation with little labor costs.

The designed engine consists of the following main components [7]:

- a fan with two attached steps;

-thirteen-stage high pressure compressor;

- turbo-annular combustion chamber;
- two-stage high pressure turbine;
- four-stage fan turbine;
- non-adjustable nozzle;
- a dividing casing with a unit drive box;
- rear support assembly;
- a reversing device.

The engine is equipped with the following systems:

- lubricants;
- fuel supply;
- automatic control;
- launch;
- cooling;
- air sampling;
- anti-icing;
- fire prevention
- control over the operation of the power plant;
- control of the reversing device;
- active control of radial clearances.

To reduce the noise level, the engine housing, which forms its flow path, is equipped with sound-absorbing acoustic panels.

The power circuit and the engine mounts ensure its strength and rigidity in all operating conditions, as well as attachments on the aircraft, in the transport box and during rigging.

Table 2.1 - A list of the main parts of the engine being designed and the construction materials used

The main parts of the turbofan engine	Materials
Fan blade	ВТ-8
Fan stator	ОТ-4
Fan skin	ОТ-4
Fan shaft	40ХНМА
Main module hull	АЛ-15
Aggregate drive box	МЛ-15
Rotor blades of attached stages	ВТ-4-1
HPC hull	1Х17Н2С
HPC rotor blades (1-8st.), (9-13st.)	ВТ-4-1 ,Х17Н3
HPC disks (1-8st.), (9-13st.)	12Х2Н4А, Х17Н3
HPC shaft	40ХНМА
Combustion chamber hull	В3102
Flame tube	ЭИ-602
Turbine hull	ЭИ-686
Nozzle blades	ЖС6УВИ
HPT rotor blades	ЖС26К
Fan turbine rotor blades	ЭИ-598
Turbine discs	ЭИ-698
nozzle	В3102

2.3. Thermogasdynamic calculation of turbofan engine

2.3.1. Thermodynamic calculation of turbojet engine without mixing flows

Data : engine type - bypass turbofan engine

thrust P = 135,250 N

bypass ratio m = 5.5

air pressure increase in the compressor $\pi^*_{K\Sigma}$ = 32.5

air pressure increase in the fan $\pi^*_{ВЛ_{II}}$ = 1.625

gas temperature in front of the turbine $T^*_Г$ = 1600 K

design condition H = 0, V = 0 [1].

Determine : parameters of the stagnant flow in the characteristic sections of the engine specific parameters and efficiency of the engine; air flow through the engine.

a) determination of the parameters of the working fluid in front of the engine (section H-H)

According to the ISA tables, we find the pressure P_H = 101325 Pa for a given height,

temperature T_H = 288.15 K and determine the parameters of the inhibited flow P^*_H and T^*_H.

$$T^*_H = T_H + \frac{V^2}{2\frac{\kappa}{\kappa-1}R} = 288{,}15K;$$

$$P^*_H = P_H\left(\frac{T^*_H}{T_H}\right)^{\frac{\kappa}{\kappa-1}} = 101325\ (Pa);$$

b) determination of air parameters at the fan inlet (section V-V)

According to the energy equation

$$T^*_B = T^*_H = 288{,}15K.$$

The coefficient of restoration of the total pressure in the inlet device σ_{BX} is taken equal to 1 and we determine P^*_B :

$$P^*_B = P^*_H\ \sigma_{BX} = 101325 \cdot 1 = 101325 \text{ (Pa)};$$

c) determination of the parameters of the working fluid behind the fan in the external circuit (section Vl-Vl)

We select the fan efficiency $\eta^*_{ВЛ_{II}}$ 0.85 and find the work of air compression in the external circuit according to the equation

$$L_{ВЛ_{II}} = \frac{K}{K-1} RT^*_B \left(\pi^{*\,\frac{K-1}{K}}_{ВЛ_{II}} - 1 \right) \frac{1}{\eta^*_{ВЛ_{II}}};$$

$$L_{ВЛ_{II}} = \frac{1{,}4}{1{,}4-1} 287{,}3 \cdot 288{,}15 \left(1{,}625^{\frac{1{,}4-1}{1{,}4}} - 1 \right) \frac{1}{0{,}85} = 50777 \text{ (J/kg)};$$

determine the pressure $P^*_{ВЛ_{II}}$ and temperature $T^*_{ВЛ_{II}}$ behind the fan:

$$P^*_{ВЛ_{II}} = P^*_B\ \pi^*_{ВЛ_{II}} = 101325 \cdot 1{,}625 = 164653 Па;$$

$$T^*_{ВЛ_{II}} = T^*_B + \frac{L_{ВЛ_{II}}}{\frac{K}{K-1} R} = 288{,}15 + \frac{50777}{\frac{1{,}4}{1{,}4-1} 287{,}3} = 338{,}6K;$$

d) determination of air parameters at the outlet from the nozzle of the external circuit (cross-section S_p-S_p)

by the energy conservation equation we have :

$$T^*_{C_{II}} = T^*_{ВЛ_{II}} = 338.6K$$

Taking into account that in the designed turbojet engine with a large degree of double-circuit, the outer contour has a short length, we take the coefficient of restoration of the total pressure in the outer contour σ_{II} = 1. Then the pressure of the stagnant flow in front of the nozzle:

$$P^*_{\text{II}} = P^*_{ВЛ_{\text{II}}} \cdot \sigma_{\text{II}} = 164653 \cdot 1 = 164653(Па);$$

pressure drop:

$$\frac{P^*_{\text{II}}}{\text{P}_{\text{H}}} = \frac{164653}{101325} = 1{,}625.$$

Little bit less critical pressure drop

$$\pi_{C_{КР}} = \left(\frac{К+1}{К}\right)^{\frac{К}{К-1}} = 1{,}89;$$

Therefore, the velocity of air outflow from the nozzle of the outer contour is determined by the shape of full expansion, taking the velocity coefficient of the nozzle of the outer contour $\varphi_{C_{\text{II}}} = 0.985$

$$C_{C_{\text{II}}} = \varphi_{C_{\text{II}}} \sqrt{2\frac{К}{К-1} RT^*_{\text{C}_{\text{II}}}\left[1-\left(\frac{P_H}{P^*_{\text{II}}}\right)^{\frac{К-1}{К}}\right]};$$

$$C_{C_{\text{II}}} = 0{,}985\sqrt{2\frac{1{,}4}{1{,}4-1} 287{,}3 \cdot 338{,}6\left[1-\left(\frac{101325}{164653}\right)^{\frac{1{,}4-1}{1{,}4}}\right]} = 292{,}67(м/с);$$

$$P_C = P_H = 101325(Па);$$

$$T_C = T^*_{\text{II}} - \frac{К-1}{К}\frac{C^2_{c_{\text{II}}}}{2\text{R}} = 338.6 - \frac{1{,}4-1}{1{,}4}\frac{292{,}67^2}{2 \cdot 287{,}3} = 295{,}97К.$$

e) Determination of air parameters behind the compressor (section K-K)

The efficiency of the compressor is determined by an approximate form, setting the efficiency of the compressor stage $\eta^*_{CT} = 0{,}89$:

$$\eta^*_K = \frac{\pi^{*\frac{К-1}{К}}_{К\Sigma} - 1}{\pi^{*\frac{К-1}{К\cdot\eta^*_{CT}}}_{К\Sigma} - 1} = \frac{32{,}5^{\frac{1{,}4-1}{1{,}4}} - 1}{32{,}5^{\frac{1{,}4-1}{1{,}4\cdot 0{,}89}} - 1} = 0{,}829;$$

find the effective work of compression in compressors:

$$L_K = \frac{K}{K-1} RT_B^* \left[\pi_{K\Sigma}^{*\frac{K-1}{K}} - 1 \right] \frac{1}{\eta_K^*} = \frac{1,4}{1,4-1} 287,3 \cdot 288,15 \left[32,5^{\frac{1,4-1}{1,4}} - 1 \right] \frac{1}{0,829} = 596430 \frac{Дж}{кг};$$

Determine the temperature and pressure behind the compressor:

$$P_K^* = P_B^* \pi_{K\Sigma}^* = 101325 \cdot 32,5 = 3293062,5 (Па);$$

$$T_K^* = T_B^* + \frac{L_K}{\frac{K}{K-1} R} = 288,15 + \frac{596430}{3,5 \cdot 287,3} = 881,3 (K).$$

f) Determination of the parameters of the working fluid at the outlet of the combustion chamber (section G-G)

Taking the coefficient of recovery of the total pressure at the outlet from the combustion chamber $\sigma_{K.C.}$ = 0.97, possible to find the pressure in front of the turbine:

$$P_Г^* = P_K^* \cdot \sigma_{K.C.} = 3293062,5 \cdot 0,97 = 3194270 (Па);$$

the gas temperature in front of the turbine $T_Г^*$ is specified in the initial data:

$$T_Г^* = 1600 \text{ K};$$

calculate the average heat capacity of the gas in the combustion chamber:

$$C_{P\,CP} = 878 + 0,208 \left(T_Г^* + 0,48 T_K^* \right) = 878 + 0,208 (1600 + 0,48 \cdot 881,3) = 1298,8 \frac{Дж}{кг \cdot K};$$

taking the efficiency of combustion $\eta_Г^* = 0,985$ and the value of the calorific value of the fuel $H_U = 42,5 \cdot 10^6 \frac{Дж}{кг}$, find the relative fuel consumption:

$$g_T = \frac{C_{P_{CP}} \left(T_Г^* - T_K^* \right)}{\eta_Г \cdot H_U} = \frac{1298,8 (1600 - 881,3)}{0,985 \cdot 42,5 \cdot 10^6} = 0,0223;$$

calculate the average excess air ratio in the combustion chamber

$$\alpha = \frac{1}{g_T l_0} = \frac{1}{0,0223 \cdot 14,7} = 3,05;$$

$l_0 = 14.7$ kg. air / kg. fuel — amount of air, theoretically unwanted for complete combustion of 1 kg of fuel.

g) Determination of gas parameters behind the turbine (section T-T) Take the relative amount of air taken for cooling the turbine parts $g_{охл}$= 0.09, and the value of the mechanical efficiency, we determine the effective operation $\eta_M = 0{,}995$ of all stages of the turbine turbine engine:

$$L_T = \frac{mL_{ВЛ_{II}} + L_K}{(1+g_T)(1-g_{охл})\eta_M} = \frac{5{,}5 \cdot 50777 + 596430}{(1+0{,}0223)(1-0{,}09)0{,}995} = 946050{,}4 \frac{Дж}{кг};$$

taking the efficiency of the turbine $\eta_T^* = 0{,}92$, we calculate the temperature and pressure of the gas behind the turbine:

$$T_T^* = T_Г^* - \frac{K_Г - 1}{K_Г}\frac{L_T}{R_Г} = 1600 - \frac{1{,}333-1}{1{,}333} \cdot \frac{946050{,}4}{288} = 779{,}39(K);$$

$$P_T^* = P_Г^*\left[1 - \frac{T_Г^* - T_T^*}{T_Г^* \cdot \eta_T^*}\right]^{\frac{K_Г}{K_Г - 1}} = 3194270\left[1 - \frac{1600 - 779{,}39}{1600 \cdot 0{,}92}\right]^{\frac{1{,}333}{1{,}333-1}} = 122490{,}7(Па);$$

h) Determine the parameters of the working fluid in the outlet section of the nozzle of the internal contour (section C_1-C_1).

Determine the pressure drop in the jet nozzle of the internal circuit and compare it with the critical:

$$\pi_T = \frac{P_T^*}{P_H} = \frac{122490{,}7}{101325} = 1{,}21 < \pi_{C_{KP}} = 1{,}85;$$

Therefore, the expansion in the jet nozzle is complete $P_C = P_H$, and the velocity of gas outflow from the nozzle is calculated by the formula:

$$C_{C_1} = \varphi_{C_1}\sqrt{2\frac{K_Г}{K_Г - 1}R_Г T_T^*\left[1 - \left(\frac{P_H}{P_T^*}\right)^{\frac{K_Г - 1}{K_Г}}\right]};$$

$$C_{C_1} = 0{,}98\sqrt{2\frac{1{,}333}{1{,}333-1}288 \cdot 779{,}39\left[1 - \left(\frac{101325}{122490{,}7}\right)^{\frac{1{,}333-1}{1{,}333}}\right]} = 282{,}63 м/с.$$

Find the static temperature of the gas in the cross section C_1-C_1

$$T_C = T_T^* - \frac{K_\Gamma - 1}{K_\Gamma}\frac{C_{C_1}^2}{2\mathrm{R}_\Gamma} = 779{,}39 - \frac{1{,}333-1}{1{,}333}\cdot\frac{282{,}63^2}{2\cdot 288} = 744{,}7K\,.$$

i) Determination of the main specific parameters of the engine and air flow rate, we calculate the specific thrust of the internal circuit:

$$P_{УД_1} = C_{C_1}\left(1+g_T\right) = 282{,}63(1+0{,}0223) = 288{,}93\frac{H\cdot c}{кг};$$

calculate the specific thrust of the outer contour:

$$P_{УД\,\mathrm{II}} = C_{C\,\mathrm{II}} = 292{,}67\frac{H\cdot c}{кг};$$

calculate the specific thrust of the TFE:

$$P_{УД_\Sigma} = \frac{P_{УД_1} + mP_{УД\,\mathrm{II}}}{1+m} = \frac{288{,}93 + 5{,}5\cdot 292{,}67}{1+5{,}5} = 292{,}1\frac{H\cdot c}{кг};$$

calculate the specific fuel consumption:

$$C_{УД} = \frac{3600\cdot g_T\left(1-g_{охл}\right)}{P_{УД_\Sigma}\left(1+m\right)} = \frac{3600\cdot 0{,}0223(1-0{,}09)}{292{,}1(1+5{,}5)} = 0{,}0385\left(кг/H\cdot ч\right);$$

air consumption is found from the ratios:

$$G_B = \frac{P}{P_{УД_\Sigma}} = \frac{135250}{292{,}1} = 463(кг/c);$$

$$G_{B_1} = \frac{G_B}{1+m} = \frac{463}{1+5.5} = 71.23(кг/c);$$

$$G_{B_{\mathrm{II}}} = \frac{m}{m+1}G_B = \frac{5{,}5}{5{,}5+1}463 = 391{,}77(кг/c);$$

calculate the internal efficiency of the TFE:

$$\eta_e = \frac{P_{УД_1}^2 + mP_{УД\,\mathrm{II}}^2}{2g_T H_U\left(1-g_{охл}\right)} = \frac{288{,}93^2 + 5{,}5\cdot 292{,}67^2}{2\cdot 0{,}0223\cdot 42{,}5\cdot 10^6\left(1-0{,}09\right)} = 0{,}322;$$

2.3.2. Gas-dynamic calculation of GTE

Data: engine type — turbofan engine

thrust $P = 135250H$;

air flow $G_B = 463(кг/c)$;

bypass ratio m = 5.5

The parameters of the working fluid in the characteristic sections of the flow path are taken from the results of the thermodynamic calculation.

Determine:

-the diametrical dimensions of the main sections of the turbine engine flow path;

-the number of compressor and turbine stages;

-high and low pressure rotor speed;

-specified value of thrust and specific fuel consumption of the projected TFE;

-analyze the results obtained, compare the parameters of the designed engine with the parameters of the existing ones, indicate the possible field of application [6].

a) Determination of the dimensions of the section at the fan inlet:

taking into account the relatively high air consumption (463 kg / s), to reduce the diameter of the engine, apply:

axial air velocity $C_{1a} = 220(м/c)$

peripheral speed of fan blades in the peripheral section $U_{1K} = 490(м/c)$

relative diameter of the hub of the first fan stage $d_1 = 0{,}42$

the reduced velocity λ_{1a} and relative flux density $q(\lambda_{1a})$ are calculated by the formulas:

$$\lambda_{1a} = \frac{C_{1a}}{C_{кр}} = \frac{220}{18{,}3\sqrt{288{,}15}} = 0{,}708$$

$$q(\lambda_{1a}) = 1{,}5774\lambda_{1a}\left(1 - \frac{1}{6}\lambda_{1a}^2\right)^{2,5} = 1{,}5774 \cdot 0{,}708\left(1 - \frac{1}{6} \cdot 0{,}708^2\right)^{2,5} = 0{,}898\,;$$

find the cross-sectional area at the fan inlet:

$$F_B = \frac{G_B\sqrt{T_B^*}}{m_B \cdot P_B^* \cdot q(\lambda_{1a})} = \frac{463 \cdot \sqrt{288{,}15}}{0{,}040348 \cdot 101325 \cdot 0{,}898} = 2{,}14\left(M^2\right);$$

calculate the diameter of the impeller at the periphery:

$$D_{1K} = \sqrt{\frac{4F_B}{\pi\left(1 - d_1^2\right)}} = \sqrt{\frac{4 \cdot 2{,}14}{3{,}14\left(1 - 0{,}42^2\right)}} = 1{,}82(м);$$

then the diameter of the impeller sleeve:

$$D_{1_{BT}} = \sqrt{D_{1_K}^2 - \frac{4}{\pi}F_B} = \sqrt{1{,}82^2 - \frac{4}{3{,}14} \cdot 2{,}14} = 0{,}77(м);$$

find the diameter of the conditional section separating the flows of the I and II circuits:

$$D_1 = \sqrt{D_{1_K}^2 - \frac{4}{\pi}\frac{G_{B_{II}}}{\mathrm{G_B}}F_B} = \sqrt{1{,}82^2 - \frac{4}{3{,}14} \cdot \frac{391{,}77}{463} \cdot 2{,}14} = 1{,}00(м).$$

b) Determine the number of turbojet fan stages:

calculate the peripheral speed of the blades on the diameters and:

$$U_1 = U_{1K}\frac{D_1}{D_{1K}} = 490\frac{1{,}00}{1{,}82} = 269{,}23(м/с);$$

$$U_{BT} = \mathrm{U}_{1K}\frac{D_{1_{BT}}}{D_{1_R}} = 490 \cdot \frac{0{,}77}{1{,}82} = 207{,}3(м/с);$$

we take the density of the lattice at the impeller hub $\left(\frac{B}{t}\right)_{BT} = 2{,}2$,

then the density of the lattice on the diameter D_1:

$$\left(\frac{B}{t}\right)_1 \approx \left(\frac{B}{t}\right)_{BT}\frac{D_{1_{BT}}}{D_1} = 2{,}2\frac{0{,}77}{1} = 1{,}694\,;$$

Calculate the air twist

$$\Delta W_{U_1} = C_{1a}\frac{1{,}55}{1+1{,}5\left(\frac{t}{B}\right)_1} = 220\frac{1{,}55}{1+1{,}5\cdot\frac{1}{1{,}694}} = 180{,}86\left(м/с\right);$$

$$\Delta W_{U_{ВТ}} = C_{1a}\frac{1{,}55}{1+1{,}5\left(\frac{t}{B}\right)_{ВТ}} = 220\frac{1{,}55}{1+1{,}5\cdot\frac{1}{2{,}2}} = 202{,}75\left(м/с\right);$$

and the work imparted to the air by the fan blades, on the diameter D_1 and $D_{ВТ}$:

$$L_{U_1} = U_1\cdot\Delta W_{U_1} = 269{,}23\cdot 180{,}86 = 48692{,}94\left(\frac{Дж}{кг}\right);$$

$$L_{U_{ВТ}} = U_{ВТ}\cdot\Delta W_{U_{ВТ1}} = 207{,}3\cdot 202{,}75 = 42030{,}08\left(\frac{Дж}{кг}\right);$$

according to the results of thermodynamic calculation in the outer circuit, the fan blades should impart work to the air $L_{ВЛ_{\text{II}}} = 50777\frac{Дж}{кг}$, but in the TFE m>4 it is possible to use a single-stage fan at $L_{U_1} \geq 0.9L_{ВЛ_{\text{II}}}$ ($48692{,}94\frac{Дж}{кг} \geq 0{,}9\cdot 50777 = 45699{,}3\frac{Дж}{кг}$);

calculate the average work of the fan in the area of the internal circuit:

$$L_{ВЛ_1} = 0{,}5\left(L_{U_{ВТ}} + L_{U_1}\right) = 0.5\left(42030.08 + 48692.94\right) = 45361{,}51\frac{Дж}{кг};$$

thus, accept the single-stage fan, the size at the inlet : $D_{1К} = 1{,}82(м)$, $D_{1_{ВТ}} = 0{,}77(м)$, $D_1 = 1{,}00(м)$, $U_{1К} = 490(м/с)$.

Work in the area of the outer circuit $L_{ВЛ_{\text{II}}} = 50777\frac{Дж}{кг}$, in the area of the inner circuit $L_{ВЛ_1} = 45361{,}51\frac{Дж}{кг}$.

c) Spreading the compression work between the compressor stages and determining the number of high-pressure turbine stages in order to check whether it is possible to execute the fan without attached steps, we determine the work that in this case falls on the high-pressure compressor:

$$L'_{КВД} = L_К - L_{ВЛ_1} = 596430 - 45361{,}51 = 551068{,}49\,\frac{Дж}{кг};$$

Calculate the work of high-pressure turbine

$$L'_{ТВД} = \frac{L'_{КВД}}{(1+g_t)(1-g_{охл})\eta_м} = \frac{551068{,}49}{(1+0{,}0223)(1-0{,}09)0{,}99} = 598343{,}57\,\frac{Дж}{кг};$$

It is necessary to use a two-stage high-pressure turbine and two stages connected to the fan, in this case it is necessary to take $L'_{ТВД}$ a decrease of $70\,\frac{КДж}{кг}$, then:

$$U_{T_{СР}} = 0{,}55\sqrt{\frac{2\cdot 528343{,}57}{2\cdot 0{,}90}} = 421{,}4\left(м/с\right);$$

therefore, it is possible to adopt an engine design with a two-stage high-pressure turbine and a single-stage fan with two stages attached.

Work of turbine $L_{ТВД} = L'_{ТВД} - 70000 = 528343{,}57\,\frac{Дж}{кг}$ can distribute between two stages:

$$L_{CT_1} = 278075{,}56\,\frac{Дж}{кг},\quad L_{CT_2} = 250268\,\frac{Дж}{кг};$$

By final value $L_{ТВД}$ improve the work $L_{КВД}$:

$$L_{КВД} = L_{ТВД}(1+\mathrm{g_t})(1-g_{ОХЛ})\eta_м = 528343{,}57(1+0{,}0223)(1-0{,}09)0{,}99 = 486599{,}18\,\frac{Дж}{кг};$$

and determine the work falling on the steps connected to the fan:

$$L_{ПР} = L_К - L_{ВЛ_1} - L_{КВД} = 596430 - 45361{,}51 - 486599{,}18 = 64469{,}31\,\frac{Дж}{кг};$$

Compression work in the internal circuit fan with connected stages:

$$L_{КНД} = L_{ВЛ_1} + L_{ПР} = 45361{,}51 + 64469{,}31 = 109830{,}82\,\frac{Дж}{кг}.$$

d) Determination of the air parameters and diametrical dimensions of the section at the outlet of the fan, the degree of air pressure increase in the fan in the zone of the inner loop is determined $\eta^*_{ВЛ_1} = \eta^*_{ВЛ_2} = 0{,}85$, taking approximately equal to the fan efficiency, adopted in thermodynamic calculation:

$$\pi^*_{КНД} = \left[1 + \frac{L_{КНД}\eta^*_{КНД}}{\frac{К}{К-1}RT^*_В}\right]^{\frac{К}{К-1}} = \left[1 + \frac{109830{,}82 \cdot 0{,}85}{3{,}5 \cdot 287{,}3 \cdot 288{,}15}\right]^{3{,}5} = 2{,}66;$$

determine the pressure and temperature of the air at the outlet of the fan:

$$P^*_{КНД} = P^*_В \cdot \pi^*_{КНД} = 101325 \cdot 2{,}66 = 269524{,}5(Па);$$

$$T^*_{КНД} = T^*_В + \frac{К-1}{КR} L_{КНД} = 288{,}15 + \frac{1{,}4-1}{1{,}4 \cdot 287{,}3} \cdot 109830{,}82 = 397{,}37(К);$$

for the designed GTE with a fan with attached steps, $C_{аВЛ_{II}} = 210(м/с)$, $C_{аКНД} = 190(м/с)$ we calculate the reduced speed λ , relative flux density $q(\lambda_a)$ and cross-sectional area at the exit from the fan in the external circuit and in the internal circuit $F_{ВЛ_{II}}$ and $F_{ВЛ_1}$

$$\lambda_{аКНД} = \frac{C_{аКНД}}{18{,}3\sqrt{T^*_{КНД}}} = \frac{190}{18{,}3\sqrt{397{,}37}} = 0.52;$$

$$\lambda_{аВЛ_{II}} = \frac{C_{аВЛ_{II}}}{С_{КР}} = \frac{C_{аВЛ_{II}}}{18{,}3\sqrt{Т^*_{ВЛ_{II}}}} = \frac{210}{18{,}3\sqrt{338{,}6}} = 0{,}62;$$

$$q(\lambda_a)_{КНД} = 0{,}73;$$

$$q(\lambda_a)_{ВЛ_{II}} = 0{,}83;$$

$$F_{КНД} = \frac{G_{B_1}\sqrt{T^*_{КНД}}}{m_B P^*_{КНД} q(\lambda_a)_{КНД}} = \frac{71{,}23\sqrt{397{,}37}}{0{,}040348 \cdot 269524{,}5 \cdot 0{,}73} = 0{,}29(м^2);$$

$$F_{ВЛ_{II}} = \frac{G_{B_{II}}\sqrt{T^*_{ВЛ_{II}}}}{m_B P^*_{ВЛ_{II}} q(\lambda_a)_{ВЛ_{II}}} = \frac{391{,}77\sqrt{338{,}6}}{0{,}040348 \cdot 164653 \cdot 0{,}83} = 1{,}48\left(м^2\right);$$

assuming the outer diameter behind the fan is 5-10% less than at the inlet, that is $D_{ВЛ_{II}} = 0{,}98 D_{1К} = 0{,}98 \cdot 1{,}82 = 1{,}78(м)$, find the diameter of the conditional section:

$$D_{II} = \sqrt{D^2_{ВЛ_{II}} - \frac{4}{\pi} F_{ВЛ_{II}}} = \sqrt{1{,}78^2 - \frac{4}{3{,}14} \cdot 1{,}48} = 1{,}13(м);$$

we take the thickness of the separating body between the I and II contours, equal to 15 mm, then the outer diameter of the I contour $D_{КНД} = 1{,}13\text{-}0{,}03\text{=}1{,}10$ м, calculate the diameter of the sleeve $D_{ВТ.КНД}$:

$$D_{ВТ_{КНД}} = \sqrt{D^2_{КНД} - \frac{4}{\pi} F_{КНД}} = \sqrt{1{,}10^2 - \frac{4}{3{,}14} \cdot 0{,}29} = 0{,}91(м);$$

So, at the exit from the fan we have:

Outer contour $D_{ВЛ_{II}} = 1{,}78(м)$;

$D_{II} = 1{,}13(м)$;

Inner contour $D_{КНД} = 1{,}10(м)$;

$D_{ВТ_{КНД}} = 0{,}91(м)$;

e) Determination of diametrical dimensions at the inlet to the high pressure compressor (HPC)

Air parameters at the inlet to the HPC:

air temperature $T^*_{B_{КВД}} = T^*_{КНД} = 397{,}37(К)$

air pressure, taking into account losses in the transition case between the fan and the low pressure compressor (LPC).

$$P^*_{B_{КВД}} = P^*_{КНД} \sigma_{ПЕР} = 269524{,}5 \cdot 0{,}99 = 266829{,}26(Па)$$

Then the air speed at the inlet to the HPC $C_{a_{КНД}} = 195(м/с)$, find

$$\lambda_{B_{КВД}} = \frac{C_{a_{КВД}}}{18,3\sqrt{T^*_{B_{КНД}}}} = \frac{195}{18,3 \cdot \sqrt{397,37}} = 0,53;$$

$$q(\lambda_B)_{КВД} = 0,74;$$

$$F_{B_{КВД}} = \frac{G_{B1}\sqrt{T^*_{B_{КВД}}}}{m_B P^*_{B_{КВД}} q(\lambda_B)_{КВД}} = \frac{71,23\sqrt{397,37}}{0,040348 \cdot 266829,26 \cdot 0,74} = 0,275(м^2);$$

the relative diameter of the rotor compressor is taken at the entrance to the HPC and the outer diameter is determined:

$$D_{1КВД} = \sqrt{\frac{4F_{B_{КВД}}}{\pi(1-d^2_{BT})}} = \sqrt{\frac{4 \cdot 0,275}{3,14(1-0,61^2)}} = 0,75(м);$$

the diameter of the rotor compressor bushing of the first stage of HPC is found by the formula:

$$D_{BT_{КВД}} = \sqrt{D^2_{1КВД} - \frac{4}{\pi}F_{B_{КВД}}} = \sqrt{0,75^2 - \frac{4}{3,14} \cdot 0,275} = 0,46(м);$$

the height of the rotor compressor blades at the inlet to the HPC is determined:

$$h_л = \frac{D_{1КВД} - D_{BT_{КВД}}}{2} = \frac{0,75-0,46}{2} = 0,145(м);$$

f) Determination of diametrical dimensions at the exit from the HPC first, we clarify the parameters of the air at the exit from the HPC. According to thermodynamic calculation pressure $P^*_K = 3293062,5(Па)$, work $L_{КВД} = 486599,18\frac{Дж}{кг}$.

the air temperature behind the HPC is specified:

$$T^*_K = T^*_{КНД} + \frac{L_{КВД}}{\frac{K}{K-1}R} = 397,37 + \frac{486599,18}{3.5 \cdot 287.3} = 881,28(K);$$

in thermodynamic calculation it was obtained $T_K^* = 881{,}3(K)$

the degree of air pressure increase in the HPC is calculated by the formula:

$$\pi_{КВД}^* = \frac{P_K^*}{P_{B_{КВД}}^*} = \frac{3293062{,}5}{266829{,}26} = 12{,}3;$$

Then the air speed at the exit from the HPC $C_{a_K} = 125(м/c)$

Determine λ_{a_K} and $q(\lambda_a)_K$:

$$\lambda_{a_K} = \frac{C_{a_K}}{18{,}3\sqrt{T_K^*}} = \frac{125}{18{,}3\sqrt{881{,}28}} = 0{,}23;$$

$q(\lambda_a)_K$ =0,36 — from the table of gas dynamic function.

cross-sectional area at the exit from the HPC:

$$F_K = \frac{G_{B1}\sqrt{T_K^*}}{m_B P_K^* q(\lambda_a)_K} = \frac{71{,}23\sqrt{881.28}}{0{,}040348 \cdot 3293062{,}5 \cdot 0{,}36} = 0{,}044(м^2);$$

Assuming $D_{1КВД} = 0{,}75 = const$, find

$$D_{BT_K} = \sqrt{D_{1КВД}^2 - \frac{4}{\pi}F_K} = \sqrt{0{,}75^2 - \frac{4}{3{,}14} \cdot 0{,}044} = 0{,}71(м);$$

$$h_л = \frac{D_{1КВД} - D_{BT_K}}{2} = \frac{0{,}75 - 0{,}71}{2} = 0{,}02(м);$$

$$d_{BT_K} = \frac{D_{BT_K}}{D_{1КВД}} = \frac{0{,}71}{0{,}75} = 0{,}945.$$

To reduce the value d_{BT_K} at the exit from the HPC, reduce the diameter D_K of the last stages to 0.67 m. Then:

$$D_{BT_K} = \sqrt{0{,}67^2 - \frac{4}{3{,}14} \cdot 0{,}044} = 0{,}625(м);$$

$$h_л = \frac{0{,}67 - 0{,}625}{2} = 0{,}0225(м);$$

$$d_{ВТ_К} = \frac{0,67}{0,625} = 0,93;$$

So, inlet on HPC $D_К = 0,75м$, $D_{ВТ} = 0,46м$, $h_л = 145мм$;

At the outlet HPC $D_К = 0,67м$, $D_{ВТ} = 0,625м$, $h_л = 22,5мм$;

g) Determination of diametrical dimensions at the inlet to the high-pressure turbine. when determining the number of stages of the theater, the value was obtained $U_{Т_{СР}} = 421,4(м/с)$, approved for the first stage of work $L_{СТ_1} = 278075,56\frac{Дж}{кг}$

then the angle of the flow from the nozzle $\alpha_1 = 20^\circ$ and find the velocity of gas outflow from the nozzle:

$$C_1 = \frac{L_{СТ_1}}{U_{Т_{СР}}\cos\alpha_1} = \frac{278075,56}{421,4 \cdot 0.9397} = 702,23(м/с);$$

$$\lambda_1 = \frac{C_1}{C_{КР}} = \frac{702,23}{18.15\sqrt{1600}} = 0,97;$$

$$q(\lambda_1)_{C_a} = 0,9989;$$

flow rate and pressure of the gas at the outlet of the nozzle is calculated by formulas:

$$G_Г = G_{В_1}(1 + g_Т)(1 - g_{охл}) = 71,23(1 + 0,0223)(1 - 0,09) = 66,26(кг/с);$$

$$P^*_{C_a} = P^*_К \sigma_{К.С} \sigma_{C_a} = 3293062,5 \cdot 0,98 \cdot 0,98 = 3162657,225(Па);$$

the cross-section area at the outlet of the nozzle is determined:

$$F_{1C_a} = \frac{G_Г\sqrt{T^*_Г}}{m_Г P^*_{C_a} q(\lambda)_{ca}\sin\alpha_1} = \frac{66,26\sqrt{1600}}{0,0396 \cdot 3162657,225 \cdot 0,9989 \cdot 0,3420} = 0,11(м^2);$$

Accept $D_{Т_{СР}} = 1,3D_К = 1,3 \cdot 0,67 = 0,871(м)$, then

$$h_л = \frac{F_{1C_a}}{\pi D_{Т_{СР}}} = \frac{0,11}{3,14 \cdot 0,871} = 0,040(м);$$

$$D_Т = D_{Т_{СР}} + h_л = 0,871 + 0,04 = 0,911(м);$$

Find $D_{ВТ} = \sqrt{D_Т^2 - \frac{4}{\pi} F_{1C_a}} = \sqrt{0{,}911^2 - \frac{4}{3{,}14} \cdot 0{,}11} = 0{,}83(м)$;

so, at the entrance to the HPT, we have: $D_Т = 0{,}911(м)$, $D_{ВТ} = 0{,}83(м)$, $D_{Т_{СР}} = 0{,}871(м)$, $h_л = 0{,}0405(м)$;

determine the axial gas velocity:

$$C_{1a} = C_1 \sin\alpha_1 = 702{,}23 \cdot 0{,}3420 = 240{,}16(м/с);$$

determine the stress in the dangerous section of the blade from the action of centrifugal forces:

$$\sigma_Р = 2К_Ф \rho U_{Т_{СР}}^2 \frac{h_л}{D_{Т_{СР}}} \cdot 10^{-6} = 2 \cdot 0{,}5 \cdot 8{,}1 \cdot 10^3 \cdot 421{,}4^2 \frac{0{,}0405}{0{,}871} \cdot 10^{-6} = 668(МПа);$$

the strength of the HPT blades can be ensured only under the conditions of using the ZS6K alloy for the manufacture of blades and intensive cooling of the blades to a temperature of 950 K. under these conditions $\sigma_{100}^{950} = 790(МПа)$ and a margin of safety

$$n = \frac{790}{668} = 1{,}2.$$

The turbine rotor blades satisfy the strength condition.

h) Determination of diametrical dimensions at the outlet of the high pressure turbine(HPT). Find the parameters of the gas at the exit from the HPT:

$$T_{ТВД}^* = T_Г^* - \frac{L_{ТВД}}{\frac{К_Г}{К_Г - 1} R_Г} = 1600 - \frac{528343{,}57}{4 \cdot 288} = 1141{,}37(К);$$

$$P_{ТВД}^* = P_Г^* \left[1 - \frac{T_Г^* - T_{ТВД}^*}{T_Г^* \eta_{ТВД}^*}\right]^{\frac{К_Г}{К_Г - 1}} = 3194270 \cdot \left[1 - \frac{1600 - 1141{,}37}{1600 \cdot 0{,}89}\right]^4 = 674581{,}08(Па);$$

Then the superficial velocity $\lambda_{2a} = 0{,}55$, which corresponds to the axial component of the gas velocity at the exit from the HPT:

$$C_{2a} = 0{,}55 \cdot 18{,}15\sqrt{1141{,}37} = 337{,}25(м / с);$$

From the tables of gas-dynamic functions, we find: $q(\lambda_{2a}) = 0{,}7651$;

taking into account that a part of the cooling air will enter the gas flow and mix with it, $g_{охл_2} = 0{,}09$ we take and find the gas flow rate at the outlet of the HPT:

$$G_Г = \mathrm{G}_{\mathrm{B}_1}(1 + g_t)(1 - g_{охл_2}) = 71{,}23(1 + 0{,}0223)(1 - 0{,}09) = 66{,}26(кг / с);$$

The cross-sectional area at the exit from the HPT is determined by the formula:

$$F_{ТВД} = \frac{G_Г\sqrt{T^*_{ТВД}}}{m_Г P^*_{ТВД}\, q(\lambda_{2a})} = \frac{66{,}26\sqrt{1141{,}37}}{0{,}0396 \cdot 674581{,}08 \cdot 0{,}7651} = 0{,}199(м^2);$$

We accept $D_{T_{CP}} = 0{,}78$ and find the height of the HPT second stage blade (along the trailing edge)

$$h_л = \frac{F_{ТВД}}{\pi D_{T_{CP}}} = \frac{0{,}199}{3{,}14 \cdot 0{,}871} = 0{,}073(м);$$

Then,

$$D_{ТВД} = D_{T_{CP}} + h_л = 0{,}871 + 0{,}073 = 0{,}944(м);$$

$$D_{BT_{ТВД}} = \sqrt{D^2_{ТВД} - \frac{4}{\pi}F_{ТВД}} = \sqrt{0{,}944^2 - \frac{4}{3{,}14} \cdot 0{,}199} = 0{,}799(м);$$

In order to make sure that the dimensions obtained are acceptable, we draw on a scale the flow path of the two-stage HPT and find that the broadening angle of the flow path does not exceed.

Therefore, the diametrical dimensions of the high-pressure turbine can be taken as final.

i) Determining the number of stages of the high pressure compressor. We calculate the work of the first stage of the HPC, taking the density of the grating $\left(\frac{B}{t}\right)_{BT} = 2$:

$$\Delta W_{U_{BT}} = C_{1a} \frac{1{,}55}{1+1{,}5\frac{t}{B}} = 195 \cdot \frac{1{,}55}{1+1{,}5\cdot 0{,}5} = 172{,}71(м/с);$$

$$U_{1BT} = U_{T_{CP}} \frac{D_{1BT}}{D_{T_{CP}}} = 421{,}4 \cdot \frac{0{,}46}{0{,}871} = 222{,}34(м/с);$$

$$U_{1K} = U_{T_{CP}} \frac{D_{K}}{D_{T_{CP}}} = 421{,}4 \cdot \frac{0{,}75}{0{,}871} = 362{,}86(м/с);$$

$$L_{CT_1} = U_{BT}\Delta W_{U_{BT}} = 222{,}34 \cdot 172{,}71 = 38400\frac{Дж}{кг}.$$

The work of the last stage of the HPC is determined by taking the density of the grating $\left(\frac{B}{t}\right)_{BT} = 1{,}8$;

$$\Delta W_{U_{BT_z}} = C_{1a_K} \frac{1{,}55}{1+1{,}5\frac{t}{B}} = 125 \cdot \frac{1{,}55}{1+1{,}5\cdot \frac{1}{1{,}8}} = 105{,}68(м/с);$$

$$U_{1BT_z} = U_{T_{CP}} \frac{D_{1BT\cdot K}}{D_{T_{CP}}} = 421{,}4 \cdot \frac{0{,}625}{0{,}871} = 302{,}4(м/с);$$

$$L_{CT_Z} = U_{BT_Z}\Delta W_{U_{BT_K}} = 302{,}4 \cdot 105{,}68 = 31955{,}8\frac{Дж}{кг};$$

average operation of a stage $L_{CP} = \frac{38400+31955{,}8}{2} = 35177{,}9\frac{Дж}{кг}$, number of HPC stages

$$Z = \frac{L_{КВД}}{L_{CP}} = \frac{486599{,}18}{35177{,}9} \approx 13$$

distribution of work $L_{КВД}$ by stages in table 2.2, the sum of work of all stages should be equal to the work of the HPC $\sum L_{CT} = L_{КВД}$.

Table 2.2 - Distribution of work between compressor stages

z	1	2	3	4	5	6	7	8	9	10	11	12	13
L_{CT} $кдж/кг$	39	40	41	42	43	44	42	39	37	35	33	32	31

The number of stages HPC Z are equal to 13. Power balance HPC and HPT check by the formulas:

$$N_{КВД} = G_{B1} L_{КВД} = 71{,}23 \cdot 486599{,}18 = 34660459{,}59 (кВТ);$$

$$N_{ТВД} = G_{Г} L_{ТВД} = 66{,}26 \cdot 528343{,}57 = 35008044{,}95 (кВТ);$$

$$\eta_{M} = \frac{N_{КВД}}{N_{ТВД}} = \frac{34660459{,}59}{35008044{,}95} = 0{,}99;$$

the high-pressure rotor speed is determined separately for the compressor and turbine according to the equations:

$$n_{КВД} = \frac{60 U_{К}}{\pi D_{К}} = \frac{60 \cdot 362{,}86}{3{,}14 \cdot 0{,}75} = 9245 (об/мин);$$

$$n_{КВД} = \frac{60 U_{T.CP}}{\pi D_{T.CP}} = \frac{60 \cdot 421{,}4}{3{,}14 \cdot 0{,}871} = 9245 (об/мин);$$

j) Determination of the number of stages and distribution of work among the stages of the low pressure turbine (LPT), taking into account that the gas temperature $T^{*}_{ТВД} = 1141{,}37 K$ at the inlet to the LPT and therefore the LPT may not be cooled, and all the air that cools the HPT elements is mixed with the gas flow, we obtain:

$$G_{Г_{ТНД}} = G_{B_1} (1 + g_t) = 71{,}23 (1 + 0{,}0223) = 72{,}82 (кг/с);$$

$$L_{ТНД} = \frac{m L_{ВЛ_{II}} + L_{КНД}}{(1 + g_t) \eta_m} = \frac{5{,}5 \cdot 50777 + 109830{,}82}{(1 + 0{,}0223) 0{,}995} = 382529{,}22 \frac{Дж}{кг};$$

Taking into account possible gas leaks, take $G_{Г} = 72 (кг/с)$ according to the execution in the scale of the drawing of the flow path, we find approximately $D_{ТНД_{CP}} = 0{,}9 м$, then

$$U_{ТНД_{СР}} = U_{1К}\,\frac{D_{ТНД_{СР}}}{D_{1К}} = 490\,\frac{0{,}9}{1{,}82} = 242{,}3\left(м/с\right);$$

Loading parameter $y*$ determine at Z=2:

$$y* = U_{ТНД_{СР}}\sqrt{\frac{z\eta^*_{ТНД}}{2L_{ТНД}}} = 242{,}3\sqrt{\frac{2\cdot 0{,}91}{2\cdot 382529{,}22}} = 0{,}37\,;$$

At Z=3:

$$y* = U_{ТНД_{СР}}\sqrt{\frac{z\eta^*_{ТНД}}{2L_{ТНД}}} = 242{,}3\sqrt{\frac{3\cdot 0{,}91}{2\cdot 382529{,}22}} = 0{,}46\,;$$

At Z=4:

$$y* = U_{ТНД_{СР}}\sqrt{\frac{z\eta^*_{ТНД}}{2L_{ТНД}}} = 242{,}3\sqrt{\frac{4\cdot 0{,}91}{2\cdot 382529{,}22}} = 0{,}53\,.$$

Although the parameter y^* did not fall within the range of 0.55-0.6, to reduce the mass of the engine, we check the possibility of using a four-stage turbine, and to improve its controllability, we will design it so that the pressure drop in the nozzle would be subcritical λ_{1Ca}<1.

Distribute the loading between four stages:

$$L_{СТ_1} = 111232{,}69\,\frac{Дж}{кг} \qquad L_{СТ2} = 100109{,}42\,\frac{Дж}{кг}$$

$$L_{СТ3} = 90098{,}48\,\frac{Дж}{кг} \qquad L_{СТ4} = 81088{,}63\,\frac{Дж}{кг}$$

k) Determination of the diametrical dimensions at the outlet of the first nozzle of the LPT.

the critical gas velocity in the nozzle of LPT is determined by:

$$C_{КР} = 18{,}15\sqrt{T^*_{ТВД}} = 18{,}15\sqrt{1141{,}37} = 613{,}18\left(м/с\right);$$

taking the angle $\alpha_1 = 25^\circ$, find the velocity of gas outflow from the nozzle, assuming $C_{2U} = 0$

$$C_1 = \frac{L_{СТ_1}}{U_{Т_{СР}}\cos\alpha_1} = \frac{111232{,}69}{242{,}3\cos 25^\circ} = 506{,}5\left(м/с\right);$$

$$\lambda_1 = \frac{C_1}{C_{KP}} = \frac{506{,}5}{613{,}18} = 0{,}83;$$

$$q(\lambda_1) = 0{,}97;$$

Consequently, the pressure drop in the nozzle is less than the critic one and it is possible to design a turbine stage with an axial gas outlet from the compressor. the cross-sectional area at the outlet of the nozzle LPT is found:

$$F_{1C_a ТНД} = \frac{G_Г \sqrt{T^*_{ТВД}}}{m_Г\, p^*_{ТВД}\, \sigma_{пер}\, \sigma_{c_a}\, q(\lambda_1) \sin\alpha_1};$$

$$F_{1C_a ТНД} = \frac{71{,}23\sqrt{1141{,}37}}{0{,}0396 \cdot 674581{,}08 \cdot 0{,}98 \cdot 0{,}98 \cdot 0{,}97 \cdot 0{,}4226} = 0{,}297\left(м^2\right);$$

At $D_{ТНД_{CP}} = 0{,}9 м$;

$$h_Л = \frac{F_{1CA}}{\pi D_{CP}} = \frac{0{,}297}{3{,}14 \cdot 0{,}9} = 0{,}105(м);$$

then the outer diameter at the outlet from the LPT nozzle

$$D_T = D_{ТНД_{CP}} + h_Л = 0{,}9 + 0{,}105 = 1{,}005 м;$$

$$D_{BT} = \sqrt{D_T^2 - \frac{4}{\pi} F_{C_a ТНД}} = \sqrt{1{,}005^2 - \frac{4}{3{,}14} \cdot 0{,}297} = 0{,}795 м;$$

so at the outlet of the LPT nozzle have:

$$D_T = 1{,}005 м \qquad D_{BT} = 0{,}795 м \qquad h_Л = 105 мм.$$

Dimensions obtained put on drawing flow part and find that the transitional body between the HPT and the LPT get the size can be considered acceptable.

l) Determination of diametrical dimensions at the outlet of the LPT. Find the parameters of the gas at the outlet from the LPT by the formulas:

$$T_T^* = T_{ТВД}^* - \frac{L_{ТНД}}{\frac{K_Г}{K_Г - 1}R} = 1141{,}37 - \frac{382529{,}22}{4 \cdot 288} = 809{,}31К\,;$$

$$P_T^* = P_{ТВД}^* \sigma_{пер} \left[1 - \frac{T_{ТВД}^* - T_T^*}{T_{ТВД}^* \eta_{ТНД}^*}\right]^{\frac{K_Г}{K_Г - 1}};$$

$$P_T^* = 674581{,}08 \cdot 0{,}98 \left[1 - \frac{1141{,}37 - 809{,}31}{1141{,}37 \cdot 0{,}91}\right]^4 = 1{,}41 \times 10^5\,Па\,;$$

At the outlet of the LPT nozzle, the axial component of the gas velocity is $C_{1a} = C_1 \sin\alpha_1 = 506{,}5 \cdot 0{,}4226 = 214{,}05(м/с)$.

Then the reduced speed at the outlet of the LPT: $\lambda_{aT} = 0{,}65$, what corresponds $C_{aT} = 335{,}62 м/с$ to the table of gas-dynamic functions $q(\lambda_{aT}) = 0{,}8564$, find the cross-sectional area at the outlet from the LPT is calculated by the formula:

$$F_T = \frac{G_Г \sqrt{T_T^*}}{m_Г\, p_T^* q(\lambda_{aT})} = \frac{72{,}82\sqrt{809{,}31}}{0{,}0396 \cdot 1{,}41 \times 10^5 \cdot 0{,}8564} = 0{,}56(м^2);$$

Accept $D_{T_{CP}} = 0{,}9 м$ and find

$$h_Л = \frac{F_T}{\pi D_{T_{CP}}} = \frac{0{,}56}{3{,}14 \cdot 0{,}9} = 0{,}198(м);$$

$$D_T = D_{T_{CP}} + h_Л = 0{,}9 + 0{,}198 = 1{,}098 м\,;$$

$$D_{BT} = \sqrt{D_T^2 - \frac{4}{\pi}F_T} = \sqrt{1{,}098^2 - \frac{4}{3{,}14} \cdot 0{,}56} = 0{,}702 м\,;$$

So, at the exit from the LPT

$$P_T^* = 1{,}41 \times 10^5\,Па \quad T_T^* = 809{,}31К \quad D_T = 1{,}098 м \quad D_{BT} = 0{,}702 м$$

$$h_Л = 0{,}198(м) \quad \frac{D_{T_{CP}}}{h_Л} = \frac{0{,}9}{0{,}198} = 4{,}55\,;$$

Draw the flowing part of the LPT on a scale and find that the geometric dimensions are acceptable. Therefore, it is possible to realize a low pressure fuel pump with four stages. Determine the voltage from the action of centrifugal forces in the dangerous section of the LPT last stage:

$$\sigma_P = 2\rho K_\Phi U^2_{ТНД_{СР}} \frac{h_Л}{D_{ТНД_{СР}}} 10^{-6} = 2 \cdot 8{,}2 \times 10^3 \cdot 0{,}5 \cdot 242{,}3^2 \frac{0{,}198}{0{,}9} \cdot 10^{-6} = 106 МПа\,;$$

from the table of heat-resistant alloys we find that for the blades of the high pressure fuel pump it is possible to use the alloy ZS6-KP, which has $\sigma^t_{500} = 155 МПа$ then the factor of safety factor $n = \frac{155}{106} = 1{,}45$, the power balance of the turbine and the fan:

$$N_{ТНД} = G_{Г_{ТНД}} L_{ТНД} = 72 \cdot 382529{,}22 = 27855777{,}8 Bt\,;$$

$$N_{ВЛ_{II}} + N_{КНД} = G_{ВЛ_{II}} L_{ВЛ_{II}} + G_{B1} L_{КНД} = 391{,}77 \cdot 50777 + 71{,}23 \cdot 109830{,}82 = 27716154{,}6 Bt\,;$$

$$\eta_M = \frac{N_{ВЛ_{II}} + N_{КНД}}{N_{ТНД}} = \frac{27716154{,}6}{27855777{,}8} = 0{,}995\,.$$

Rotation frequency η of the low pressure rotor is determined separately for the fan and the formulas:

$$n_{КНД} = \frac{60 U_{1K}}{\pi D_{1K}} = \frac{60 \cdot 490}{3{,}14 \cdot 1{,}82} = 5145 (об / мин)\,;$$

$$n_{ТНД} = \frac{60 U_{T_{CP}}}{\pi D_{T_{CP}}} = \frac{60 \cdot 242{,}3}{3{,}14 \cdot 0{,}9} = 5145 (об / мин)\,;$$

m) Determination of the cross-sectional diameters at the exit from the nozzles of a by-pass turbojet engine. Outflow from the nozzle of the inner contour is subcritical, expansion is complete, because $\frac{P_T^* \sigma_{CT}}{P_H} = \frac{1{,}41 \times 10^5 \cdot 0{,}98}{1{,}01 \times 10^5} = 1{,}37$, that smaller $\pi_{KP} = 1{,}85$

Find the speed of the nozzle flow:

$$C_{C_1} = \sqrt{2\frac{K_\Gamma}{K_\Gamma - 1} R_\Gamma T_T^* \left[1 - \left(\frac{P_H}{P_T^* \sigma_C}\right)^{\frac{K_\Gamma - 1}{K_\Gamma}}\right]};$$

$$C_{C_1} = \sqrt{2 \cdot 4 \cdot 288 \cdot 809{,}31\left[1 - \left(\frac{1{,}013}{1{,}41 \cdot 0{,}98}\right)^{0{,}25}\right]} = 373{,}17(м/с);$$

$$\lambda_{C1} = \frac{C_{C1}}{C_{KP}} = \frac{373{,}17}{18{,}15\sqrt{809{,}31}} = 0{,}723;$$

$$q(\lambda_{C_1}) = 0{,}9077;$$

Determine the area of the nozzle and its diameter:

$$F_{C_1} = \frac{G_\Gamma \sqrt{T_T^*}}{m_\Gamma p_T^* \sigma_1 q(\lambda_{C_1})} = \frac{71{,}23\sqrt{809{,}31}}{0{,}0396 \cdot 1{,}41 \times 10^5 \cdot 0{,}98 \cdot 0{,}9077} = 0{,}408(м^2);$$

$$D_{C_1} = \sqrt{\frac{4F_{C_1}}{\pi}} = \sqrt{\frac{4 \cdot 0{,}408}{3{,}14}} = 0{,}72м;$$

The velocity of the outflow from the nozzle of the outer contour is determined in a thermodynamic calculation $C_{C_{II}} = 292{,}67 м/с$. The reduced velocity and relative flow density are found by the formulas:

$$\lambda_{C_{II}} = \frac{C_{C_{II}}}{C_{KP}} = \frac{292{,}67}{18{,}3\sqrt{338{,}6}} = 0{,}869;$$

$$q(\lambda_{C_{II}}) = 0{,}98;$$

Find the cross-sectional area of the nozzle:

$$F_{C_{II}} = \frac{G_{B_{II}} \sqrt{T_{BЛ_{II}}^*}}{m_B p_{C_{II}}^* \sigma_{C_{II}} q(\lambda_{C_{II}})} = \frac{391{,}77\sqrt{338{,}6}}{0{,}040348 \cdot 164653 \cdot 0{,}98 \cdot 0{,}98} = 1{,}13(м^2);$$

The inner diameter of the outer contour nozzle is determined from the engine drawing. The outer diameter is calculated by the formula:

$$D_{C_{BH}} = 1100мм$$

$$D_{C_{\text{II}}}=\sqrt{D^2_{C_{BH}}+\frac{4}{\pi}F_{C_{\text{II}}}}=\sqrt{1{,}10^2+\frac{4}{3{,}14}\cdot 1{,}13}=1{,}628(м)$$

n) specification of engine parameters

In conclusion of the gas-dynamic calculation, we find the refined values of the parameters of the projected turbofan:

calculate the specific thrust

$$P_{УД_1}=C_{C_1}(1+g_T)=373{,}17(1+0{,}0223)=381{,}49\frac{H\cdot c}{кг};$$

$$P_{УД_{\text{II}}}=C_{C_{\text{II}}}=292{,}67\frac{H\cdot c}{кг};$$

$$P_{УД_\Sigma}=\frac{P_{УД_1}+mP_{УД_{\text{II}}}}{1+m}=\frac{381{,}49+5{,}5\cdot 292.67}{1+5{,}5}=306{,}33\frac{H\cdot c}{кг};$$

Thrust of engine:

$$P=P_{уД_\Sigma}G=306{,}33\cdot 463=141{,}83(KH);$$

Specific fuel consumption according to the equation:

$$C_{УД}=\frac{3600\cdot g_T(1-g_{охл})}{P_{УД_\Sigma}(1+m)}=\frac{3600\cdot 0{,}0223(1-0.09)}{306{,}33(1+5.5)}=0{,}0367(кг/H\cdot ч).$$

The obtained engine parameters do not coincide with the results of the thermodynamic calculation. In the end, we accept the results of the gas dynamic calculation.

2.4. Gas-dynamic calculation of an axial turbine stage

The initial data of the gas-dynamic calculation of the axial turbine stage are the gas parameters and geometric dimensions at the turbine inlet obtained in the gas-dynamic calculation of the engine.

The purpose of the gas-dynamic calculation of the stage is to determine the geometric dimensions of the stage, to construct plans of velocities in three sections along the height of the blade and to construct the blade profile.

Provide a gas-dynamic calculation of the first stage of a high-pressure turbine turbojet engine. From the gas-dynamic calculation of the engine, the following are known:

- gas pressure at the HPT inlet: $P_Г^* = P_0^* = 3162657{,}2 Па$

- gas temperature at the entrance to the HPT: $T_Г^* = T_0^* = 1600 К$

- mass flow rate of gas: $G_Г = 66{,}26 кг/с$

- operation of the HPT stage: $L_{СТ} = 278075{,}56 \frac{Дж}{кг}$

- peripheral speed on the average diameter of the compressor rotor: $U_{1СР} = 421{,}4 м/с$

- angle of exit of the gas flow at the outlet of the nozzle: $\alpha_1 = 20°$

- end, middle and bushing diameters before compressor rotor: $D_{1К} = 0{,}911 м$, $D_{1СР} = 0{,}871 м$, $D_{ВТ} = 0{,}83 м$

-absolute speed at the exit from the nozzle: $C_{1СР} = 702{,}23 м/с$

- reduced speed at the exit from the nozzle: $\lambda_1 = 0{,}97$

- coefficient of recovery of full pressure in the nozzle: $\sigma_{са} = 0{,}98$ [20]

2.4.1 Determine the geometric dimensions of the axial turbine stage.

a) The cross-sectional area at the entrance to the of the first stage of the HPT is determined in the gas-dynamic calculation of the engine:

$$F_1 = \frac{G_Г \sqrt{T_Г^*}}{m_Г P_{C_a}^* q(\lambda)_{ca} \sin\alpha_1} = \frac{66{,}26\sqrt{1600}}{0{,}0396 \cdot 3162657{,}225 \cdot 0{,}9989 \cdot 0{,}3420} = 0{,}11\left(м^2\right);$$

geometric dimensions in front of the impeller are known:

$$D_{1K} = 0{,}911(м) \quad D_{1BT} = 0{,}83(м) \quad h_1 = 0{,}0405(м) \quad \bar{d}_{BT} = \frac{0{,}83}{0{,}911} = 0{,}91;$$

b) In order to determine the diametric dimensions at the outlet of the impeller, the parameters of the working body in this section are calculated.

find the gas temperature at the exit from the stage:

$$T_2^* = T_0^* - \frac{L_{CT}}{\frac{K_Г}{K_Г - 1} R_Г} = 1600 - \frac{278075{,}56}{4 \cdot 288} = 1358{,}31(K);$$

calculate the pressure behind the stage:

$$P_2^* = P_0^* \left[1 - \frac{T_0^* - T_2^*}{T_0^* \eta_{CT}^*}\right]^{\frac{K_Г}{K_Г - 1}} = 3162657{,}2 \cdot \left[1 - \frac{1600 - 1358{,}31}{1600 \cdot 0{,}90}\right]^4 = 1515463{,}31(Па);$$

At $\eta_{CT}^* = 0{,}9$.

The axial component of the absolute speed is set at the outlet of the impeller

$$C_{2a} = C_{1a} + \Delta C_a \quad , \qquad \Delta C_a = 40м/с \;;$$

$$C_{1a} = C_1 \sin\alpha_1 = \lambda_{C_1} \cdot 18{,}15\sqrt{T_Г^*} \sin 20°;$$

$$C_{1a} = 0{,}97 \cdot 18{,}15 \cdot \sqrt{1600} \cdot 0{,}3420 = 240{,}84(м/с);$$

$$C_{2a} = 240{,}84 + 40 = 280{,}84(м/с);$$

The driven speed is calculated by the formula:

$$\lambda_{C_{2a}} = \frac{C_{2a}}{18{,}15\sqrt{T_2^*}} = \frac{280{,}84}{18{,}15 \cdot \sqrt{1358{,}31}} = 0{,}42;$$

$$q\left(\lambda_{C_{2a}}\right) = 0{,}6179;$$

Determine the cross-sectional area at the outlet of the impeller:

$$F_2 = \frac{G_Г \sqrt{T_2^*}}{m_Г P_2^* q(\lambda_{C_{2a}})} = \frac{66{,}26\sqrt{1358{,}31}}{0{,}0396 \cdot 1515463{,}31 \cdot 0{,}6179} = 0{,}112(м^2);$$

The formula for the flow path of the turbine stage is $D_К = const$, then $D_{2К} = D_{1К} = 0{,}911м$

Determine the diametrical dimensions at the outlet of the impeller:

$$D_{2ВТ} = \sqrt{D_{2К}^2 - \frac{4}{\pi} F_2} = \sqrt{0{,}911^2 - \frac{4}{3{,}14} \cdot 0{,}112} = 0{,}829(м);$$

$$D_{2СР} = \frac{D_{2К} + D_{2ВТ}}{2} = \frac{0{,}911 + 0{,}829}{2} = 0{,}87(м);$$

$$h_2 = \frac{D_{2К} - D_{2ВТ}}{2} = \frac{0{,}911 - 0{,}829}{2} = 0{,}041(м);$$

c) Calculation of the turbine stage at the middle radius

Determine the load factor of the step on the middle radius:

$$\mu_{CP} = \frac{L_{CT}}{U_{CP}^2} = \frac{278075{,}56}{421{,}4^2} = 1{,}566$$

Absolute nozzle exit velocity and superficial velocity λ_{C1} calculated under the condition of the axial outlet of the gas flow

$$C_{1CP} = \frac{L_{CT}}{U_{CP} \cos\alpha_1} = \frac{278075{,}56}{421{,}4 \cdot 0{,}9397} = 702{,}23(м/с);$$

$$\lambda_{C1_{CP}} = \frac{C_{1CP}}{C_{KP}} = \frac{702{,}23}{18{,}15\sqrt{1600}} = 0{,}97;$$

As, λ_{C_1} <1,25 then the specified operation of the turbine stage can be obtained with the axial outlet of the gas flow ($C_{2U} = 0$).

The axial component of the absolute speed and the parameter $\overline{C}_{1aCP}$ in front of the impeller are determined by the formulas:

$$C_{1aCP} = C_1 \sin\alpha_1 = 702{,}23 \cdot 0{,}3420 = 240{,}16(м/с);$$

$$\overline{C}_{1aCP} = \frac{C_{1aCP}}{U_{CP}} = \frac{240{,}16}{421{,}4} = 0{,}5699;$$

The circumferential components of the absolute speed at the inlet and outlet of the impeller, as well as parameters C_{U_m}, $\overline{C}_{1U}$ and $\overline{C}_{2U}$ determined by the formulas:

$$C_{1U} = C_1 \cos\alpha_1 = 702{,}23 \cdot \cos 20° = 659{,}88 (м/с);$$

$$C_{2U} = \frac{L_{CT}}{U_{CP}} - C_{1U} = \frac{278075{,}56}{421{,}4} - 659{,}88 = 0;$$

$$C_{U_m} = \frac{C_{1U} - C_{2U}}{2} = \frac{659{,}88 - 0}{2} = 329{,}94 м/с;$$

$$\overline{C}_{1U} = \frac{C_{1U}}{U_{CP}} = \frac{659{,}88}{421{,}4} = 1{,}566;$$

$$\overline{C}_{2U} = \frac{C_{2U}}{U_{CP}} = \frac{0}{421{,}4} = 0.$$

Find the relative gas velocity W_{CP} and its circumferential component $W_{1U_{CP}}$ in front of the impeller by the formulas:

$$W_{1U_{CP}} = C_{1U_{CP}} - U_{CP} = 659{,}88 - 421{,}4 = 238{,}48 м/с;$$

$$W_{1CP} = \sqrt{C_{1aCP}^2 + W_{1U_{CP}}^2} = \sqrt{240{,}16^2 + 238{,}48^2} = 338{,}45 м/с;$$

the angle of gas entry into the impeller in relative motion is calculated by the formula

$$\beta_1 = arctg\,\frac{C_{1a}}{W_{1U}} = arctg\,\frac{240{,}16}{238{,}48} = 45{,}2°;$$

Absolute gas velocity at the outlet of the impeller C_2 and driven speed λ_{C_2} calculate by the formulas:

$$C_2 = \sqrt{C_{2a}^2 + C_{2U}^2} = \sqrt{280{,}84^2 + 0^2} = 280{,}84 м/с;$$

$$\lambda_{C_2} = \frac{C_2}{18{,}15\sqrt{T_2^*}} = \frac{280{,}84}{18{,}15 \cdot \sqrt{1358{,}31}} = 0{,}42;$$

the angle of exit of the flow from the impeller in relative motion is found by the formula:

$$\beta_2 = arctg\,\frac{C_{2a}}{C_{2U} + U} = arctg\,\frac{280{,}84}{0 + 421{,}4} = 33{,}68°.$$

Then determine the relative velocity at the outlet of the impeller and its circumferential component:

$$W_2 = \frac{C_{2a}}{\sin\beta_2} = \frac{280{,}84}{\sin 33{,}68°} = 506{,}42 м/с;$$

$$W_{2U} = W_2 \cos\beta_2 = 506{,}42 \cdot \cos 33{,}68° = 421{,}4 м/с;$$

The temperature of the stalled flow and the critical gas velocity in relative motion are calculated by the formulas:

$$T^*_{W1} = T^*_{W2} = T^*_0 - \frac{K_Г - 1}{2K_Г R_Г}\left(C_1^2 - W_1^2\right) = 1600 - \frac{1{,}33 - 1}{2 \cdot 1{,}33 \cdot 288}\left(702{,}23^2 - 338{,}45^2\right) = 1436{,}9K$$

$$a_{KPW} = 18{,}15\sqrt{T^*_{W_1}} = 18{,}15 \cdot \sqrt{1436{,}9} = 688 м/с;$$

The twist in the impeller is calculated by the formula:

$$\Delta W_U = W_{1U} + W_{2U} = 238{,}48 + 421{,}4 = 659{,}88 м/с;$$

The driven speeds at the inlet and outlet of the impeller are determined by the formulas:

$$\lambda_{W1} = \frac{W_1}{a_{KPW}} = \frac{338{,}45}{688} = 0{,}49;$$

$$\lambda_{W2} = \frac{W_2}{a_{KPW}} = \frac{506{,}42}{688} = 0{,}736.$$

Find the kinematic degree of reactivity as follows:

$$\rho_K = 1 - \frac{C_{1U}}{U} + \frac{\Delta W_U}{2U} = 1 - \frac{659{,}88}{421{,}4} + \frac{659{,}88}{2 \cdot 421{,}4} = 0{,}217;$$

Peripheral speeds at the inlet and outlet of the impeller at a given diameter are assumed to be the same $(U_1 = U_2)$, we check the operation of the stage using the equation $L_{CT} = \frac{1}{2}\left(C_1^2 - C_2^2 + W_2^2 - W_1^2\right) = \frac{1}{2}\left(702{,}23^2 - 280{,}84^2 + 506{,}42^2 - 338{,}45^2\right) = 278084{,}34 \frac{Дж}{кг}$,

and calculate the relative deviation of the received step work from the original work value $L_{CT.U}$

$$\delta L_{CT} = \frac{L_{CT} - L_{CT.U}}{L_{CT.U}} = \frac{278084{,}34 - 278075{,}56}{278075{,}56} = 0{,}0032\%;$$

$\delta L_{CT.U}$ <3%, so its mean that calculation are correct.

d) To calculate the flow parameters at different radiuses of the turbine stage, we select the law of blade profiling along the height.

for this, determine the degree of reactivity of the sleeve at the indicator $m = 1$:

$$\rho_{BT} = 1 - (1 - \rho_{CP})\left(\frac{D_{CP}}{D_{BT}}\right)^{m+1} = 1 - (1 - 0{,}217)\left(\frac{0{,}871}{0{,}911}\right)^{1+1} = 0{,}178;$$

Since ρ_{BT} > 0, then we choose the law of constant circulation.

Table 2.3 - Kinematic parameter of a turbine stage, profiled according to the law $C_u r = const$

Magnitude and calculation formula	Cross-section		
	Sleeve	Average	Peripheral
$D, м$	0,83	0,871	0,911
$u = u_{CP}\dfrac{D}{D_{CP}}, м/с$	401,56	421,4	440,75
$\mu = \dfrac{L_{CT}}{u^2}$	1,724	1,57	1,43
$C_{1a} = C_{1aCP} = const, м/с$	240,16	240,16	240,16
$C_{1u} = C_{1ucc}\dfrac{D_{CP}}{D}, м/с$	692,48	659,88	630,91
$C_1 = \sqrt{C_{1a}^2 + C_{1u}^2}, м/с$	732,94	702,22	675,1
$\lambda_{C1} = \dfrac{C_1}{18{,}15\sqrt{T_1^*}}$	0,99	0,967	0,93
$\alpha_1 = arctg\dfrac{C_{1a}}{C_{1u}}, град$	19,13	20	20,84
$W_{1U} = C_{1U} - U, м/с$	271,08	238,48	209,51
$W_1 = \sqrt{C_{1a}^2 + W_{1u}^2}, м/с$	362,16	338,45	318,7

$\beta_1 = arctg\dfrac{C_{1a}}{W_{1u}}, град$	41,5	45,2	48,9
$C_{2a} = C_{2aCP} = const, м/с$	280,84	280,84	280,84
$C_{2u} = C_{2uCC}\dfrac{D_{CP}}{D}, м/с$	0	0	0
$C_2 = \sqrt{C_{2a}^2 + C_{2u}^2}, м/с$	280,84	280,84	280,84
$\alpha_2 = arctg\dfrac{C_{2a}}{C_{2u}}, град$	90	90	90
$\lambda_{C_2} = \dfrac{C_2}{18{,}15\sqrt{T_2^*}}$	0,42	0,42	0,42
$\beta_2 = arctg\dfrac{C_{2a}}{C_{2u} + U}, град$	34,97	33,68	32,5
$W_2 = \dfrac{C_{2a}}{\sin\beta_2}, м/с$	490,12	506,42	522,98
$W_{2U} = W_2\cos\beta_2, м/с$	401,6	421,4	441,1
$T_{W1}^* = T_0^* - \dfrac{К_Г - 1}{2К_Г R_Г}\left(C_1^2 - W_1^2\right), К$	1425,4	1436,9	1447,7
$\lambda_{W_1} = \dfrac{W_1}{18{,}15\sqrt{T_{W1}^*}}$	0,53	0,49	0,46
$\lambda_{W_2} = \dfrac{W_2}{18{,}15\sqrt{T_{W_1}^*}}$	0,71	0,736	0,76
$\rho_К = 1 - \dfrac{C_{1U}}{U} + \dfrac{\Delta W_U}{2U}$	0,16	0,217	0,265
$L_{CT} = \dfrac{1}{2}\left(C_1^2 - C_2^2 + W_2^2 - W_1^2\right), \dfrac{Дж}{кг}$	278085,94	278084,34	278083,08
$\delta L_{CT} = \dfrac{L_{CT} - L_{CT.U}}{L_{CT.U}}, \%$	0,0037	0,0032	0,0027

Table continuation 2.3

e) To construct the blade profile, we set the relative pitch of the nozzle on the average diameter $\left(\frac{t}{B}\right)_{CP} = 0{,}9$, elongation of the nozzle $\bar{h}_{Л_1} = 1{,}4$ blade and determine the chord of the profile at the average diameter:

$$B_{C_aCP} = \frac{h_1}{\bar{h}_{Л_1}} = \frac{40{,}5}{1{,}4} = 29мм;$$

Then we find the spacing of the nozzle lattice on the average radius

$$t_{CaCP} = B_{CaCP}\left(\frac{t}{B}\right)_{CP} = 29 \cdot 0{,}9 = 26{,}1мм;$$

and determine the number of nozzle blades

$$Z_{Ca} = \frac{\pi D_{1CP}}{t_{CaCP}} = \frac{3{,}14 \cdot 871}{26{,}1} = 104{,}8;$$

$$t_{CaCP} = \frac{\pi D_{1CP}}{Z_{Ca}} = \frac{3{,}14 \cdot 871}{105} = 26мм;$$

The relative spacing of the impeller at the average radius is chosen $\left(\frac{t}{B}\right)_{PK} = 0{,}7$, parameter $\left(\frac{h_Л}{\delta_{PK.CP}}\right) = 1{,}4$ and find the chord of the profile and the pitch of the impeller:

$$B_{PK} = \frac{h_1}{\left(\frac{h_{Л1}}{B_{PK.CP}}\right)} = \frac{40{,}5}{1{,}4} = 29мм;$$

$$t_{PK.CP} = B_{PK}\left(\frac{t}{B}\right) = 29 \cdot 0{,}7 = 20{,}3мм;$$

The number of impeller blades is calculated by the formula:

$$Z_{PK} = \frac{\pi D_{1CP}}{t_{PK.CP}} = \frac{3{,}14 \cdot 871}{20{,}3} = 134{,}7;$$

$$t_{PK.CP} = \frac{3{,}14 \cdot 871}{135} = 20{,}26\text{мм};$$

By setting the flow lag angle $\delta = -4°$, determine the bending angle of the trailing edge by the formula:

$$\beta_2^{/} = \beta_2 + \delta = 33{,}68 - 4 = 29{,}68°;$$

We set the angle of attack $i = -2°$, calculate the angle of installation of the leading edge:

$$\beta_1^{/} = \beta_1 + i = 45{,}2 - 2 = 43{,}2°;$$

The bending angle of the profile is calculated by the formula:

$$\theta^{/} = 180 - \left(\beta_1^{/} + \beta_2^{/}\right) = 180 - (43{,}2 + 29{,}68) = 107{,}12°;$$

and calculate the bending angles of the leading χ_1 and trailing χ_2 edges, setting the value $\frac{\alpha}{B} = 0{,}45$:

$$\chi_1 = \frac{\theta^{/}}{2}\left[1 + 2\left(1 - 2\frac{\alpha}{B}\right)\right] = \frac{107{,}12}{2}\left[1 + 2(1 - 2 \cdot 0{,}45)\right] = 64{,}27°;$$

$$\chi_2 = \theta^{/} - \chi_1 = 107{,}12 - 64{,}27° = 42{,}85^{\circ};$$

Find the angle of installation of the profile:

$$\nu = 180 - \left(\beta_1^{/} + \chi_1\right) = 180 - (43{,}2 + 64{,}27) = 72{,}53°;$$

And the width of the blade:

$$S = B_{PK} \sin\nu = 29 \cdot \sin 72{,}53° = 28\text{мм}.$$

Table 2.4 - Geometric characteristics of the turbine blade profile

$\overline{X} = \frac{X}{B}100$	0	1,25	2,5	7,5	10	15	20	30
$X = \frac{B\overline{X}}{100}$, мм	0	0,37	0,73	2,19	2,93	4,39	5,86	8,79
$\overline{У}_1 = \overline{У}_2 = \frac{У}{C_{\max}}100$	0	11,7	15,4	19,9	27,4	34	39,5	47,2
$У_1 = У_2 = \frac{\overline{У}C_{\max}}{100}$	0	0,78	1,00	1,33	1,84	2,28	2,65	3,16
$\overline{X} = \frac{X}{B}100$	40	50	60	70	80	90	95	100
$X = \frac{B\overline{X}}{100}$, мм	11,7	14,63	17,58	20,5	23,44	26,33	27,8	29,25
$\overline{У}_1 = \overline{У}_2 = \frac{У}{C_{\max}}100$	50	47,6	37,0	25,1	14,2	8,5	7,2	0
$У_1 = У_2 = \frac{\overline{У}C_{\max}}{100}$	3,35	3,19	2,48	1,68	0,95	0,57	0,48	0

2.5 Calculation of the strength of the main elements designed engine

2.5.1 Strength calculation of the first stage of the HPT

The strength calculation of the disk is performed as a test one after the turbine assembly has been extracted and the material has been selected. The purpose of the calculation is to determine the change along the radius of the disk of equivalent stresses and safety factors for the long-term strength of the material on the basis of 100 and 1000 h at the corresponding temperatures.

a) Need to divide the design disk scheme into a number of characteristic regions using the main sections as in Fig. 2.1

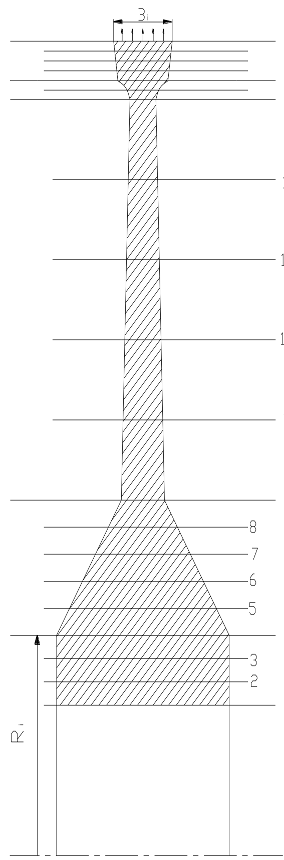

Figure: 2.1 - Design scheme of the turbine disk

Table 2.5 – Obtained data of sections dimensions

Number of section	Dimensions of section		The driven dimensions of the main sections		
	R_i ,м	B_i ,м	$R_Г = R \cdot 10^4$	$B_Г = B \cdot 10^4$	n
1	2	3	4	5	6
1	0,090	0,100	0900	1000	01

2	0,100	0,100			
3	0,110	0,100			
4	0,120	0,100	1200	1000	04
5	0,132	0,085			
6	0,143	0,070			
7	0,155	0,055			
8	0,166	0,040			
9	0,178	0,025	1700	0250	09
10	0,212	0,023			
11	0,247	0,021			
12	0,281	0,019			
13	0,316	0,017			
14	0,350	0,015	3500	0150	14
15	0,354	0,018			
16	0,358	0,029	3580	0290	16
17	0,362	0,030			
18	0,366	0,032			
19	0,370	0,033			
20	0,375	0,034	3750	0340	20

Table continuation 2.5

b) Determine the stress from centrifugal forces in the root section of the rotor blade:

$$\sigma_p = \rho\omega^2\left\{\frac{R_0^2 - R^2}{2} - h_л\left(1-\overline{F}\right)\left[\frac{R_K}{1+q} + \frac{h_л}{2+q} - \left(\frac{R_K}{1+q} + \frac{R-R_K}{2+q}\right)\left(\frac{R-R_K}{h_л}\right)^{1+q}\right]\right\};$$

$$\sigma_p = 8{,}1\cdot10^3\cdot967{,}64^2\left\{\frac{0{,}456^2 - 0{,}415^2}{2} - 0{,}0405\left(1-0{,}3\right)\left[\frac{0{,}415}{1+0{,}6} + \frac{0{,}0405}{2+0{,}6} - 0\right]\right\} = 77Мпа;$$

c) Determine the contour load from the calculation of the axial turbine stage, we know that the area at the root of the rotor blade $F_K = 113 \cdot 10^{-6} м^2$ and number of rotor blades $Z_{рл} = 135$

$$\sigma_{R_л} = \frac{Z_{рл}\sigma_{pk}F_K + 2\pi\rho_{ср}R_f^2\varpi^2 dh}{2\pi R_K B_K};$$

$$\sigma_{R_л} = \frac{135 \cdot 77 \cdot 113 + 2 \cdot 3{,}14 \cdot 8{,}2 \cdot 10^3 \cdot 395^2 \cdot 10^{-6} \cdot 967{,}64^2 \cdot 10^{-6} \cdot 0{,}034 \cdot 0{,}04}{2 \cdot 3{,}14 \cdot 0{,}3747 \cdot 0{,}034} = 140 Мпа;$$

d) Determine the values of the temperature of the disc on the rim and on the radius of the hole.

$$T_ц = 300°C$$

$$T_H = T_Г^* - 657 - 273 = 670°C;$$

e) Record the obtained data in Table 2.6

Table 2.6 – Systematized the obtained value

Parameter	Symbol	Unit	Parameter value	Number of Significant Digits	Values given
1	2	3	4	5	6
Contour load	σ	MPa	140	3	140
Angular velocity	ω	Rad/s	967,64	5	967,64
Rim temperature	T_H	$°C$	670	3	670
Parameter	Symbol	Unit	Parameter value	Number of significant digits	Values given

1	2	3	4	5	6
Temperature at the center of the disc	$T_ц$	$°C$	300	3	300
Material parameter	ЭИ	-	3	1	3
Equation parameter	S	-	2	1	2
Number of Main Sections	K_0	-	06	2	06

Table continuation 2.6

2.6. Development of systems for the projected turbofan

2.6.1. Starting system

2.6.1.1 Composition and purpose of GTE starting systems

The starting system of a gas turbine engine is a set of devices designed for forced spin up of the engine rotor at startup. It includes a starting device, a power source, a power transmission system, etc.

The starting systems of the gas turbine engine are used to transfer the engine from an inoperative state to a state of operation in idle mode. Low gas steady-state mode of GTE operation on the ground at a minimum rotor speed and thrust (power), at which its stable operation and a given throttle response are ensured.

2.6.1.2. Requirements for starting systems of gas turbine engines

The launch system must:

- to ensure reliable launch on the ground and in flight for the shortest possible time without overshooting of the gas temperature in front of the turbine and the rotor speed and with stable operation of the main engine components;

- provide fully automated engine start. The crew's action should be reduced only to pressing the "Start" button;

- be autonomous and have an energy source on board the aircraft for the operation of starting devices (batteries, auxiliary power unit). At the same time, it should be possible to launch a gas turbine engine from airfield energy sources;

- have units with a minimum weight and dimensions.

2.6.1.3 Starting system design

Starting the engine is providing by several systems included in the starting system:

The pre-spinning system of the engine rotor is using to spin up the rotor to the speed at which the engine compressor raises the air pressure to a value sufficient for ignition and stable combustion of fuel in the combustion chamber.

The rotor is spinning up using starting devices or starters. The source of energy is batteries, auxiliary power plant or airfield facilities. In non-starter starting systems, the rotor is spun up by supplying air to the engine turbine through special branch pipes.

The ignition system ignites the starting fuel. The main elements of the system:

- electric spark plugs;

- usually, each candle has its own starting coil.

- starting coils producing pulsating current with a voltage of 2.5-5 kV.

The fuel switch automatically doses the main fuel by optimizing the ratio between fuel consumption and airflow through the engine. Optimization is carried out from the condition of the minimum start-up duration without overshoot of engine parameters and with stable operation of its main components.

The automatic launch control system performs automatic start-up control system automatically switches on and off the units of the starting system at the required starting time and when the engine parameters reach the preset values. The main element of this system is the automatic launch panel. For GTE's of I to IV generations, this system is built on the principle of program control. The program mechanism at certain points in the start time gives signals to turn on the shutdown of the units of the starting system. In engines of the 5th generation, to which the engine under design belongs, electronic automatic start control systems are used, in which microprocessor technology is used. Such systems control units of starting systems according to the principle of analyzing changes in engine parameters depending on specific atmospheric conditions.

2.6.1.4. Selecting the type of starting device

Starting devices of any type consist of a power generator (engine), which transmits torque to its rotor through a gearbox and a clutch mechanism with the elements of the drive box of the GTE being launched. The clutch mechanism is designed to disconnect the output shaft of the starting device after it is turned off with the drive box of the engine being started. Freewheel clutches (for example, roller overrunning or ratchet) are usually used as such mechanisms.

Depending on the type of power generator used, starting devices are divided into three classes: electrical, turbine and hydraulic. For the designed engine, in order to minimize the mass of the starting system, we select an air-turbine starting device, i.e. air turbo starter.

Air turbo starters (ATS) are most widely used. The power element of the ATS is an air turbine, which transmits torque to the gears of the drive box and then to the engine rotor through a gearbox and a clutch ratchet. The air supply to the ATS is carried out from the onboard auxiliary power unit (APU) of the compressed air turbine generator, which is a low-power GTE with a re-sized compressor. The APU is pre-started using an electric starter powered by an on-board battery or a ground source.

In ATS, small-sized active-type air turbines are used. In order to obtain optimal peripheral speeds, the rotational speed of the rotors of air turbines reaches 30,000 - 40,000 rpm for high-power ATS and up to 60,000 rpm for ATS of low power. Planetary gears (one-stage or two-stage) with gear ratios of 8 - 15 are usually used as ATS gearboxes.

A ratchet clutch is installed on the output shaft of the gearbox, which, when the transmission of torque from the air turbine connects this shaft to the drive box and prevents reverse transmission of torque after the air supply to the ATS is cut off. At the frequency of rotation of the starter shutdown torque centrifugal forces acting on the rotating ensure their disengagement, which excludes their intense wear.

In addition to the above elements, the ATS has an air supply unit made in the form of an air valve or damper. This unit ensures that the air supply to the turbine is switched on and off using the solenoid valves of the command unit, as well as automatic stabilization of the air pressure at a given level. To control the air valve (damper), a servo drive is used, which operates from a difference in air pressure.

The air parameters required for the operation of the PTS are as follows:

- air pressure: p_B = from 0.25 to 0.35 MPa;

- air temperature: T_B = from 150 to 180 °C;

- air consumption depending on the required power of the starting device: G_B = from 0.3 to 1.2 kg / s

2.6.1.5. Gas turbine engine start-up diagram. Characteristics of the launch stages

The starting diagram is called the dependence of three torques on the rotor speed of the engine being started: the moment transmitted to the rotor by the $M_{ПУ}$ (n) starting device; the moment of resistance of the rotor to rotation of the $M_C(n)$; torque arising on the turbine rotor after ignition of the main fuel $M_T(n)$.

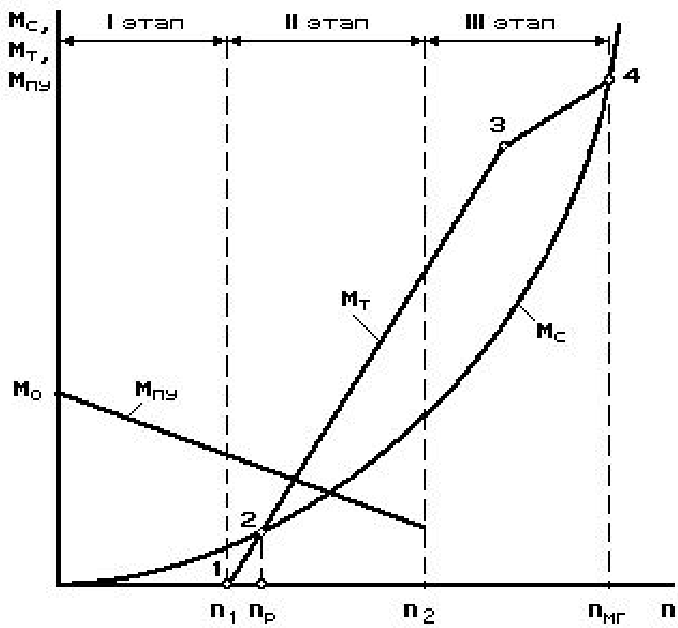

Figure 2.2 - Engine start diagram

There are three characteristic stages on the startup diagram:

Stage I - cold scrolling of the GTE rotor by the starting device;

Stage II - support stage;

Stage III - the stage of the engine's independent entry to idle mode under the influence of excess turbine torque.

At the first stage, the rotor of the engine is forcibly rotated by the starting device. The working fuel does not enter the combustion chamber.

At the beginning of stage II, at the engine rotor speed $n = n_1$, the working fuel supplied to the combustion chamber ignites, as a result of which the temperature of the gases $T^*_Г$ rises and a torque $M_Т$ occurs on the turbine rotor. The rotor of the engine spins up from two sources of mechanical energy - the engine turbine and the starting device, which during the entire II stage operates in the turbine tracking mode.

Inside stage II, there is a characteristic rotational speed $n_Р$, at which dynamic equilibrium takes place, i.e. equality of the moments of the turbine and resistance($M_Т$= $M_С$). However, at this rotational speed, the starting device cannot be turned off, since this equilibrium is unstable and any random deviation of the rotational speed from the value of $n_Р$ will lead either to stop the engine or to an unacceptably slow acceleration of the rotor with the possibility of "hot" or "cold" hovering. Stage II ends by turning off the starter at the rotor speed n_2, upon reaching which the excess torque $M_{ИЗБ} = M_Т – M_С$ can provide independent engine output to idle mode in a short time and with stable operation of its units.

At the end of stage III, at $n = n_{МГ}$, a stable dynamic equilibrium of the rotor takes place ($M_Т$= $M_С$). In case of any deviation of the rotational speed from the equilibrium value by the value Δn, an automatic return to the initial rotational speed will be ensure under the influence of the difference in the $M_Т – M_С$ torques of the corresponding direction.

The dosage of fuel into the engine when it is started is carried out in such a way as to prevent the temperature of the gases in front of the turbine $T_Г$ from exceeding the limit value according to the conditions of the gas-dynamic stability of the compressor and the strength of the turbine rotor parts. 200 K.

Calculation of the required power of the starting device

The purpose of the calculation is to determine the required maximum power of the starting device, build a start diagram and determine the start time.

Determination of the required maximum power of the starting device. An accurate determination of the required power of the starting device is possible on the basis of the theory of power machines of the corresponding type.

In preliminary calculations, the required maximum power of the starting device $N_{ПУmax}$ can be estimated using the statistical data of the completed designs of starting devices. On the basis of statistical data, the values of the specific powers of the starting devices are determined:

$$N^{*}_{ПУ} = \frac{N_{ПУ..max}}{P_{max}},$$

Where P_{max}— thrust (kN) of the engine at maximum mode.

The specific power of the starting devices has the following meaning for the TGD with a thrust of more than 10 kN:

$$N^{*}_{ПУ} = 0{,}8 – 1{,}2 \text{ kV/kN}.$$

The required maximum values of the starting device power are calculated by the formula:

$$N_{ПУ.max} = N_{ПУ} * P_{max} = 0{,}8*141{,}83 = 113{,}46 \text{ kV}.$$

Determination of the moment of the starting device $M_{ПУ}(n)$

When solving this problem, the relationship equation between the power of the starting device and the torque applied to the rotor of the engine is used:

$$N_{ПУ} = M_{ПУ}\omega = \pi M_{ПУ}\, n/ 30 \qquad (2.1)$$

The type of the $M_{ПУ}(n)$ depends on the type of the used trigger. An ATS used on the engine under design is characterized by a decrease in $M_{ПУ}$ with an increase in the engine rotor speed, approximately according to a linear law of the form:

$$M_{ПУ}(n) = M_0 - bn$$

where M_0, b are constants that must be determined to solve the problem.

Using equation (3.1) for the considered variant, obtain

$$N_{ПУ} = \pi (M_0 - bn)\, n / 30 \qquad (2.2)$$

It follows from formula (3.2) that $N_{ПУ} = 0$ at n=0 or $M_0 - bn = 0$.

To determine the maximum of function (3.2), we determine its first derivative:

$$dN_{ПУ} / d_n = \pi(M_0 - 2bn)/30$$

At $dN_{ПУ} / dn = 0$

Then $(M_0 - bn_M) = 0$ we find the rotor speed n_M corresponding to the maximum power of the starting device:

$$n_M = M_0 / 2b. \qquad (2.3)$$

The value of n_M is determined from statistical data through the rotor speed n_2:

$$n_2 = n\cdot_2\, n_{TK} = 0.43*9245 = 3975{,}35 \text{ rpm};$$

$$n_M = n_2 / k = 3975{,}35/1.5 = 2650{,}23 \text{ rpm};$$

where n^*_2 = 0.43 is the relative rotor speed at the moment the starting device is turned off; k = 1.5 is the statistical coefficient for ATS.

From here we find the initial moment of the starting device M_0:

$$M_0 = \frac{60N_{ПУ.\max}}{\pi n_М} = \frac{60 \times 113460}{3{,}14 \times 2650{,}23} = 818{,}05(Н \cdot М);$$

Substituting the value of $n_М$ into the accepted linear dependence for the $M_{ПУ}$, we get:

$$M_{ПУ}(n_М) = M_0 - bn_М = M_0 / 2 = 409\, Н \cdot М$$

The constant b for the linear function $M_{ПУ}(n)$ is obtained by the formula:

$$b = \frac{30N_{ПУ.\max}}{\pi n_М^2} = \frac{30 \times 113460}{3.14 \times 2650.23^2} = 0{,}154 .$$

Determination of the moment of resistance of the rotor to rotation

The problem is solved according to the condition of the power balance on the rotor when the engine is running at idle mode. The main resistance to rotation during start-up is provided by the compressor rotor. Part of the power (no more than 20 - 30%) is spent on the drive of the engine units and overcoming the friction forces in the bearings of the bearings and pumping air through the low pressure compressor.

Thus, we can write:

$$M_С = (1{,}2\ldots1{,}3)M_К$$

where $M_К$ is the moment of resistance to rotation of the compressor rotor, for which a quadratic dependence is taken:

$$M_К = cn^2, \tag{2.4}$$

The power spent on rotation of the compressor in idle mode is determined by the ratio known from the thermodynamics of the TFE:

$$N_{К.МГ} = \frac{(L_{АД.К} G_{В})_{МГ}}{\eta_{К.МГ}}$$

where $L_{АД.К}$ - adiabatic operation of the compressor in idle mode;

$G_{В}$ - air consumption in the same mode;

$\eta_{К}$ - compressor efficiency.

On the other hand, from equation (2.1), taking into account formula (2.4), it follows:

$$N_{К,МГ} = \frac{\pi}{30} M_{К,МГ} n_{МГ} = \frac{\pi}{30} C n_{МГ}^{3} \qquad (2.5)$$

Equating the right-hand sides of relations (2.5) and (2.6), we obtain the formula for calculating the constant C:

$$C = \frac{30}{\pi} \cdot \frac{(L_{АДК} G_{В})_{МГ}}{\eta_{К} n_{МГ}^{3}} \qquad (2.6)$$

All values in parentheses in this formula must be in idle mode. They are determined by the throttle characteristics of the engine. For an approximate estimate of the constant C, the indicated values can be used, corresponding to the calculated (maximum) mode:

$$C = \frac{30}{\pi} . \frac{596430 \times 71{,}23}{0{,}89 \times 9245^{3}} = 5{,}77 \times 10^{-4}$$

With a known constant C, the moment of resistance is:

$$M_{C}(n) = 1{,}25 C n^{2}$$

Determination of the moment of the turbine $M_{T}(n)$

Reliable data for determining the $M_{T}(n)$function can be obtained only on the basis of bench tests of the turbine unit or the engine as a whole. In approximate calculations, this function is approximated by segments of two straight lines passing through known points on the $M_{C}(n)$ curve (Figure 2.4). The turbine moment for the second stage of the $M_{тII}$ start-up is determined by the straight line segment drawn through points 1 and 2. The straight line segment for the M_{TIII} moment (the III start-up stage) is drawn through the points 3 and 4. In this case, we take:

$$n_1 = n^*_1\, n_{max} = 0{,}19*9245 = 1756{,}6 \text{ rpm};$$

$$n_P = n^*_P\, n_{max} = 0{,}23*9245 = 2126{,}35 \text{ rpm};$$

$$n_2 = n^*_2\, n_{max} = 0{,}43*9245 = 3975{,}35 \text{ rpm};$$

$$n_{МГ} = n^*_{МГ}\, n_{max} = 0{,}6*9245 = 5547 \text{ rpm}.$$

Calculating start time

The calculation is carried out using the equation of dynamics of unsteady rotational motion of the rotor (Newton's second law for rotation of a body with acceleration), according to which the moment of inertia of a rotating rotor M_J is equal to the product of its mass polar moment of inertia J_P by angular acceleration:

$$M_J = J_P \frac{d\varphi}{dt} \tag{2.8}$$

Using another formula for writing equation (2.8):

$$M_J = J_P \frac{d\omega}{dt} = \frac{\pi}{30} J_P \frac{dn}{dt}$$

Then:

$$dt = \frac{\pi}{30} J_P \frac{dn}{M_J}$$

We find the launch time by integrating this ratio:

$$t_{ЗАП} = \frac{\pi}{30} \mathrm{J}_P \frac{n_{МГ} dn}{M_J(n)} \tag{2.9}$$

In accordance with Newton's third law, the moment of inertia forces opposing the accelerated rotation of the rotor must be overcome by the excess torque supplied to the rotor (with respect to the condition of uniform rotation).

Excess torques can be determined using the trigger diagram (see Figure 2.4) using the following formulas:

- for the I stage of launch $M_{JI}(n) = M_{ПУ} - M_C$;

- for the II stage of launch $M_{JII}(n) = M_{ПУ} + M_T - M_C$;

- for the III stage of launch $M_{JIII}(n) = M_T - M_C$.

It is convenient to calculate the start time as the sum of the durations of three stages:

$$t_{ЗАП} = t_I + t_{II} + t_{III}$$

$$t_{ЗАП} = \frac{\pi}{30} J_p \left[\int_0^{n_1} \frac{dn}{M_{JI}(n)} + \int_{n_1}^{n_2} \frac{dn}{M_{JII}(n)} + \int_{n_2}^{n_{МГ}} \frac{dn}{M_{JIII}(n)} \right] \quad (2.10)$$

The integrals in this formula can be found by numerical methods, for example, the method of rectangles, according to which the integration interval is divided into several sections, and then the products of discrete values of the integrand and the final increments of the rotor speed Δn are summed up.

The scheme of dividing the diagram of excess moments for the first stage of the launch into sections is shown in Fig. 2.6

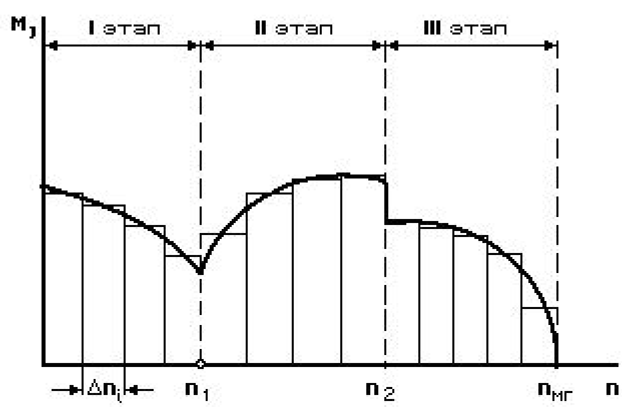

Figure 2.6 - Excess moments diagram

The numerical integration formula for this stage is as follows:

$$\int_{0}^{n_1} \frac{dn}{M_{j\mathrm{I}}(n)} = \sum_{i=1}^{K} \frac{\Delta n_i}{M_{j\mathrm{I}}(n_i)}$$

For the first and second stages of the launch with a relatively smooth change in the moments $M_{\mathrm{J.I}}$ and $M_{\mathrm{J.II}}$, sufficient accuracy of numerical integration can be obtained with the number of sections k = 4, and for the third stage with k = 5.

The mass polar moment of inertia of the high pressure rotor is defined below:

$$J_{\mathrm{Р,ВД}} = J_{\mathrm{Р.К}} + J_{\mathrm{Р.Т}}$$

$$J_{Р,К} = K_{КВД} \cdot Z_{КВД} \cdot D_{КВД}^{4} = 4 \cdot 13 \cdot 0{,}71 = 13{,}22 кg \cdot м^{2}$$

Table 2.7 - Results of calculations of start time

Data	I stage				II stage				III stage				
Δn, rpm	439	439	439	439	555	555	555	555	314	314	314	314	314
$M_{j,\ Nm}$	700	630	550	465	470	520	520	520	275	250	200	90	45
Δt, c	1.84	2.0	2.34	2.7	3.4	2.9	2.9	2.9	2.97	3.1	4.6	6.3	16

- Cold scrolling time: $t_{\mathrm{ХП}}$ = 8.84 s.
- Operating time of the starting device: $t_{\mathrm{ПУ}}$ = 20.94 s.
- Start time: $t_{\mathrm{ЗАП}}$ = 53.81 s.

Conclusion: The starting time $t_{\mathrm{ЗАП}}$ = 53.81 obtained as a result of the calculations corresponds to the technical specifications for the GTE starting systems.

2.6.2. Engine oil system

The engine lubrication system performs the following functions :

-provides the supply of the required amount of oil for lubrication of rubbing engine parts (bearings of bearings and drive, gearing of gearboxes and drives, etc.), regardless of the conditions and modes of flight;

-cools heated parts and removes heat to the environment;

-removes wear products of rubbing pairs from the engine ;

-provides control of the technical condition of the engine by the content of wear products.

-protect parts from corrosion [11].

The venting system is designed to remove air from the oil cavities into the atmosphere or the gas-turbine engine flow path and clean this air from oil with the latter returning to the engine oil system. The cavities are connected to the atmosphere using a prompter, in which, under the action of centrifugal forces, liquid oil is released from the oil emulsions The oil from the prompter is returned to the engine, and gases and vapors are removed to the atmosphere.

Lubrication systems for aircraft gas turbine engines are subdivided according to the principle of operation into open and circulating. In an open-loop system, the oil is used once and the atmosphere is vented after being fed into the engine.

In the circulating system, after cleaning, air separation and cooling, the oil returns to the engine again, i.e. it is used repeatedly.

In civil aviation engines, only circulation systems are used, made in a closed or short-circuited circuit. In a closed-circuit lubrication system, the oil, after passing through the engine, completely returns to the oil tank, and according to the short-circuit circuit, only a small part of the oil (10-15%) returns to the tank to heat the reserve amount of oil, and the main amount of oil moves through the circulating loop without returning to the tank. The oil tank in short-circuited systems is used to store a reserve amount of oil used to feed the main circulation circuit. In addition, a distinction is made between open and closed systems. In an open system, the oil tank is connected directly to the atmosphere, and in a closed system to ensure the height of the system, the tank is connected to the atmosphere through a valve that maintains an overpressure of 0.02 ... 0.05 MPa in it. The engine being designed uses a closed, closed circulation oil system, consisting of an oil tank, a main oil pump OMH-30, a mesh filter МФС-30 24, evacuating oil pumps MHO-I and MHO-3OK, a centrifugal air separator with a filter - ЦВС-30 signaling device, ЦС-3OK centrifugal prompter and 4845T fuel-oil cooler.

All units of the oil system are mounting on the engine and when installing the engine on an aircraft, additional connections to the aircraft systems are not required. When the engine is running, oil from tank 1 is supplyed to the main oil pump. This pump includes a pumping and pumping out stage; a pressure reducing valve adjusted to a maximum pressure of 0.45 MLa; a non-return valve, adjusted to a pressure of 0.05 to 0.06 MPa and designed to prevent the possibility of oil flowing from the oil tank into the engine when the aircraft is parked; valve designed to remove air from the channel at the inlet to the injection stage.

Oil from the delivery stage of the main pump enters the strainer, in which a bypass valve is installed, which allows oil to pass into the engine when the filter is clogged.

After passing through the filter, oil enters the engine in the following five directions:

-along the outer pipeline and the channel of the inlet duct blade for lubricating the ball bearing of the front support of the LPC and along the inner tube passing inside the coupling and connecting bolts for lubricating the intermediate roller bearing of the low pressure pump;

-through the inner channels of the front drive box and the separating housing for lubricating the bearings and gears of the front drive box and the central drive, as well as lubricating the ball bearing of the rear support of the LPC, the ball bearing of the front support of the HPC.

-through the external pipeline for lubrication of bearings and gear wheels of the rear drive box;

-through the external pipeline to the turbine shaft casing for lubrication of the ball bearing of the HPC rear support and the roller bearing of the HPT rotor support;

-through the external pipeline for lubrication of the roller bearing of the rear support of the LPT rotor.

To ensure that an increase in flight altitude does not lead to a decrease in oil pumping through the engine, the injection stage is designed so that the capacity of the main oil pump exceeds the required oil pumping through the engine by 1.5 ... 2.5 times. The excess oil supplied by the pump is bypassed by the pressure reducing valve to the pump inlet. As a result of a decrease in the productivity of the injection stage, as the flight altitude increases, the amount of by-passed oil decreases, which is achieved by covering the reduction valve. When the flow rate becomes equal to the required oil pumping through the engine, the pressure reducing valve is completely closed. A further increase in flight altitude leads to an even greater decrease in pressure and pumping of oil through the engine. Under the action of the rotating parts of the engine and under the influence of partial evaporation, the oil foams, its volume increases and several times exceeds the initial one, therefore, the lubrication system of the engine being designed has six pumping stages and only one pumping stage. The total capacity of the pumping stages at the nominal operating mode of the engine is 300 l / min, and the capacity of the pumping stage of the main pump is 110 l / min.

The separation of air and gases from the oil in the lubrication system is achieved using a centrifugal air separator.

The return of oil to the tank is as follows:

-from the cavity of the LPC front support, oil is pumped out by an oil pump and enters through the channels of two blades and then through an external pipeline into the control panel cavity;

-from the distribution housing and the control panel, the oil is pumped out by the evacuation stage of the main oil pump 34 and enters the centrifugal air separator;

-from the gearbox, from the cavities of the shaft casing and the rear support of the injection pump, oil is pumped out by a four-stage pump 28 and also enters the centrifugal air separator.

The oil, separated from the air in the centrifugal air separator and cleaned from mechanical particles in the filter and signaling device included in the design of the centrifugal air separator, flows through an external pipeline for cooling to the fuel-oil radiator. Cooled oil flows from the radiator to the oil tank.

Air-oil emulsion from the centrifugal air separator is discharged to the control panel.

If the oil filter or the signaling filter is completely clogged, the oil will bypass the filters through the bypass valves.

The venting system consists of channels and pipelines connecting the cavities of the separating body, control panel, shaft casing, gearbox, rear support of the injection pump and an oil tank with a centrifugal breather. Air from the breather enters the atmosphere through an external pipeline. The centrifugal prompter maintains an overpressure in the vented cavities of the engine and in the oil tank equal to 0.045 MPa.

The oil pressure in the lubrication system is measured after the injection stage of the main oil pump after the mesh filter by the IDT-8 sensor included in the set of the EMI-ZRTI electric inductive motor indicator, which is installed in the cockpit.

The oil temperature is measured at the inlet to the injection stage of the main oil pump by the П-63 receiver, also included in the ЭМИ-ЗРТИ kit.

In addition, the oil system is equipped with a minimum oil pressure indicator at the engine inlet МСТВ-2, adjusted to a pressure of (0.22 0.045) MPa; a thermal signaling device installed in the line for pumping oil from the cavity of the rear support of the HPC and having a signal lamp in common with the filter-signaling device. The measurement of the oil reserve in the tank is carried out by the ДТПР sensor of the lever-float oil meter МЭС-2247Д. The ДТПР sensor has a signaling device that gives a signal when the oil level in the tank (6±1) l is reached (excluding 8 l of oil in the negative overload compartment).

Conclusion on the design part

1. The engine under design is a turbojet two-circuit twin-shaft engine without mixing the air and gas flows of the external and internal circuits, which have separate jet nozzles and a thrust reversal device.

2. The radial dimensions of the engine elements are obtained from the gas-dynamic calculation. But after clarification, the specific fuel consumption and thrust do not coincide with the results from the thermodynamic calculation, i.e. the specific fuel consumption $C_{УД}$ was reduced from $0{,}0385 кг/Н \cdot ч$ to $0{,}0367 кг/Н \cdot ч$, the thrust was increased from 135.25kN to 141.83kN due to the difference in the clarity of the method.

3. After constructing the root section of the first turbine supene blade, he calculated the strength of its disk and obtained a safety factor of 1.34.

4. According to the development of the starting system, the starting time $t_{ЗАП}$ = 53.81 was obtained; it corresponds to the specifications for the GTE starting systems.

3.Methods of increasing the fuel efficiency of gas turbine engines

3.1. Analysis of general methods for increasing fuel efficiency power installations of the aircraft

The fuel efficiency of power plants has a direct impact on the economic performance of airlines, since the share of fuel costs in the structure of operating costs is very high.

The main parameter that characterizes the fuel efficiency of an engine is the specific fuel consumption. From the point of view of the development of aircraft construction, scientists are constantly trying to reduce the specific fuel consumption, and this is explained from Fig. 3.1, over the past 30 years, the specific fuel consumption 3has decreased by 31%, i.e. from $0{,}69\textit{кг}/\text{кгс}\cdot\text{ч}$ to $0{,}48\textit{кг}/\text{кгс}\cdot\text{ч}$.

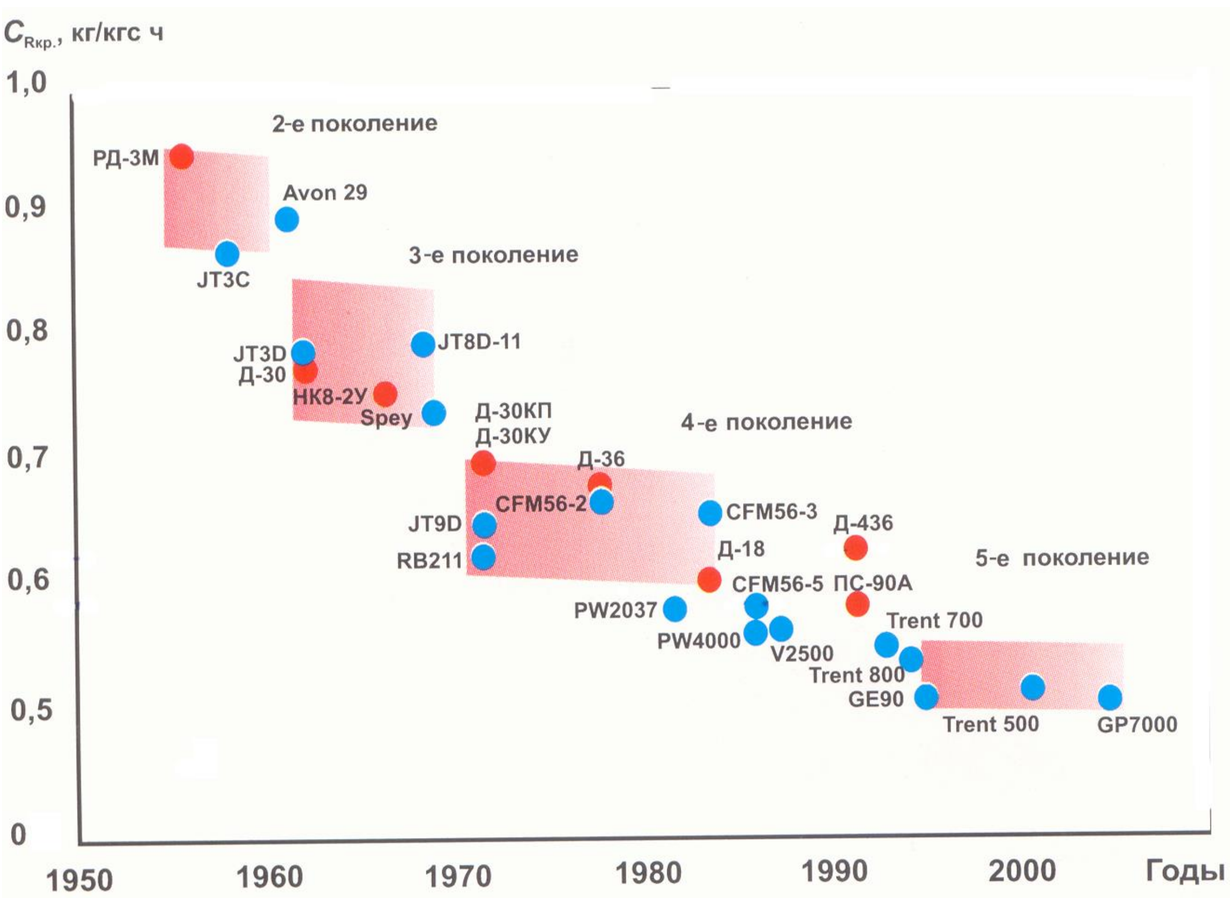

Figure 3.1. - Change in specific fuel consumption by years [12]

As shown in the thermal and gas-dynamic calculations, the specific fuel consumption is determined by the level of the parameters of the turbojet engine operating cycle.

Firstly, $\pi_K^*, T_Г^*$ and m , as well as the efficiency of its components (compressor, turbine, combustion chamber, etc.). Therefore, the main ways to improve the fuel efficiency of the turbojet engine are:

- temperature rise of gases in front of the turbine $T_Г^*$;

- increasing the degree of air pressure increase in the engine $\pi_{\Sigma к}^*$;

- increasing the degree of bypass m;

- increasing the efficiency of compressor, η_K, turbine η_T, combustion process $\eta_{K.C.}$;

- the use of new, more efficient fuels.

The temperature of the gases in front of the turbine is a very important parameter. An increase in gas temperature leads to an increase in specific thrust and a decrease in specific fuel consumption.

At the same time, an increase in the gas temperature leads to the need to develop constructive measures to ensure the reliable operation of parts of the "hot" part of the engine and to improve the technology of manufacturing turbine parts. Operational experience shows that a significant number of defects are associated with the thermal load of the turbine and combustion chamber parts. Measures to ensure reliable operation at high temperatures are:

- effective cooling of parts of the "hot" part of the engine;

- the use of more heat-resistant materials;

- active control of radial clearances.

Increasing the degree of air pressure increase in the compressor is an effective means of increasing the gas turbine engine efficiency. To increase the efficiency of the thermodynamic cycle, a strict combination of the degree of bypass, the degree of increase in air pressure in the compressor and the temperature of the gases in front of the turbine is required.

Attaching additional masses of the working fluid to the main engine circuit makes it possible to significantly reduce the specific fuel consumption. While a significant increase in the bypass ratio of the engine leads to an increase in the diameter of the fan, the loads acting on the rotor blades, and the number of stages of the fan turbine.

All this leads to a significant increase in engine mass. But if we have expediently chosen bypass ratio, then this problem can be solved.

In addition to these traditional methods, scientists in the United States are now investigating a new method that increases the efficiency and efficiency of the motor. We know that usually the cooling air into the turbine is taken from the HPC. The more air is taken from the internal circuit, the less the efficiency of the engine. Therefore, scientists and designers are trying to take cooling air from the external circuit. In this case, the pre-compression of the cooling air is carried out in a separate small-sized drive compressor. But the constructive development has not yet been completed. Therefore, this method of improving fuel efficiency is not used in this project. But improving the fuel efficiency of the engine by reducing air intake for cooling can be achieved by improving the cooling system of the turbine blade. Below we will take a closer look at such a new cooling system, namely microcirculation cooling.

3.2. Application of microcirculation cooling method

The authors propose (US Pat. No. 2004/0151587A1.) [14] instead of the traditional cooling method and design shown in Fig. 3.2, use a microcirculation cooling system.

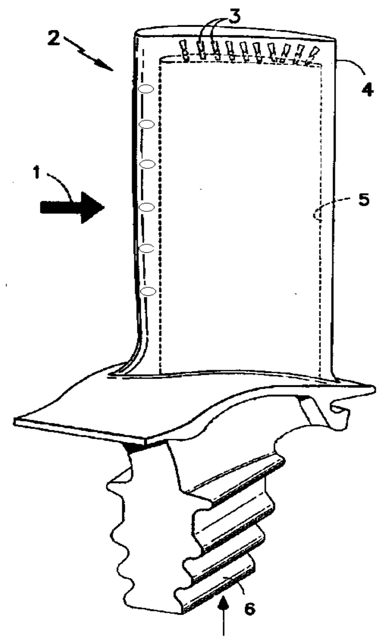

Figure: 3.2 Conventional turbine blade

In the traditional method, the cooling air supplied through the holes in the tail (pt.6) is fed into the inner longitudinal channels of the airfoil of the blade, and then passes partially to the hole (pt.3) in the tip of the blade and then into the gas-air duct (convective cooling method). However, the efficiency of the convective method is not high enough, therefore, in the 90s of the last century, cooling was used. With this method, the cooling air is partially removed through the holes (pt.2) from the leading edge and creates a film to prevent direct contact of hot gases with the blade surface. Despite the high cooling efficiency, this method has and still has a drawback: the effective profile thickness increases by the thickness of the cooling film. As a result, the efficiency of the stage decreases, which negatively affects the fuel efficiency of the engine. Therefore, the patent proposes to use the convective cooling method, but at a new level: instead of 3-4 radial channels, as it was in the traditional method (Fig.3.2), use a highly developed system of microcirculation channels located under the blade surface (Fig.3.3 and fig 3.4).

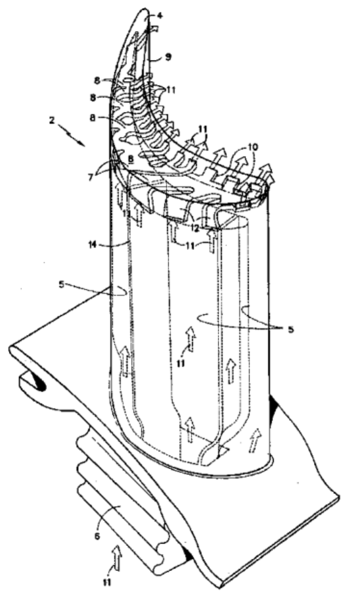

Figure 3.3 - Blade with microcirculation cooling

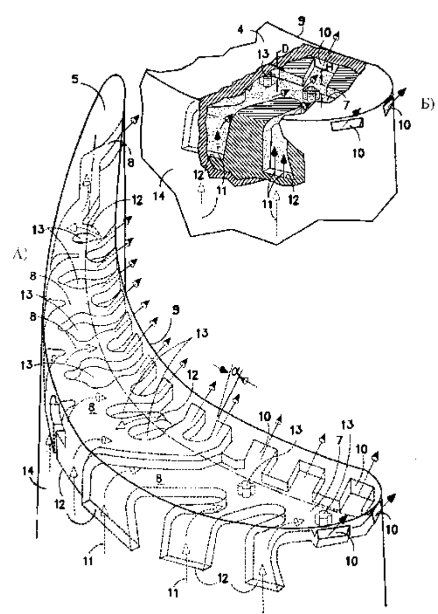

Figure 3.4 – A) General view of the blade end

B) Enlarged view of the blade end on the leading edge

In the cooling system of the present invention (Fig.3.4), at least one cavity (pt.7), which is transversely located between the trough of the blade (pt.9) and the back of the blade (pt.14). Many inlets (pt.12) and outlets (pt.10) are connected to the cavity (pt.7). Cooling air (pt.11) from the cavity (pt.5) flows through the inlets (pt.12), passes into the cavity (pt.7) and is ejected through outlets (pt.10). The cavity (pt.7) contains many micro-passages (pt.8) through which the cooling air (pt.11) flows.

Compared with the traditional paddle shown in Figure 3.2, the present invention has the following advantages :

-the cooling air (pt.11) through the inlets (pt.12) hits the end of the vane (pt.4) close to the back of the vane (pt.14). This is very important because there is always a vortex at the end of the back of the vane (pt.14), which leads to high temperatures. In addition, the shape of the separate inlets (pt.12) can reduce the intake of air from the compressor by 0.5%. This means that it is possible to increase the efficiency of the turbojet engine and its fuel efficiency.

-subsonic cooling air (pt.11) is accelerated in the converging micro-passage (pt.8), so the rate of heat transfer increases and the efficiency of heat transfer from the surface of the channels increases.

-the present invention has rectangular expansion outlets (pt.10) directed at an angle of about horizontal. This shape leads to an increase in the cooling area of the film at the end of the blade (pt.4) and a decrease in the flow of gas (pt.1) through the end of the blade (pt.4).

-in the cavity (pt.7), bases (pt.13) are used, which lead to turbulences of the cooling air (pt.11) and increase the heat conduction area.

-its known that for most conventional blades, there are holes at the leading edge that form layers of air cooling, which leads to an increase in the effective thickness of the turbine blade. The greater the blade thickness, the lower the turbine efficiency.

The stylish design only accepts film cooling at the end of the blade. Therefore, it is possible to slightly increase the efficiency of the turbine and obtain a higher fuel efficiency of the engine.

For these purposes, must used refractory metals Molybdenum and Walfram, which have sufficient ductility at high temperatures. The plastic foil can form a suitable shape for the micropass. The separately cast back of the blade with microchannels formed in it is then welded along the leading and trailing edges to the main body of the blade, which includes: a shank, an inner shelf and a profile part of the blade with a trough. For the outlet of the cooling air, it is necessary on the surface of the trough at the end of the profile (pt.4).

After registration of the micropassage, its need to remove the filler by chemical methods. In general, the application of this invention increases not only the blade life, but also the fuel efficiency, turbine efficiency and the overall efficiency of the GTE.

3.3. Assessment of the influence of the relative amount of air sampling $g_{охл}$ on the specific fuel consumption $C_{уд}$

Let estimate the influence of the relative amount of air taken for cooling $g_{охл}$ of the turbine parts on the specific fuel consumption $C_{уд}$ and internal efficiency of the engine η_e at a constant efficiency of the turbine $\eta_T^* = 0{,}92$, as was assumed in the thermodynamic calculation.

In this case, we will compare the values $C_{уд}$ and η_e for different $g_{охл}$.

1. With a decrease $g_{охл}$ of 0.5% from the original

Then $g_{охл}$ = 0.085

a) determination of gas parameters behind the turbine (section T-T)

We take the value of the mechanical efficiency $\eta_M = 0{,}995$, determine the effective operation of all stages of the TFE turbine:

$$L_T = \frac{mL_{ВЛ_{II}} + L_K}{(1+g_T)(1-g_{охл})\eta_M} = \frac{5{,}5 \cdot 50777 + 596430}{(1+0{,}0223)(1-0{,}085)0{,}995} = 940880{,}7\,\frac{Дж}{кг};$$

taking the efficiency of the turbine $\eta_M = 0{,}995$, we calculate the temperature and pressure of the gas behind the turbine:

$$T_T^* = T_Г^* - \frac{K_Г - 1}{K_Г}\frac{L_T}{R_Г} = 1600 - \frac{1{,}333-1}{1{,}333} \cdot \frac{940880{,}7}{288} = 783{,}26(K);$$

$$P_T^* = P_Г^*\left[1 - \frac{T_Г^* - T_T^*}{T_Г^* \cdot \eta_T^*}\right]^{\frac{K_Г}{K_Г - 1}} = 3194270\left[1 - \frac{1600 - 783{,}26}{1600 \cdot 0{,}92}\right]^{\frac{1{,}333}{1{,}333-1}} = 125428{,}1(Па);$$

b) determine the parameters of the working fluid in the outlet section of the nozzle of the inner contour (section S_1- S_1)

determine the pressure drop in the jet nozzle of the inner loop and compare it with the critical

$$\pi_T = \frac{P_T^*}{P_H} = \frac{125428{,}1}{101325} = 1{,}24 < \pi_{C_{КР}} = 1{,}85;$$

Consequently, the expansion in the jet nozzle is complete $P_C = P_H$, and the rate of gas outflow from the nozzle is calculated by the formula:

$$C_{C_1} = \varphi_{C_1}\sqrt{2\frac{K_Г}{K_Г - 1}R_Г T_T^*\left[1 - \left(\frac{P_H}{P_T^*}\right)^{\frac{K_Г - 1}{K_Г}}\right]};$$

$$C_{C_1} = 0{,}98\sqrt{2\frac{1{,}333}{1{,}333-1}288 \cdot 783{,}26\left[1 - \left(\frac{101325}{125428{,}1}\right)^{\frac{1{,}333-1}{1{,}333}}\right]} = 300{,}1\,м/с;$$

find the static temperature:

$$T_C = T_T^* - \frac{K_Г - 1}{K_Г}\frac{C_{C_1}^2}{2R_Г} = 783{,}26 - \frac{1{,}333 - 1}{1{,}333}\cdot\frac{300{,}1^2}{2\cdot 288} = 744{,}17K;$$

c) determination of the main specific parameters of the engine and air consumption, calculate the specific thrust of the internal contour:

$$P_{УД_1} = C_{C_1}(1 + g_T) = 300{,}1(1 + 0{,}0223) = 306{,}79\frac{Н\cdot с}{кг};$$

calculate the specific thrust of the outer contour:

$$P_{УД_{II}} = C_{C_{II}} = 292{,}67\frac{Н\cdot с}{кг};$$

calculate the specific thrust of the TFE:

$$P_{УД_\Sigma} = \frac{P_{УД_1} + mP_{УД_{II}}}{1+m} = \frac{306{,}79 + 5{,}5\cdot 292.67}{1+5{,}5} = 294{,}84\frac{Н\cdot с}{кг};$$

we calculate the specific fuel consumption:

$$C_{УД} = \frac{3600\cdot g_T(1 - g_{охл})}{P_{УД_\Sigma}(1+m)} = \frac{3600\cdot 0{,}0223(1 - 0{,}085)}{294{,}84(1+5{,}5)} = 0{,}0383(кг/Н\cdot ч);$$

air consumption is found from the ratios:

$$G_B = \frac{P}{P_{УД_\Sigma}} = \frac{135250}{294{,}84} = 458{,}72(кг/с);$$

$$G_{B_1} = \frac{G_B}{1+m} = \frac{458{,}72}{1+5{,}5} = 70{,}57(кг/с);$$

$$G_{B_{II}} = \frac{m}{m+1}G_B = \frac{5{,}5}{5{,}5+1}458{,}72 = 388{,}15(кг/с)$$

calculate the internal efficiency of the TFE:

$$\eta_e = \frac{P^2_{УД_1} + mP^2_{УД_{II}}}{2g_T H_U (1 - g_{охл})} = \frac{306{,}79^2 + 5{,}5 \cdot 292{,}67^2}{2 \cdot 0{,}0223 \cdot 42{,}5 \cdot 10^6 (1 - 0{,}085)} = 0{,}326;$$

Conclusion: $C_{УД}$ reduced from $0{,}0385 кг/Н \cdot ч$ to $0{,}0383 кг/Н \cdot ч$, i.e. on 0,52%.

2. With a decrease $g_{охл}$ of 1% from the original

Then $g_{охл}$ = 0,08

a) determination of gas parameters behind the turbine (section T-T)

determine the effective operation of all stages of the TFE turbine :

$$L_T = \frac{mL_{ВЛ_{II}} + L_K}{(1 + g_T)(1 - g_{охл})\eta_M} = \frac{5{,}5 \cdot 50777 + 596430}{(1 + 0{,}0223)(1 - 0{,}08)0{,}995} = 935767{,}2 \frac{Дж}{кг};$$

calculate the temperature and pressure of the gas behind the turbine:

$$T^*_T = T^*_Г - \frac{K_Г - 1}{K_Г}\frac{L_T}{R_Г} = 1600 - \frac{1{,}333 - 1}{1{,}333} \cdot \frac{935767{,}2}{288} = 787{,}7(K);$$

$$P^*_T = P^*_Г \left[1 - \frac{T^*_Г - T^*_T}{T^*_Г \cdot \eta^*_T}\right]^{\frac{K_Г}{K_Г - 1}} = 3194270\left[1 - \frac{1600 - 787{,}7}{1600 \cdot 0{,}92}\right]^{\frac{1{,}333}{1{,}333-1}} = 128862{,}4(Па);$$

b) Determine the parameters of the working fluid in the outlet section of the nozzle of the inner contour (section $S_1 - S_1$) and determine the pressure drop in the jet nozzle of the inner contour and compare it with the critical

$$\pi_T = \frac{P^*_T}{P_H} = \frac{128862{,}4}{101325} = 1{,}27 < \pi_{C_{КР}} = 1{,}85;$$

Consequently, the expansion in the jet nozzle is complete $P_C = P_H$, and the velocity of gas outflow from the nozzle is calculated by the formula:

$$C_{C_1} = \varphi_{C_1}\sqrt{2\frac{K_Г}{K_Г - 1}R_Г T^*_T\left[1 - \left(\frac{P_H}{P^*_T}\right)^{\frac{K_Г - 1}{K_Г}}\right]};$$

$$C_{C_1} = 0{,}98\sqrt{2\frac{1{,}333}{1{,}333-1}288\cdot 787{,}7\left[1-(\frac{101325}{128862{,}4})^{\frac{1{,}333-1}{1{,}333}}\right]} = 325{,}37\,м/с\,;$$

find the static gas temperature

$$T_C = T_Г^* - \frac{К_Г - 1}{К_Г}\frac{C_{C_1}^2}{2\mathrm{R}_Г} = 787{,}7 - \frac{1{,}333-1}{1{,}333}\cdot\frac{325{,}37^2}{2\cdot 288} = 741{,}75К\,;$$

c) determination of the main specific parameters of the engine and air flow

calculate the specific thrust of the inner contour:

$$P_{УД_1} = C_{C_1}\left(1+g_T\right) = 325{,}37\left(1+0{,}0223\right) = 332{,}63\frac{Н\cdot с}{кг}\,;$$

calculate the specific thrust of the outer contour:

$$P_{УД\,\mathrm{II}} = C_{C\,\mathrm{II}} = 292{,}67\frac{Н\cdot с}{кг}\,;$$

calculate the specific thrust of the TFE:

$$P_{УД_\Sigma} = \frac{P_{УД_1} + mP_{УД\,\mathrm{II}}}{1+m} = \frac{332{,}63 + 5{,}5\cdot 292.67}{1+5{,}5} = 298{,}82\frac{Н\cdot с}{кг}\,;$$

calculate the specific fuel consumption:

$$C_{УД} = \frac{3600\cdot g_T\left(1-g_{охл}\right)}{P_{УД_\Sigma}\left(1+m\right)} = \frac{3600\cdot 0{,}0223(1-0{,}08)}{298{,}82\left(1+5{,}5\right)} = 0{,}038\left(кг/Н\cdot ч\right);$$

air consumption is found from the ratios:

$$G_B = \frac{P}{P_{УД_\Sigma}} = \frac{135250}{298{,}82} = 452{,}6(кг/с)\,;$$

$$G_{B_1} = \frac{G_B}{1+m} = \frac{452{,}6}{1+5{,}5} = 69{,}63(кг/с)\,;$$

$$G_{B_{\mathrm{II}}} = \frac{m}{m+1}G_B = \frac{5{,}5}{5{,}5+1}452{,}6 = 382{,}97(кг/с)\,;$$

calculate the internal efficiency of the TFE:

$$\eta_e = \frac{P^2_{УД_1} + mP^2_{УД_{II}}}{2g_T H_U (1 - g_{охл})} = \frac{332{,}63^2 + 5{,}5 \cdot 292{,}67^2}{2 \cdot 0{,}0223 \cdot 42{,}5 \cdot 10^6 (1 - 0{,}08)} = 0{,}334;$$

Conclusion: $C_{УД}$ reduced from $0{,}0385 кг / Н \cdot ч$ to $0{,}038 кг / Н \cdot ч$, i.e. by 1.3%.

3. With a decrease $g_{охл}$ of 1.5% from the original

Then $g_{охл}$ = 0.075

a) determination of gas parameters behind the turbine (section T-T)

determine the effective operation of all stages of the TFE turbine

$$L_T = \frac{mL_{ВЛ_{II}} + L_K}{(1 + g_T)(1 - g_{охл})\eta_M} = \frac{5{,}5 \cdot 50777 + 596430}{(1 + 0{,}0223)(1 - 0{,}075)0{,}995} = 930708{,}99 \frac{Дж}{кг};$$

calculate the temperature and pressure of the gas behind the turbine:

$$T_T^* = T_Г^* - \frac{K_Г - 1}{K_Г}\frac{L_T}{R_Г} = 1600 - \frac{1{,}333 - 1}{1{,}333} \cdot \frac{930708{,}99}{288} = 792{,}09(K);$$

$$P_T^* = P_Г^* \left[1 - \frac{T_Г^* - T_T^*}{T_Г^* \cdot \eta_T^*}\right]^{\frac{K_Г}{K_Г - 1}} = 3194270\left[1 - \frac{1600 - 792{,}09}{1600 \cdot 0{,}92}\right]^{\frac{1{,}333}{1{,}333 - 1}} = 132326{,}9(Па);$$

b) determine the parameters of the working fluid in the outlet section of the nozzle of the inner contour (section S_1 –S_1)

determine the pressure drop in the jet nozzle of the inner loop and compare it with the critical

$$\pi_T = \frac{P_T^*}{P_H} = \frac{132326{,}9}{101325} = 1{,}3 < \pi_{C_{КР}} = 1{,}85;$$

Consequently, the expansion in the jet nozzle is complete $P_C = P_H$, and the velocity of gas outflow from the nozzle is calculated by the formula:

$$C_{C_1} = \varphi_{C_1} \sqrt{2 \frac{K_Г}{K_Г - 1} R_Г T_T^* \left[1 - \left(\frac{P_H}{P_T^*} \right)^{\frac{K_Г - 1}{K_Г}} \right]};$$

$$C_{C_1} = 0{,}98 \sqrt{2 \frac{1{,}333}{1{,}333 - 1} 288 \cdot 792{,}09 \left[1 - \left(\frac{101325}{132326{,}9} \right)^{\frac{1{,}333-1}{1{,}333}} \right]} = 336{,}38 м/с;$$

find the static gas temperature

$$T_C = T_T^* - \frac{K_Г - 1}{K_Г} \frac{C_{C_1}^2}{2R_Г} = 792{,}09 - \frac{1{,}333 - 1}{1{,}333} \cdot \frac{336{,}38^2}{2 \cdot 288} = 742{,}98 K;$$

c) determination of the main specific parameters of the engine and air flow

we calculate the specific thrust of the inner contour:

$$P_{УД_1} = C_{C_1}(1 + g_T) = 336{,}38(1 + 0{,}0223) = 343{,}88 \frac{Н \cdot с}{кг};$$

calculate the specific thrust of the outer contour:

$$P_{УД_{II}} = C_{C_{II}} = 292{,}67 \frac{Н \cdot с}{кг};$$

calculate the specific thrust of the TFE:

$$P_{УД_\Sigma} = \frac{P_{УД_1} + mP_{УД_{II}}}{1 + m} = \frac{343{,}88 + 5{,}5 \cdot 292{,}67}{1 + 5{,}5} = 301 \frac{Н \cdot с}{кг};$$

calculate the specific fuel consumption:

$$C_{УД} = \frac{3600 \cdot g_T (1 - g_{охл})}{P_{УД_\Sigma}(1 + m)} = \frac{3600 \cdot 0{,}0223(1 - 0{,}075)}{301(1 + 5{,}5)} = 0{,}0379 (кг / Н \cdot ч);$$

air consumption is found from the ratios:

$$G_B = \frac{P}{P_{УД_\Sigma}} = \frac{135250}{301} = 449{,}34 (кг/с);$$

$$G_{B_1} = \frac{G_B}{1+m} = \frac{449,34}{1+5,5} = 69,13(кг/с);$$

$$G_{B_{II}} = \frac{m}{m+1} G_B = \frac{5,5}{5,5+1} 449,34 = 380,2(кг/с);$$

calculate the internal efficiency of the TFE:

$$\eta_e = \frac{P_{УД_1}^2 + mP_{УД_{II}}^2}{2g_T H_U (1-g_{охл})} = \frac{343,88^2 + 5,5 \cdot 292,67^2}{2 \cdot 0,0223 \cdot 42,5 \cdot 10^6 (1-0,075)} = 0,336;$$

conclusion: $C_{УД}$ reduced from $0,0385 кг/Н \cdot ч$ to $0,0379 кг/Н \cdot ч$, i.e. by 1.6%.

Table 3.1 – Systematize the received calculations

$g_{охл}$	0,09	0,085	0,08	0,075
$C_{уд}$ $(кг/н \cdot ч)$	0,0385	0,0383	0,038	0,0379
η_e	0,322	0,326	0,334	0,336

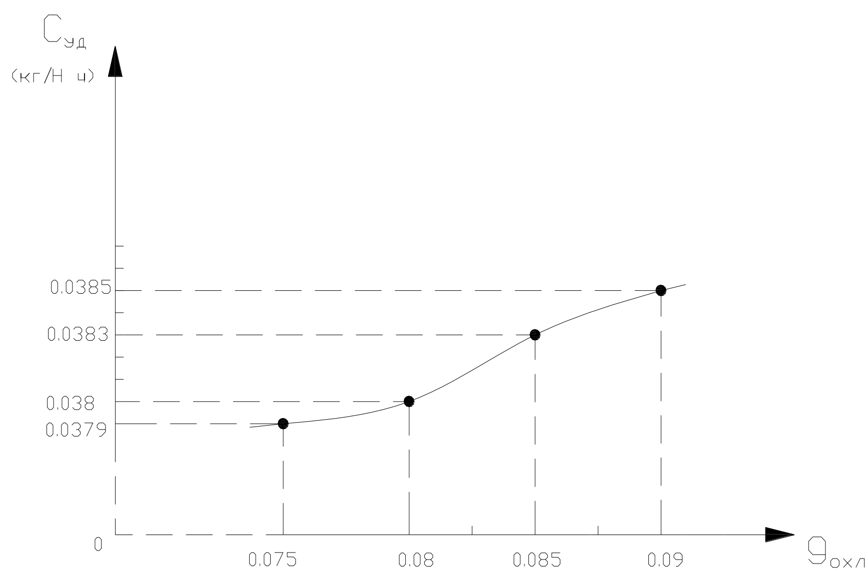

Figure 3.5 - Dependence of specific fuel consumption on the relative amount of air bleed from the compressor

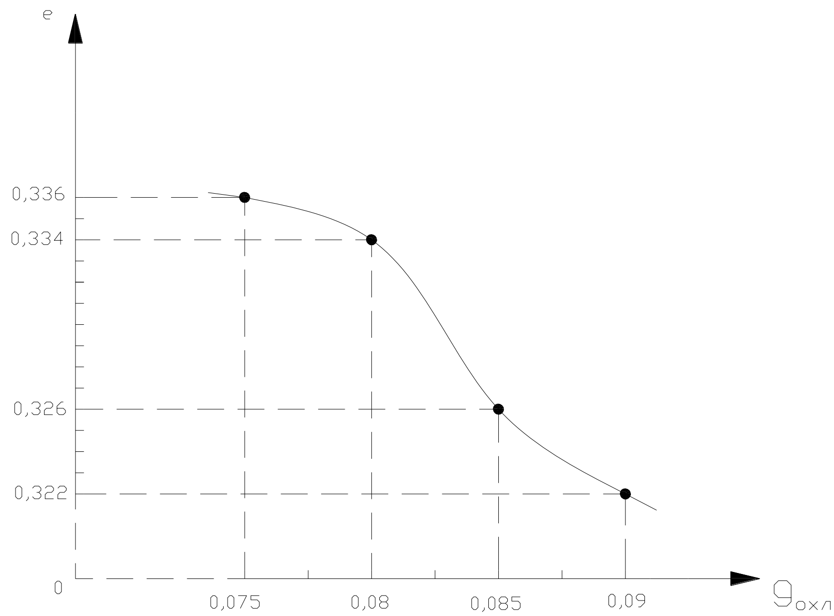

Figure 3.6 - Dependence of the internal efficiency of the engine η_e on the relative amount of air taken from the compressor $g_{охл}$

3.4. Assessment of the influence of the turbine efficiency η_T^* on specific fuel consumption $C_{УД}$

Application of the patent not only leads to a decrease in the relative amount of air intake, but also to an increase in the efficiency of the turbine. Therefore, we will evaluate the influence of the turbine efficiency η_T^* on the specific fuel consumption $C_{УД}$ at $g_{охл} = 0{,}085$.

In this case, we will compare the values $C_{уд}$ and η_e for different η_T^*.

Initial data: $C_{уд} = 0{,}0385 кг/\text{Н} \cdot \text{ч}$ $\eta_T^* = 0{,}92$, , $\eta_e = 0{,}322$.

1. With an increase η_T^* of 0.5% from the original

Then η_T^* = 0.925

a) determination of gas parameters behind the turbine (section T-T)

We take the value of the mechanical efficiency $\eta_M = 0{,}995$, determine the effective operation of all stages of the TFE:

$$L_T = \frac{mL_{ВЛ_{II}} + L_K}{(1+g_T)(1-g_{охл})\eta_M} = \frac{5{,}5\cdot 50777 + 596430}{(1+0{,}0223)(1-0{,}085)0{,}995} = 940880{,}7\,\frac{Дж}{кг};$$

calculate the temperature and pressure of the gas behind the turbine:

$$T_T^* = T_Г^* - \frac{K_Г - 1}{K_Г}\frac{L_T}{R_Г} = 1600 - \frac{1{,}333-1}{1{,}333}\cdot\frac{940880{,}7}{288} = 783{,}26(K);$$

$$P_T^* = P_Г^*\left[1 - \frac{T_Г^* - T_T^*}{T_Г^*\cdot\eta_T^*}\right]^{\frac{K_Г}{K_Г-1}} = 3194270\left[1-\frac{1600-783{,}26}{1600\cdot 0{,}925}\right]^{\frac{1{,}333}{1{,}333-1}} = 128842{,}75(Па);$$

b) determine the parameters of the working fluid in the outlet section of the nozzle of the inner contour (section S_1-S_1)

determine the pressure drop in the jet nozzle of the inner loop and compare it with the critical

$$\pi_T = \frac{P_T^*}{P_H} = \frac{128842{,}75}{101325} = 1{,}27 < \pi_{C_{КР}} = 1{,}85;$$

Consequently, the expansion in the jet nozzle is complete, $P_C = P_H$ and the velocity of gas outflow from the nozzle is calculated by the formula:

$$C_{C_1} = \varphi_{C_1}\sqrt{2\frac{K_Г}{K_Г-1}R_Г T_T^*\left[1-\left(\frac{P_H}{P_T^*}\right)^{\frac{K_Г-1}{K_Г}}\right]};$$

$$C_{C_1} = 0{,}98\sqrt{2\frac{1{,}333}{1{,}333-1}288\cdot 783{,}26\left[1-\left(\frac{101325}{128842{,}75}\right)^{\frac{1{,}333-1}{1{,}333}}\right]} = 317{,}86\,м/с;$$

find the static gas temperature

$$T_C = T_T^* - \frac{K_Г-1}{K_Г}\frac{C_{C_1}^2}{2R_Г} = 783{,}26 - \frac{1{,}333-1}{1{,}333}\cdot\frac{317{,}86^2}{2\cdot 288} = 739{,}4K;$$

c) determination of the main specific parameters of the engine and air flow calculate the specific thrust of the inner contour:

$$P_{УД_1} = C_{C_1}\left(1 + g_T\right) = 317{,}86(1 + 0{,}0223) = 324{,}95\,\frac{Н \cdot с}{кг};$$

Determine the specific thrust of the outer contour:

$$P_{УД_{\text{II}}} = C_{C_{\text{II}}} = 292{,}67\,\frac{Н \cdot с}{кг};$$

Determine the specific thrust of the TFE:

$$P_{УД_\Sigma} = \frac{P_{УД_1} + mP_{УД_{\text{II}}}}{1 + m} = \frac{324{,}95 + 5{,}5 \cdot 292{,}67}{1 + 5{,}5} = 297{,}64\,\frac{Н \cdot с}{кг};$$

Determine the specific fuel consumption:

$$C_{УД} = \frac{3600 \cdot g_T\left(1 - g_{охл}\right)}{P_{УД_\Sigma}\left(1 + m\right)} = \frac{3600 \cdot 0{,}0223(1 - 0{,}085)}{297{,}64(1 + 5{,}5)} = 0{,}0379\left(кг / Н \cdot ч\right);$$

air consumption is found from the ratios:

$$G_B = \frac{P}{P_{УД_\Sigma}} = \frac{135250}{297{,}64} = 454{,}41(кг / с);$$

$$G_{B_1} = \frac{G_B}{1 + m} = \frac{454{,}41}{1 + 5{,}5} = 69{,}91(кг / с);$$

$$G_{B_{\text{II}}} = \frac{m}{m + 1}G_B = \frac{5{,}5}{5{,}5 + 1}454{,}41 = 384{,}5(кг / с);$$

calculate the internal efficiency of the TFE:

$$\eta_e = \frac{P_{УД_1}^2 + mP_{УД_{\text{II}}}^2}{2g_T H_U\left(1 - g_{охл}\right)} = \frac{324{,}95^2 + 5{,}5 \cdot 292{,}67^2}{2 \cdot 0{,}0223 \cdot 42{,}5 \cdot 10^6\left(1 - 0{,}085\right)} = 0{,}333;$$

2. At an increase η_T^* of 1% from the original

Then η_T^* = 0.93

a) determination of gas parameters behind the turbine (section T-T)

Take the value of the mechanical efficiency $\eta_M = 0{,}995$, determine the effective operation of all stages of the turbine TFE:

$$L_T = \frac{mL_{ВЛ_{II}} + L_K}{(1+g_T)(1-g_{охл})\eta_M} = \frac{5{,}5\cdot 50777 + 596430}{(1+0{,}0223)(1-0{,}085)0{,}995} = 940880{,}7\,\frac{Дж}{кг};$$

taking the efficiency of the turbine $\eta_T^* = 0{,}93$, we calculate the temperature and pressure of the gas behind the turbine:

$$T_T^* = T_Г^* - \frac{K_Г - 1}{K_Г}\frac{L_T}{R_Г} = 1600 - \frac{1{,}333-1}{1{,}333}\cdot\frac{940880{,}7}{288} = 783{,}26(K);$$

$$P_T^* = P_Г^*\left[1 - \frac{T_Г^* - T_T^*}{T_Г^*\cdot\eta_T^*}\right]^{\frac{K_Г}{K_Г-1}} = 3194270\left[1 - \frac{1600-783{,}26}{1600\cdot 0{,}93}\right]^{\frac{1{,}333}{1{,}333-1}} = 132270{,}5(Па);$$

b) determine the parameters of the working fluid in the outlet section of the nozzle of the inner contour (section S_1 –S_1)

determine the pressure drop in the jet nozzle of the inner loop and compare it with the critical

$$\pi_T = \frac{P_T^*}{P_H} = \frac{132270{,}5}{101325} = 1{,}3 < \pi_{C_{KP}} = 1{,}85;$$

Consequently, the expansion in the jet nozzle is complete, and the rate of gas outflow from the nozzle is calculated by the formula:

$$C_{C_1} = \varphi_{C_1}\sqrt{2\frac{K_Г}{K_Г-1}R_Г T_T^*\left[1-\left(\frac{P_H}{P_T^*}\right)^{\frac{K_Г-1}{K_Г}}\right]};$$

$$C_{C_1} = 0{,}98\sqrt{2\frac{1{,}333}{1{,}333-1}288\cdot 783{,}26\left[1-\left(\frac{101325}{132270{,}5}\right)^{\frac{1{,}333-1}{1{,}333}}\right]} = 334{,}37\,м/с;$$

find the static gas temperature

$$T_C = T_T^* - \frac{K_\Gamma - 1}{K_\Gamma}\frac{C_{C_1}^2}{2R_\Gamma} = 783{,}26 - \frac{1{,}333-1}{1{,}333}\cdot\frac{334{,}37^2}{2\cdot 288} = 734{,}77K\,;$$

c) determination of the main specific parameters of the engine and air flow calculate the specific thrust of the inner contour:

$$P_{УД_1} = C_{C_1}(1+g_T) = 334{,}37(1+0{,}0223) = 341{,}83\frac{H\cdot c}{кг};$$

determine the specific thrust of the outer contour:

$$P_{УД_{II}} = C_{C_{II}} = 292{,}67\frac{H\cdot c}{кг}\quad;$$

determine the specific thrust of the TFE:

$$P_{УД_\Sigma} = \frac{P_{УД_1} + mP_{УД_{II}}}{1+m} = \frac{341{,}83 + 5{,}5\cdot 292{,}67}{1+5{,}5} = 300{,}23\frac{H\cdot c}{кг};$$

determine the specific fuel consumption:

$$C_{УД} = \frac{3600\cdot g_T(1-g_{охл})}{P_{УД_\Sigma}(1+m)} = \frac{3600\cdot 0{,}0223(1-0{,}085)}{300{,}23(1+5{,}5)} = 0{,}0376(кг/H\cdot ч);$$

air consumption is found from the ratios:

$$G_B = \frac{P}{P_{УД_\Sigma}} = \frac{135250}{300{,}23} = 450{,}49(кг/с);$$

$$G_{B_1} = \frac{G_B}{1+m} = \frac{450{,}49}{1+5{,}5} = 69{,}31(кг/с);$$

$$G_{B_{II}} = \frac{m}{m+1}G_B = \frac{5{,}5}{5{,}5+1}450{,}49 = 381{,}18(кг/с);$$

calculate the internal efficiency of the TFE:

$$\eta_e = \frac{P_{УД_1}^2 + mP_{УД_{II}}^2}{2g_T H_U(1-g_{охл})} = \frac{341{,}83^2 + 5{,}5\cdot 292{,}67^2}{2\cdot 0{,}0223\cdot 42{,}5\cdot 10^6(1-0{,}085)} = 0{,}339;$$

At $g_{охл} = 0{,}085$

Table 3.2 - Systematize the received calculations

η_T^*	0,92	0,925	0,93
$C_{УД}$ $(кг/н \cdot ч)$	0,0383	0,0379	0,0376
η_e	0,326	0,333	0,339

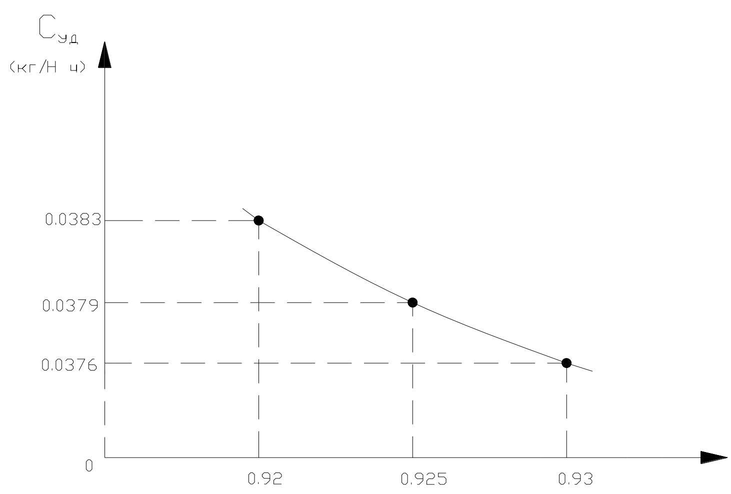

Figure 4.7 - Dependence of specific fuel consumption on turbine efficiency

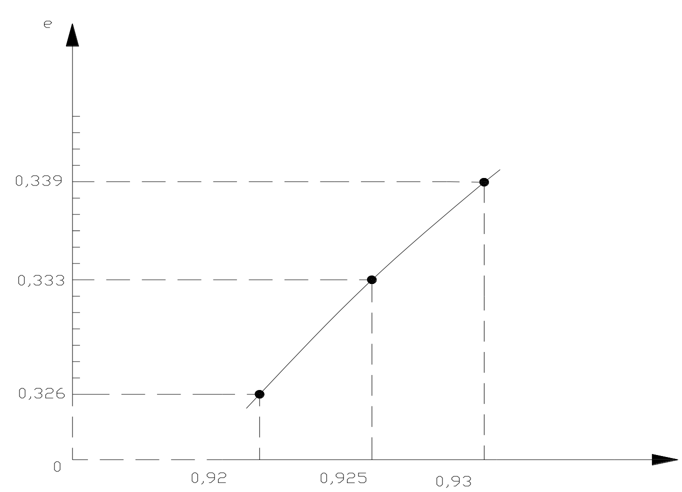

Figure 4.8 - Dependence of the internal efficiency of the engine on the efficiency of the turbine

3.5. Estimation of fuel economy of the designed engine

Taking into account that after the refinement of the gas-dynamic calculation, the specific fuel consumption decreased by 4% from the result of the thermodynamic calculation, i.e. reduced from $0{,}0385 кг/Н \cdot ч$ to $0{,}0367 кг/Н \cdot ч$.

Therefore, at $g_{охл} = 0{,}085$ and $\eta_T^* = 0.93$, it is possible to similarly reduce the specific fuel consumption by 4% of $0{,}0376 кг/Н \cdot ч$, and received $C_{УД} = 0{,}0361 (кг/н \cdot ч)$.

If take into account that in cruising modes the amount of air for cooling is reduced in the same way as in takeoff mode, and the turbine efficiency increases in the same way, then it is approximately possible to estimate the fuel economy over the entire resource (say 5000 hours). At the same time, we use the throttle characteristics of the PS-90A prototype engine. We accept from $P_{КР} = 77{,}4\%$ the takeoff mode and $C_{УДкр}$ =96,8% of the takeoff mode, i.e. $P_{КР} = 109{,}77 КН$, $C_{УДкр} = 0{,}0349 кг/Н \cdot ч$.

a) determine the fuel economy of the engine in takeoff mode:

we take the total take-off time 5% of the total resource, i.e. $\tau_{взл.} = 250 ч$

$$\Delta \mathrm{M}^1_{\text{топл.}} = P_{взл.} \cdot \tau_{взл.} \cdot \Delta C_{УДвзл.} = 141{,}83 \cdot 10^6 \cdot 250 \cdot (0{,}0367 - 0{,}0361) = 21274 (kg)$$

b) Determine the fuel economy of the engine in cruising mode:

initial cruising specific fuel consumption

$$C^{/}_{УДкр} = 0{,}0367 \cdot 96{,}8\% = 0{,}0355 кг/Н \cdot ч$$

$$\Delta \mathrm{M}^2_{\text{топл.}} = P_{кр.} \cdot \tau_{кр.} \cdot \Delta C_{УДкр.} = 109{,}77 \cdot 10^6 \cdot 4750 \cdot (0{,}0355 - 0{,}0349) = 312844 (kg)$$

c) Determine the total fuel economy for a resource of 5000 h

$$\Delta M_{топл.} = \Delta M^1_{топл.} + \Delta M^2_{топл.} = 21274 + 312844 = 334118 (\mathrm{kg})$$

Conclusions on the research part

A new microcirculating cooling method, taken from a patent, improves fuel efficiency by:

-reduction of the relative quantity of cooling air intake $g_{охл}$ by 0.5% from the initial, i.e. decreased from 0.09 to 0.085

- increase in turbine efficiency according to the most significant preliminary estimate

from 0.92 to 0.93 ;

- increase in the internal efficiency η_e of the TFE by 5.3% of the original, i.e. increased from 0.322 to 0.339

- decrease in specific fuel consumption by 1.6% of the initial, i.e. reduced from $0{,}0367 кг/Н \cdot ч$ to $0{,}0361 кг/Н \cdot ч$;

In addition, this cooling method can increase the turbine blade life cycle.

The performed calculations show that for 5000 hours the fuel economy due to the above efficiency amounted to 334 tons for each of two aircraft engines.

4. OCCUPATIONAL HEALTH

4.1. Dangerous and harmful production factors during the operation of gas turbine engines

During servicing power plants, workers may be affected by the following hazardous and harmful production factors:

- unprotected moving parts of the aircraft and power plant, suspended machinery and production equipment;

- vehicles for the delivery of engines, units, equipment to and from the aircraft;

- flying fragments, elements, parts of the control system;

- falling engines and other parts of aviation equipment, tools and materials during maintenance of high-level control systems and units;

- jets of exhaust gases, objects caught in these jets;

- air suction flows;

- air atmospheric flows;

- increased levels of noise, vibration, ultra- and infrasound during starting and testing of aircraft engines and during ultrasonic control of the control system;

- physical overloads during maintenance of power plant (PP) units located in hard-to-reach places;

- the location of the workplace close to unshielded height differences of 1.3 m or more;

- increased level of infrared radiation from the heated parts of the blood pressure;

- increased level of ultraviolet and thermal radiation during welding;

- chemicals that make up the materials used (primers, sealants, adhesives, etc.) [19].

During various types of work on the equipment, mechanical oscillations of different frequencies are generated, which have an adverse effect on the human body in the form of noise and vibration.

Noise, as a set of wave oscillations of particles in the air that form sounds, adversely affect a person, interfere with his work and rest. Prolonged exposure to intense sound (above 80 dBA) on human hearing leads to its partial or complete loss.

Depending on the duration and intensity of the noise there is a more or less decrease in the sensitivity of the auditory organs, which is expressed in a temporary shift of the hearing threshold, which disappears after the noise, and with a longer duration or intensity of noise there are irreversible hearing loss. threshold of audibility.

Through the fibers of the auditory nerves, noise stimulation is transmitted to the central and autonomic nervous systems, and through them acts on internal organs, leading to significant changes in the functional state of the body, affects the mental state, causes anxiety and irritation. The higher the frequency composition of the noise, the more intense and long they are, the faster and more powerful they have an adverse effect on the hearing organ.

4.2 Organizational and constructive-technological measures to reduce the impact of harmful production factors

The project provides all the necessary technical solutions and measures that ensure the safe operation of all in compliance with operating regulations and all safety requirements:

- application of equipment in explosion-proof execution in rooms and outdoor installations in which there are explosive environments;

- to ensure normal operating conditions, all the necessary automatic control and protection systems are provided, which are triggered by deviations from the specified parameters;

- control and regulation of all major technological parameters is carried out from the operating room;

- installation and repair of equipment, performed with the help of special lifting equipment;

- installed lightning protection and protection of equipment and pipelines from repeated lightning and static electricity;

- stationary gas analyzers are installed indoors and outdoors;

- if necessary, service areas, installation and operational passages are provided;

- provided access to equipment units during their maintenance;

- hot surfaces of the equipment in service areas are covered with thermal insulation;

- provided a system of collection and organized discharge of gas into the atmosphere.

The number of service personnel and the time they spend at the equipment, as a source of noise, vibration and possible emissions, is regulated by standards and regulations.

The operation of the main technological equipment is carried out in an automated mode and does not require the constant presence of service personnel.

To create normal operating conditions, all the necessary systems of automatic control and protection are provided, which are triggered by deviations from the specified parameters. In places where natural gas may leak, an alarm of explosive gas concentration in the air is provided. A siren is provided to provide an audible alarm.

Elimination of the causes of emergencies and elimination of accidents must be carried out in accordance with the instructions for operation and safety, developed at the enterprise, taking into account the applicable regulations, as well as instructions from the manufacturers of equipment.

Calculation of ventilation equipment for explosion hazard:

The emergency ventilation system is provided in the production room, where a large amount of explosive substance may suddenly enter the air. This danger is posed by GTE in engine rooms. Table 4.1 shows the volume fractions of combustible components of natural gas.

The initial data for the calculation of emergency ventilation are:

- volume fractions of natural gas components are given in Table 4.1

- geometric dimensions of the compressor hall;

- the amount of gas emitted in the room.

Table 4.1 - Volume fractions of natural gas components

№ p / p.	Component composition of gas	Volume fractions of components
1	Methane CH_4	95,26
2	Ethan C_2H_4	1,123
3	Propane C_3H_8	0,986
4	Butane C_4H_{10}	0,121
5	Pentane C_5H_{12}	0,017

Determine the lower explosive limit by the Leshatelle formula of the volumetric composition of the gas:

$$L_{H.B} = \frac{100}{\sum_{i=1}^{n} \frac{r_i}{L_i^{H.B}}},$$

where n – the number of components of natural gas;

r_i – volume fraction of the i-th component;

$L_i^{H.B}$ – the lower limit of explosiveness of the i-th component of the mixture with air.

$$L_{H.B} = \frac{100}{\frac{95,26}{5,3} + \frac{1,123}{3} + \frac{0,986}{2,2} + \frac{0,121}{1,9} + \frac{0,017}{1,3}} = 5,299 \ \%.$$

Emergency ventilation is activated automatically when the concentration of explosive mixture in the room reaches 15% of the lower explosive limit, i.e. based on the data obtained, choose the type of fan.

Fan performance can be calculated by the following formula:

$$L = n \cdot V_{пр},$$

where n – multiplicity of air exchange;

V_{np} – volume of the room.

The volume of the room is determined gaspumping unit (GPU) by the following formula:

$$V_{пр} = (1 - 0,3) \cdot V_{ГПА},$$

where $V_{ГМК}$ –volume of , 543,9 м^3 .:

$$V_{ГМК} = a \cdot b \cdot c,$$

$$V_{ГМК} = 9,2 \cdot 8,1 \cdot 7,3 = 543,9 м^3$$

$$V_{ПР} = (1 - 0,3) \cdot 543,9 = 380,8 \ м^3$$

Determine the amount of gas emitted into the room in the event of failure of one GPU.

Volume of the supercharger is equal to 0.2237 m3.

Determine the volume of gas reduced to standard conditions in the supercharger:

$$V = \frac{P_{BC}}{P_{CT}} \cdot \frac{T_{CT}}{T_{BC}} \cdot \frac{1}{z},$$

where P_{BC} i T_{BC} – respectively, the pressure and temperature of the gas under suction conditions, for the worst conditions P_{BC}=3,5 *МПа*, T_{BC}=283^0*К*.

P_{CT} i T_{CT} – respectively the pressure and temperature of the gas under standard conditions: P_{CT}=101325 *Па*, T_{CT}=293,15^0*К*.

Then the coefficient of compressibility of the gas for suction conditions is equal:

$$z = 1 - 5{,}5 \cdot 10^6 \cdot \frac{P_{BC} \cdot \Delta^{1,3}}{T_{BC}{}^{3,3}}.$$

The mass of gas that enters the room is determined:

$$M = V \cdot \rho_{CT}.$$

Therefore:

$$z = 1 - 5{,}5 \cdot 10^6 \cdot \frac{3.5 \cdot 0{,}591^{1,3}}{283^{3,3}} = 0{,}921;$$

$$V = \frac{3{,}5}{0{,}101325} \cdot \frac{293{,}15}{283} \cdot \frac{1}{0{,}921} = 38{,}831 м^3;$$

Check if an explosive mixture has formed:

$$\alpha = \frac{38{,}831}{380{,}8} = 10{,}19\%$$

Conclusion: the concentration of gas in the air exceeds the upper limit of the flash. This situation is dangerous and requires the creation of forced ventilation.

The allowable concentration of natural gas for this room is 5%, ie the allowable volume of gas in the room is equal to:

$$V_{Г.ДОП} = 380{,}8 \cdot 0{,}05 = 19{,}4, м^3$$

Assuming that the gas from the GPU is emitted within two minutes, the gas consumption reduced to the flow rate for one hour is equal to:

$$G = \frac{38{,}831}{120} \cdot 3600 = 1164{,}9 \frac{м^3}{год}.$$

Then the multiplicity of air exchange is defined as:

$$n = \frac{1164{,}9}{38.831 - 19{,}4} = 38{,}59.$$

The frequency of air exchange, for emergency ventilation is in the range from 20 to 40, we accept - accepted with a margin, if the time of sudden release is less than two minutes.

Then the required fan performance is determined by the formula:

$$L = 40 \cdot 380{,}8 = 15231{,}9 \frac{м^3}{год}.$$

4. 3 Occupational Safety Instruction

4.3.1 General safety requirements [20]

1. Men and women at least 18 years of age are allowed to work as engine testers (hereinafter - tester) (to work on running engines on leaded gasoline women and younger people 18 years are not allowed), trained and certified in the specialty, and also tested knowledge of electrical safety in the amount group I.

2. Upon admission to work, the examiner undergoes a medical examination, introductory instruction on occupational safety and initial instruction at the workplace,

which must be confirmed by his signature in safety briefing checklist and logs of registration of introductory briefing and briefing at the work location.

During subsequent work, the tester passes:

- periodic medical examinations - at least once every 12 months (when running in engines running on leaded gasoline once every 12 months);

- repeated briefings: on labor safety - at least once every 6 months with a receipt in the workplace briefing log;

- at least once every 12 months for electrical safety in the amount group I.

3. The tester should remember that due to non-compliance with the provisions of this Instruction, the Internal Labor Regulations, Of the rules for the technical operation of engines, mechanisms and equipment and tools used for testing, as well as violations of the technological process during work, a danger may arise:

a) injuries when working with electrical machines, locksmith and fitting and assembly tools, on drilling and sharpening machine tools;

b) electric shock if accidentally touching live parts of electrical equipment, as well as in case of damage or lack of grounding;

c) in case of careless movement on the territory of the enterprise, workshop, area, walking on unsecured floorings;

d) when working on oily, wet, covered with ice or snow the floor, as well as when the workplace is cluttered with equipment and foreign objects;

e) while being in the danger zone under a raised or moving load (equipment) and moving with poor visibility, or in the dark.

4. In the case of work in unfavorable working conditions, the tester may be charged additional payments to the tariff rate in the amount of up to 24 percent - for

work on testing and adjusting jet and turboprop engines in closed boxes, fuel equipment for them, as well as on testing piston engines and units for them when operating on leaded gasoline and in the amount of up to 12 percent - for work on testing aviation and turboprop engines and internal combustion (diesel, carburetor) in rooms. Free overalls, safety shoes and other personal protective equipment are issued:

- cotton semi-overalls - for 12 months;

- combined mittens - for 2 months;

- anti-noise earphones - until wear.

For an aircraft engine mechanic tester:

- cotton suit with fire retardant impregnation - for 12 months; combined mittens - for 3 months;

- tarpaulin boots - for 12 months;

- leather helmet with a silencer - for 36 months;

- goggles - until worn out.

In winter, in addition: a cotton jacket with wadding combined with a fur collar, cotton trousers with wadding, woolen liner for the period of wear, set for the respective climatic regions. When testing engines running on leaded gasoline, In addition, underwear is issued for 6 months.

Additional leave may be granted for immediate work at a motor testing station for testing engines running on leaded gasoline:

- when working in boxes - 12 working days per year and duration

shortened working day 6 hours;

- when working indoors - 12 working days;

- when working at open-type test stations - 6 workers days (engine tester directly involved in testing diesel engines and diesel generators: when working in specially equipped boxes, soundproofed from the surrounding premises, working inside the box directly at the diesel engine - 12 working days per year and the duration of a reduced working day - 6 hours; at test benches indoors - 12 working days).

In connection with the contamination of the body caused by the production technology, 400 grams of soap is issued monthly free of charge in addition to the soap that is at the washbasins in accordance with the approved List works and professions that give employees the right to receive free soap.

5. The tester is obliged:

a) work only on the equipment on which he was trained and approved, provided that safe working practices on the equipment he knows;

b) do not allow persons not related to the work performed to the workplace;

c) when performing work in a related profession, know and perform requirements of labor protection instructions for these professions;

d) use only serviceable tools and equipment, devices with unexpired verification periods;

e) work on an electric hoist only if trained to do so and there is a certificate for the right to drive the telfer;

f) follow the instructions of the foreman, workers of the labor protection service and fire service, report cases of injuries, malfunctions of mechanisms, equipment and devices at the workplace;

g) keep the workplace clean and tidy, do not clutter the approaches and the service area of the workplace, put production waste and used rags in a special container;

h) be able to provide first aid to the victim;

i) comply with this Labor Protection Instruction, Internal Labor Regulations, Rules for the technical operation of equipment and mechanisms used during work and the requirements of technological processes;

j) do not allow smoking in areas not designated for these purposes.

6. For personal safety, the tester is obliged:

a) use special clothing and personal protective equipment by appointment;

b) perform only the work for which he was trained, received the task of the foreman and instruction on labor protection;

c) comply with the requirements of posters and safety signs;

d) do not lift or carry by hand a weight in excess of the setting norms: for men more than 30 kg, and for women - more than 10 kg;

e) be attentive to the warning signals of lifting machines, cars and other types of moving transport;

f) observe personal hygiene, keep an individual locker clean and tidy, store overalls hanging, do not store foreign objects in individual lockers for overalls.

7. This instruction is handed over to the test person against receipt.

In case of non-compliance with the instructions, the tester may be disciplined in accordance with the rules internal labor regulations, if this violation does not entail criminal liability.

If the violation is related to causing property damage the enterprise, the tester is financially liable in the manner prescribed by law.

4.4. Fire and explosive safety during GTE maintenance

Aircraft engines are fire hazardous objects. This is due to the projection of fuel combustion processes in them, its supply under high pressure, high temperature of the engine body and adjacent units, the possibility of a flame ejection when starting the engine.

An engine fire can ignite flammable materials in the immediate vicinity of the engine as well as aircraft structures.

According to ГОСТ 12.1.004-85, hazardous fire factors affecting people in relation to an aircraft engine are:

- open flame;
- sparks;
- high air temperature;
- smoke;
- low oxygen content in the air;
- emission of toxic substances during combustion.

Engine fires can be caused by the following:

- careless handling of open flames near the engine;
- leakage of fuels and lubricants;
- short circuit of the wiring;
- heating of the engine bearings, burnout of the combustion chamber flame tubes;
- violation of the technology of starting the engine and its testing (restarting after a failed one without intermediate cold cranking to remove fuel residues from the engine).

An engine explosion can be caused by:

- destruction of engine parts and disruption of underwater highways by flying debris;

- accumulation of fuel vapors in the engine compartment;

- insufficient drainage of fuel from the explosive zones of the turbojet engine;

- short circuit of electrical wiring or spark from careless blow of the tool during maintenance;

- burnout of the combustion chamber flame tube and ejection of a flame on the fuel supply lines to the nozzles.

To reduce the possible impact on the operating personnel of hazardous factors of fire and explosion at the design stage, the following design measures are provided:

- design of highly loaded engine elements with a sufficient safety factor;

- the engine body should, if possible, localize the flying parts during destruction;

- the falling fuel lines have electrical insulation rather than closed thermal insulation in the zone of elevated temperatures;

- engine units and assemblies have reliable seals;

- mating parts and engine assemblies must have metallization to remove residual static electricity;

- efficient drainage of fuel and fire hazard zones of the engine is provided;

- the engine compartments are separated by fire-fighting screens;

- the engine has an effective lubrication system, which ensures reliable cooling of the rotor bearings;

- an alarm and fire extinguishing system was used to warn the crew or technical personnel about a possible fire on the engine and to eliminate it.

It informs the crew in advance about the temperature rise in the fire hazardous zones of the engine and automatically turns on the first stage of fire extinguishing in the event of a fire.

The fire-fighting system consists of a fire extinguisher, two blocks of electromagnetic distribution valves, spray manifold, impact mechanism and alarm system. Fire extinguishers are discharged in three turns. All fire extinguishers are united by a common manifold.

The nacelle spray manifolds are mounted on the engines. To eject the extinguishing agent in a finely atomized state, holes d = 0.8 mm are drilled in the manifold. The manifold are made of steel pipes. Each nacelle has 18 fire alarm sensors.

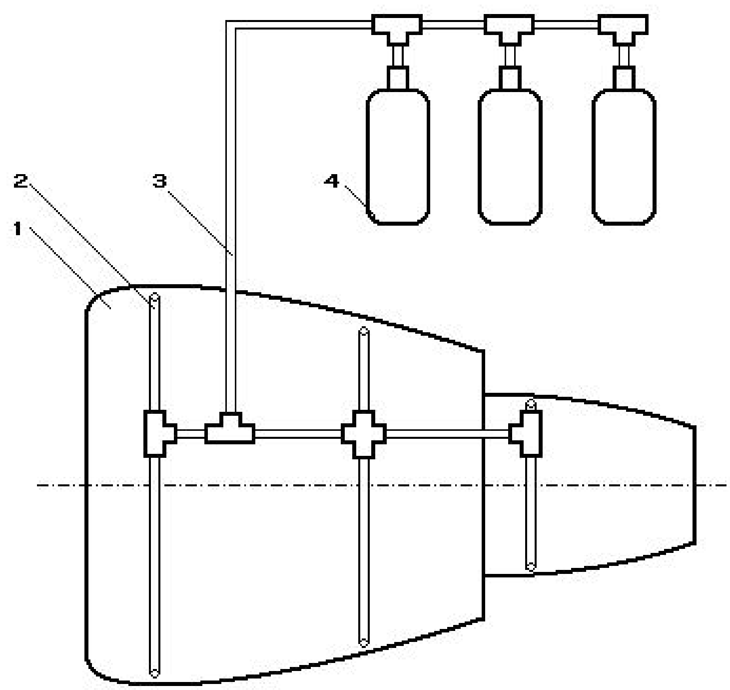

Figure 4.1 - Gas turbine engine fire system diagram

1 - gas turbine engine; 2 - spray manifolds;

3 - mains supply of OM; 4 - fire extinguishers.

At the same time, the circuit for supplying current to the lamp is closed, the button and the electromagnetic valve for supplying the extinguishing composition. The electromagnetic valve opens the supply of the extinguishing agent and closes the limit switches, which ensure the self-locking of the crane and the preparation of the switching circuit of the second line and third line of fire extinguishers. If a fire occurs again, if the queue of fire extinguishers has already been used up, the fire extinguishers are not automatically turned on and the third phase of fire extinguishers is turned on manually.

When fuel vapors are generated in a confined space in certain volumes, an explosion can occur in the presence of an ignition source.

Let's calculate the combustion chamber of the designed engine for explosion hazard.

The check calculation of the combustion chamber consists in determining its specific heat intensity and comparing the obtained value with the recommended ones.

The specific heat-intensity of the combustion chamber is determined by the formula:

$$Q_{\text{КС}} = \frac{G_T \cdot H_U \cdot Z_{KC}}{V \cdot P_K} = \frac{5205 \cdot 43 \cdot 10^6 \cdot 0{,}99}{0{,}05 \cdot 3000000} = 1{,}49 \cdot 10^6\ Дж/\left(м^3 \cdot ч \cdot Па\right);$$

Where $G_{\text{Т}}$ - hourly fuel consumption, kg / h;

H_{U} - is the net calorific value of the fuel, J / kg;

$Z_{\text{КС}}$ - is the fuel combustion efficiency;

$V_{\text{Ж}}$ - is the volume of the flame tube, m^3;

$P_{\text{К}}$ - static air pressure in the combustion chamber, Pa.

The obtained specific heat density for engines with a longer service life is within the recommended range: (from 1.2 up to 4.5) · 10^6 J / (m^3 · h · Pa).

Conclusion on labor protection part

This part discusses:

- dangerous and harmful production factors that occur during operation and repair of the designed gas turbine;

- organizational, design and technological measures to reduce the level of dangerous and harmful production factors;

- fire and explosion safety during maintenance of GTE;

- basic requirements for compliance with the rules of labor protection during operation of the designed gas turbine;

- the specific heat-intensity of the combustion chamber is $1.49 \cdot 10^6$ J/($m^3 \cdot h \cdot Pa$) , which is excellent for a prototype.

5. ENVIRONMENTAL PROTECTION

5.1. Analysis of the environmental hazard of the engine being designed

Aircraft engines create the following adverse environmental impacts:

- emissions of various harmful products of fuel combustion (emission);

- noise generated by engines on the ground. The emission is usually characterized by the amount of harmful substances (in grams) released during the combustion of 1 kg of fuel - the emission index El.

In aviation, emission limits are set for four emission components: carbon monoxide (CO), unburned hydrocarbons (C_nH_m), nitrogen oxides (NO), and soot particles (smoke).

The first two components are formed during incomplete combustion of fuel in the combustion chamber, which occurs at reduced engine operating conditions. Nitrogen oxides are formed in areas of the combustion chamber with a high temperature, so their emission increases sharply during takeoff. The highest engine smoke is also observed during takeoff [21].

5.2. Ensuring environmental safety

Since the aircraft quickly leaves the airfield area after takeoff, the greatest threat to the environment is represent by emissions of carbon oxides and unburned hydrocarbons at idle modes during taxiing before takeoff and after landing. At these stages, you can turn off some of the engines and taxi on one or two engines, which leads to a decrease in environmental pollution. When turning off some of the engines while taxiing, the noise level generated by the aircraft on the terrain in the airfield area is simultaneously reduced. To reduce the noise level in the designed engine, such design solutions are used as the use of acoustic panels that absorb noise, as well as an increase in the gaps between the rotor blades and straighteners in the fan.

5.3. Calculation of the control parameter of the prototype engine emission for compliance with their standards

When drawing up and monitoring the implementation of plans for environmental protection at CA enterprises, carbon monoxide (CO), unburned hydrocarbons (CH), nitrogen oxides (NOx), sulfur oxides (SOx) and particulate matter are taken into account.

The mass of emissions of harmful substances (EHS) in the airport area is calculated for the take-off and landing cycle (TLC) [22].

Table 5.1. — The characteristics of the TLC modes

Operating mode characteristic	$\overline{P}$	Duration, min.
Idle mode when taxiing before departure	0,07	15,0
Takeoff mode	1,00	0,7
Climb mode (up to 1000m)	0,35	2,2
Landing mode (from a height of 1000m)	0,30	4,0
Idle mode when taxiing after arrival	0,07	7,0

The calculation $M_{ia/n}$ of the mass of annual emissions of CH, CO, NOx, SOx and particulate matter for an engine of one type of aircraft is performed using the formula:

$$M_{ia/n} = \sum_{i=1}^{n} M_{iн} + \sum_{i=1}^{n} M_{iBn} \tag{5.1}$$

where $\sum_{i=1}^{n} M_{iн}$ is the mass of EHS during ground operations (starting, warming up, taxiing before take-off and after landing);

$$\sum_{i=1}^{n} M_{iH} = \sum_{i=1}^{n} K_{iH} G_{TH} \tag{5.2}$$

where K_{iH} is the emission factor for ground operations , kg. EHS / kg. fuel;

G_{TH} - mass of fuel consumed by aircraft engines of this type during ground operations per year, kg / year.

$$G_{TH} = C_{УДМГ} P_{МГ} T_{МГ} \tag{5.3}$$

where $C_{УДМГ}$ is the specific fuel consumption when the engine is running in idle mode, kg / h; $P_{МГ}$ - engine thrust at idle mode, N; $T_{МГ}$ - regime operation of engines at idle mode, h / year.

$$T_{МГ} = t_{МГ}.N.n \tag{5.4}$$

where $t_{МГ}$ - is the engine operating time in the idle mode for one TLC, h; N - is the annual number of take-offs and landings of aircraft of this type at the airport; n - is the number of engines on this type of aircraft;

Table 5.2. — Ingredient values of harmful substances

Harmful substances	CO	CH	NO_x	SO_x	solid particl.
K_{iH} (projected engine kg.EHS/kg.fuel)	0,0075	0,00055	0,00017	0,00021	0,00096
K_{iH} (basic version of PS-90A engine, kg.EHS/kg.fuel)	0,0085	0,00068	0,00021	0,00024	0,00096

For comparison, will take Tu-204 aircraft with PS-90A engines as the basic version.

The thrust of the designed engine and PS-90A engine at idle mode are:

$$P_{МГ}^{пр} = 11000 \text{ Н} = 11 \text{ kN}.$$

$$P_{МГ}^{б} = 12500 \text{ Н} = 12{,}5 \text{ kN}.$$

The specific fuel consumption on idle mode, when working on the ground of the designed and base engines:

$$C_{УД}^{пр} = 0{,}042 \text{ kg/h};$$

$$C_{УД}^{б} = 0{,}044 \text{ kg/h};$$

Time for idle mode:

$$t_{МГ}^{пр} = t_{МГ}^{б} = 15 + 7 = 22 \text{ min.} = 0{,}367 \text{ h}.$$

Accept on average 3 take-offs and landings per day for the projected and base aircraft at the base airport. Then the annual number of takeoffs and landings will be:

$$N^{пр} = N^{б} = 365 \cdot 3 = 1095;$$

The number of engines on the designed and base aircraft, respectively:

$$n^{пр} = 2 \; ; \; n^{б} = 2;$$

The engine operation at idle mode is determined by the formula given earlier:

$$T_{МГ}^{пр} = t_{МГ}^{пр} . N^{пр} . n^{пр} = 0{,}367 \cdot 1095 \cdot 2 = 803{,}73 \text{ h/year}.$$

$$T_{МГ}^{б} = t_{МГ}^{б} . N^{б} . n^{б} = 0{,}367 \cdot 1095 \cdot 2 = 803{,}73 \text{ h/year}.$$

The mass of fuel consumed in the idle mode will be:

$$G_{ТН}^{пр} = C_{УДМГ}^{пр} . P_{МГ}^{пр} . T_{МГ}^{пр} = 0{,}042 \cdot 11000 \cdot 803{,}73 = 371320 \text{ kg/h}.$$

$$G^{б}_{ТН} = C^{б}_{УДМГ}.P^{б}_{МГ}.T^{б}_{МГ} = 0{,}044 \cdot 12500 \cdot 803{,}73 = 442100 \text{ kg/h}.$$

The mass emitted during the year during takeoff and landing operations for various types of EHS is determined by the formula:

$$\sum_{i=1}^{n} M_{iBn} = \sum_{i=1}^{n}\left[n\left(W_{i1}T_{1Bn} + W_{i2}T_{2Bn} + W_{i3}T_{3Bn}\right)\right]N \qquad (5.5)$$

Where: T_{1Bn} - operating time of engines during takeoff, h;

T_{2Bn} - operating time of engines when climbing 1000m, h;

T_{3Bn} - operating time of engines when descending from an altitude of 1000m, h;

W_i - mass rate of emission factors at a certain operating mode of the engine, kg / h.

The corresponding mass emission rates for different operating modes of the engine of the designed and basic variants are presented in Table 5.3.

Table 5.3. – Mass emission rate

Engine type	P_{max}, kN	Engine operating mode	W_i, kg/h				
			CO	CH	NO_x	SO_x	Solid part.
Project variant	141,8	1. Take-off	3,5	0,2	6,0	0,16	0,55
		2. Nominal	3,5	0,2	4,5	0,14	0,6
		3. 0,42 nominal	6,0	0,8	1,5	0,08	0,39
Base variant	160	1. Take-off	6,5	0,2	7,5	0,175	0,701
		2. Nominal	7,0	0,2	5,5	0,161	0,643
		3. 0,42 nominal	20	1,0	1,5	0,097	0,39

The results of calculations of explosive emissions during ground operations M_{iH}, during takeoff and landing M_{iBn}, and annual emissions $M_{ia/n}$ for various categories of explosives are presented in Table 5.4.

Table 5.4. – Annual emission of harmful substances

EHS	Harmful substances				
	CO	CH	NO	SO_X	Solid part.
M_{iH}^{np},kg	2784,9	204	63	7,8	30,6
$M_{iH}^{б}$,kg	3316	243	93	10,6	42,4
M_{iBn}^{np},kg	1253,3	138,70	745,80	27,29	119,86
$M_{iBn}^{б}$,kg	3668,3	168,10	857,40	31,75	127,68
$M_{ia/n}^{np}$,kg	4038,2	342,7	808,8	35,09	150,46
$M_{ia/n}^{б}$,kg	6984,3	421,1	950,4	42,35	170,28

As we can see from the table above, the annual emissions of harmful substances in the area of the base airport for the projected aircraft are much less than those for the base aircraft, which testifies in favor of the projected option from the point of view of ecology.

5.4. Measures to improve environmental safety the designed object

The organization of work on environmental protection in CA is determined by special provisions on the protection of nature, the environment and the improvement of the use of natural resources in CA.

The development of environmental measures and control over their timely implementation is carried out by the Civil Aviation Department [24].

At airlines, the most relevant areas of activity to reduce the impact of aviation on the environment are as follows:

–Reduction of atmospheric air pollution by harmful substances from aircraft engines, gasoline engines and diesel engines of ground equipment and special vehicles;

–Reduction of the discharge of untreated wastewater and harmful emissions from the territories of airlines into the soil, rivers and water bodies;

–Reduction of the irritating effect of aircraft and other industrial noise;

–Protection from the effects of electromagnetic fields erosion control;

–Remediation of lands and soils for their further use for agricultural purposes;

The implementation of organizational and technical measures for the protection of nature and the rational use of natural resources is the responsibility of the head of the airline. The management of these activities is entrusted to chief engineers and deputy chiefs of airports, factories, educational institutions and organizations.

In CA, a set of measures has been developed to completely stop the discharge of untreated wastewater into rivers and other bodies of water. In the treatment facilities of airports and civil aviation enterprises, mechanical, chemical, physicochemical, biological treatment methods are used.

Mechanical cleaning with the use of sedimentation tanks, oil traps and self-traps ensures the release of up to 60% of undissolved coarse impurities, mineral and organic contaminants from domestic wastewater, and up to 95% from industrial wastewater.

When using chemical treatment methods, wastewater from charging and storage stations and galvanic workshops is effectively treated with chemical reagents and mineral coagulants. The resulting compounds become less toxic or precipitate.

Physicochemical cleaning methods (flotation, extraction, electrocoagulation) are most often used in conjunction with mechanical and chemical cleaning.

The process of cleaning by flotation is the action of molecular forces that promote the fusion of organic substances (for example, oil products) with air bubbles and the resulting foam float to the surface.

The electrocoagulation method is based on the use of electric current to carry out the coagulation process.

The biological method of wastewater treatment with the use of installations operating according to the method of complete oxidation is based on the ability of microorganisms to use unoxidized inorganic and dissolved organic substances of wastewater in the course of their life. This method consists in the mineralization of organic wastewater pollution using biochemical processes occurring inside the cells of microorganisms.

The biochemical treatment method is used, as a rule, at the last stage of the entire complex of treatment facilities. This method is universal, since practically all organic substances undergo biochemical decomposition. The method is based on the ability of microorganisms to use various dissolved organic substances and mineral compounds of wastewater in the process of their vital activity.

In biochemical wastewater treatment, all substances necessary for life are obtained from microorganisms from the treated wastewater. The purification efficiency depends on a number of factors: the composition of the water, the nature of pollutants, their concentration, the presence of a sufficient amount of biogenic elements (nitrogen, phosphorus, potassium, iron) in the water, the amount of dissolved oxygen, the content of hydrogen ions, and temperature. So, for example, the concentration of hydrogen ions in waste water should be in the range from 6.5 to 8.5 pH, and the temperature from 6 ° C to 30 ° C.

Combined treatment methods can be used depending on the wastewater consumption, their physical and chemical composition.

Effective in-plant measures for the protection of soil and facilities are:

-improvement of existing technological processes, creation of closed, cyclical, low-waste or non-waste processes;

- correct operation and improvement of existing dust and gas treatment facilities and sewage treatment facilities; conducting an inventory of sources of emissions of harmful substances into the atmosphere and water bodies and creating on the basis of these data schematic maps.

In order to prevent depletion of water in aviation enterprises, it is advisable to provide for the integrated use of water. For example, the use of technical and purified water in the processes of washing parts, assemblies and aircraft, when washing products in galvanic workshops, when watering and cleaning artificial coatings of hangars, parking areas, taxiways and runways.

For airports from III up to V classes, it is necessary to provide for joint treatment of industrial and domestic water for their subsequent use for technical water supply.

In order to save water resources, it is necessary to reuse water in technological operations. For this, wastewater is subjected to post-treatment methods. Reuse of treated water reduces discharge into the sewer system and reduces the consumption of natural water by 20-25 times.

Conclusion of environmental protection part

1. In this section, we made calculations for the emission of harmful substances, and we can understand that in the area of the base airport for the projected aircraft there are significantly less similar emissions for the base aircraft, which testifies in favor of the projected option from an environmental point of view.

2. In order to prevent depletion of water in aviation enterprises, it is advisable to provide for the integrated use of water.

3. Improvement of existing technological processes, creation of closed, cyclical, low-waste or non-waste processes.

Correct operation and improvement of existing dust and gas treatment facilities and sewage treatment facilities; conducting an inventory of sources of emissions of harmful substances into the atmosphere and into water bodies and creating maps based on these data.

CONCLUSIONS ON DIPLOMA WORK

In his thesis, taking into account the economic crisis and based on the need to develop the aviation industry of Ukraine, a draft design of a unified turbojet engine for a medium-haul passenger aircraft with a takeoff weight of 90 to 110 tons was developed.

In the final, obtained the following results:

1. The performed mass calculation of the aircraft for middle-range airlines made it possible to determine the take-off required thrust of one engine, as well as to select the basic geometric characteristics of the aircraft and, on this basis, to develop a drawing of the general view of the aircraft.

2. The placement of the main engines under the wing provides a decrease in the wing's tendency to flutter, relieves the thin wing in flight from normal load and dampens the wing vibrations during bumpy flight.

3. The choice of the Russian-made PS-90A engine as a prototype engine made it possible to obtain a relatively simple design that does not require the use of very complex technologies, which corresponds to the current state of the Ukrainian aircraft industry.

4.As a result of thermogasdynamic calculation, it was shown that the unified turbojet engine for medium-haul aircraft in terms of its technical characteristics ($C_{уд}$=0,0367kg/h) corresponds to the current state of the world engine building, which is confirmed by its comparison with the statistical data of engines of world engine building firms.

5.As a result of the calculations for the strength of the main parts of the high-pressure turbine (rotor blades and disk), the correct choice of materials for them and their geometric characteristics was confirmed. The minimum safety factor of these parts complies with the strength standards.

6. The lubrication and starting systems developed during the design of the engine ensure reliable engine operation. The engine starting time obtained as a result of calculations is 53.81 seconds, which corresponds to the technical conditions.

7. Based on the analysis of modern and promising methods of increasing the fuel efficiency of the gas turbine engine, carried out in the research part of the thesis, microcirculation cooling of the turbine rotor blade was selected and introduced into the design of the turbojet engine being designed, which provides a decrease in air intake for cooling while maintaining the permissible temperature of the blade material.

8. The above calculations confirmed the possibility of reducing the relative amount of air taken to cool the high-pressure turbine by 0.5%, ie. from 9% to 8.5%, which ensures a decrease in specific fuel consumption by 1.6% from the initial one. At the same time, the fuel economy for 5000 hours of operation of one engine is 334T.

9. As a result of the development of measures aimed at improving the environmental safety of the engine under design, the annual emissions of harmful substances in the area of the base airport for the projected aircraft were calculated, which are significantly less than similar emissions for the base aircraft, which testifies in favor of the projected option from the point ecology view.

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