**МІНІСТЕРСТВО ОСВІТИ І НАУКИ УКРАЇНИ**

**НАЦІОНАЛЬНИЙ АВІАЦІЙНИЙ УНІВЕРСИТЕТ**

Кафедра авіаційних двигунів

**ДОПУСТИТИ ДО ЗАХИСТУ**

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“_____”_____________20__р.

# ДИПЛОМНА РОБОТА

( ПОЯСНЮВАЛЬНА ЗАПИСКА )

ВИПУСКНИКА ОСВІТНЬОГО СТУПЕНЯ

**МАГІСТР**

## Тема: «Діагностування проточної частини гелікоптерного газотурбінного двигуна»

**Виконав:** _______________ Горбач З.Я.

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**Нормоконтролер :** ____________________/______________________/

**КИЇВ 2020**

**MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE**

**NATIONAL AVIATION UNIVERSITY**

Department of Aircraft Engines

The Head of the department
doctor of science, professor

______U.M.Tereshenko

“_____”______________20__

# MASTER DEGREE THESIS

(EXPLANOTARY NOTE)

**Topic: « Diagnostic of the flow path of a helicopter gas turbine engine »**

**Fulfilled by:** __________________ Horbach Z.Y.

**Supervisor:**
**Candidate of Engineering Sciences**
**assoc. professor** __________________ Yakushenko O.S.

**Consultants with specific sections of the explanatory note:**

**Labour precautions:**
**Candidate of Engineering Sciences**
**assoc. professor** _________________ Kovalova O.V.

**Environmental protection:**
**Candidate of Engineering Sciences**
**assoc. professor** ________________ Radomska M.M.

**Standards Inspector**________________________ /________________________/

**Kyiv 2020**

**NATIONAL AVIATION UNIVERSITY**

Educational and Research Airspace Institute
Aircraft faculty
The Aircraft Engines Department
Educational degree: «Master» direction (spatiality) «Aircraft Maintenance» 8.07010301 «Maintenance and repair of aircraft and aircraft engines»

**APPROVED BY**

Head of the Department

________________U.M.Tereshenko

“____”____________20__

# Graduation Project Assignment

**HORBACH ZAKHAR YAROSLAVOVICH**

1. Topic: «Diagnostic of the gas turbine engine flow area by thermodynamic parameters» approved by the Rector’s order of 30.11.2020 р. №514/ст.
2. The Graduation Project to be performed from 22.09.2020 to 15.12.2020.
3. Initial data for the project: statistic of aircraft engine thermodynamic data, operation documentation.
4. The content of the explanatory note: aircraft engine calculation thermos-gas-dynamic and dimension parameter, thrust calculation of the engine, creation of mathematical model for aircraft engine diagnostic.

5. Time and Work Schedule

| № | Task | Deadline | Mark |
|---|---|---|---|
| 1 | *Thermodynamic process calculation* | *22.08 – 29.08.2020* | |
| 2 | *Gas dynamic process calculation* | *30.08 – 10.09.2020* | |
| 3 | *Engine systems designing* | *11.09 – 20.09.2020* | |
| 4 | *Review of diagnosis methods* | *30.09 – 16.10.2020* | |
| 5 | *Creation of method of engine diagnosing by its thermos-gas-dynamic parameters* | *17.10 – 05.11.2020* | |
| 6 | *Creation of labour precautions measure* | *06.11 – 12.11.2020* | |
| 7. | *Creation of environmental protection measure* | *13.11 – 17.11.2020* | |
| 8 | *Explanotary note completing* | *18.11– 10.12.2020* | |
| 9 | *Drawing and presentation completing* | *11.12– 15.12.2020* | |

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

| Section | Adviser | Date, Signature | |
|---|---|---|---|
| | | Assignment Delivered | Assignment Accepted |
| Labour precautions | Candidate of Engineering Sciences assoc. professor Kovolova O.V. | | |
| Environmental protection | Candidate of Engineering Sciences assoc. professor Radomska M.M. | | |

8. Date of task assignment: “_____»___________ 2020

Supervisor of diploma work ________________ Yakushenko O.S.
(supervisor`s signature) (name & initials)

Assignment is accepted for execution ________________ Horbach Z.Y.
(undergraduate student`s signature) (name & initials)

## ABSTRACT

Explanatory note to the thesis "Diagnosis of the flowing part of the turbocharged gas turbine engine TV3-117».

116 p., 26 figures., 5 tables., 26 references.

The object of study - the flowing part TB3-117.

Subject of study – measured parameters in different section of GTE.

The purpose of the work – to make the diagnostic of the GTE using main measured parameters.

**CONTENT**

## LIST OF ABBREVIATIONS

| | |
|---|---|
| GTE – | gas turbine engine |
| HPK – | high pressure compressor |
| MM - | mathematical model |
| DE – | design element |
| CC | combustion chamber |
| SE – | structural element |
| CAC – | standard atmospheric conditions |
| PT | power turbine |
| HPT – | high pressure turbine |
| LPT – | low pressure turbine |
| MR – | maintenance and repair |

# INTRODUCTION

Technical diagnostics of complex objects is a direction in science and technology, which is the process of determining the technical state of an object to be diagnosed with a certain accuracy.

The technical condition is understood as a set of properties of an object subject to change in the course of production or operation, characterized at a certain point in time by the features established by the technical documentation [18] for this object.

The totality of technical conditions, satisfying or not satisfying the requirements that determine the serviceability, operability or correct functioning of the object, forms the corresponding types of the technical state of the object. Determination of the type of technical condition is possible if the technical condition, determined by diagnostics, and the requirements that determine the serviceability, operability and correct functioning of the object [23], are known, - specified, for example, in the form of a specification in the technical documentation of the nomenclature and permissible values of quantitative and qualitative characteristics of properties object.

An aircraft gas turbine engine (GTE) is practically a complex technical object (hybrid object) [21]. Checking the serviceability, operability and correct functioning of the aviation GTE is necessary during the operation of the latter to ensure flight safety. Rapid troubleshooting of complex engine systems is also required to reduce aircraft downtime, thereby increasing aircraft economy.

The main goal of technical diagnostics of an aviation GTE is the effective organization of processes for assessing its technical condition, which is based on the main provisions of the general theory of technical diagnostics, methods for constructing and analyzing mathematical models of diagnosed objects, and methods for constructing diagnostic algorithms.

Technical diagnostics of an aviation GTE is a process of researching the latter. The end of this study is the conclusion about the state of the GTE as an object of diagnostics: the engine is in good working order, the engine is faulty, as fault in the engine [20].

In the general case, the diagnostic process consists of separate parts, each of which is characterized by a test or working action applied to the diagnostic object and the object's response to this impact, called a response. The result of an elementary check is the value of the object's response. The formal description of the diagnostic process, called the algorithm for diagnosing the technical state of an object, is an accepted sequence of elementary checks and rules for analyzing their results.

One of the main factors that significantly affect the efficiency of the process of diagnosing an aviation GTE is the quality of the diagnostic algorithms [24]. Optimization of diagnostic algorithms depends on a number of circumstances and factors.

Thus, the number of elementary checks required to solve specific diagnostic problems is, as a rule, less than the number of all physically possible and realizable elementary checks of the engine. Different elementary checks require different costs for their implementation and provide different information about the technical condition of the engine. In addition, the same elementary checks can be performed in a different sequence.

Therefore, to solve one and the same diagnostic problem (for example, to check serviceability), several algorithms can be constructed that differ from each other either in the composition of elementary checks, or in the sequence of their implementation, or both.

The development of methods for constructing optimal algorithms for diagnosing the technical state of an aviation gas turbine engine, requiring minimum costs for their implementation, is dictated by the need to increase labor productivity in individual diagnostic operations, to reduce the time it takes to detect malfunctions in the process of using the engine for its intended purpose in order to improve the safety of the aircraft flight. shorter time for troubleshooting [16].

One of the acute problems in the development of diagnostic systems is to obtain reliable and sufficient information about the technical state of the object under study.

If earlier it was believed that the collection of information on the technical state of an aviation GTE should mainly be carried out in ground conditions during its operation according to special programs, now the main attention is paid to the collection of diagnostic information directly in flight, i.e., in the process of using the engine. by appointment.

The availability of reliable statistical data significantly expands the possibilities of efficient organization of diagnostic processes. The collection of such data is possible only through the use of reliably operating built-in diagnostic instrumentation, which ensures high accuracy of measurements and their automatic recording. Only then is the reliability of the diagnostic results guaranteed, which minimizes the influence of subjective factors and simplifies the statistical processing of the results.

At present, a part of the technical diagnostics system of an aviation GTE has been practically developed, which is able to perceive the primary initial information, process it and perform analysis to detect malfunctions and determine the causes of their occurrence [24]. The existing methods and means of monitoring the technical condition of the aviation GTE already now allow detecting at an early stage of development such malfunctions as: expansion of the launch time limits; high launch rate; freezing of the rotor speed during start-up; underestimation or overestimation of the rotational speed of small hectares; drop or increase in speed; lack or interruption of fuel supply; failure of the ignition system; overheating of parts; poor quality setting of thermocouples, etc.

The object of study - the flowing part TB3-117.

Subject of study – measured parameters in different section of GTE.

The purpose of the work – to make the diagnostic of the GTE using main measured parameters.

Main goals of work – to calculate main parameters, select the sensors, analyze measurement errors, describe influence of measurement deviation, analyze diagnostic deviation trend.

# 1 MAIN TASKS OF TECHNICAL DIAGNOSTICS AVIATION GTE

## 1.1 General tasks of technical diagnostics

Technical diagnostics of an aviation GTE can solve three types of problems. The first type includes tasks to determine the state in which the engine is at the present time. These are diagnostic tasks. So no problem arises to conclude on the guaranteed safe operation of the engine. on this particular flight. The second type includes tasks to determine the state in which the engine will find itself at some future moment in time. These are forecasting tasks that arise to establish the safe life of the engine, to determine the timing of preventive checks and repairs. The third type includes the problem of determining the state in which the engine was at a certain moment of time in the past. These are genesis problems [20]. Tasks of this nature arise in connection with the investigation of incidents and the prerequisites for them.

In all cases, knowledge of the state of the aviation gas turbine engine at the present moment in time is mandatory for both forecasting and genesis.

Aviation GTE is diagnosed during production and operation and, if necessary, its storage.

For a gas turbine engine at each stage, certain technical requirements (technical conditions) are set. An indispensable condition for normal operation is the compliance of the GTE parameters with the technical requirements [23]. However, in the components and systems of the engine, malfunctions can occur that violate this compliance. Naturally, the problem arises to create initially (at the stage of production) or restore the compliance of the engine parameters with the technical requirements disturbed by a malfunction (at the stage of storage or operation). The solution to this problem is impossible without reliable periodic or continuous technical diagnostics.

In many cases, it is necessary to make sure that the engine is in good working order, that is, there is not a single malfunction in its components and systems.

This is called an engine health check.

During the production process, it reveals whether the assembled engine contains defective parts and assemblies, and their installation and adjustment are errors. During the repair process, the serviceability check allows you to make sure that all faults identified during operation and defect have been eliminated, and during storage - in the occurrence of any faults during this time.

During operation, during preventive checks before using the engine for its intended purpose, it is necessary to make sure that it is able to perform all the functions provided for by its operating algorithm of operation. Such a check, carried out, for example, during pre-flight preparation and engine testing, is called an engine performance check. It is less complete than a serviceability check, since it can leave undetected malfunctions, which, due to their insignificance, do not have a noticeable effect on the operation of the engine and do not interfere with its intended use.

During operation, if it is necessary for the engine to perform its working algorithm of functioning, for example, during flight, it is necessary to monitor the appearance of malfunctions in the engine that disrupt its normal operation [21]. This check, carried out by the aircraft crew, is less complete than a performance check, since it only makes sure that the engine is functioning correctly in a given operating mode and at a given time.

A properly functioning engine may have malfunctions that prevent it from operating correctly (normally) in other modes or in different flight conditions. An efficient engine will function correctly in all modes in all permissible flight conditions and for the entire specified time.

A properly functioning engine may be malfunctioning and therefore defective. A healthy engine may also be faulty.

One of the important tasks of technical diagnostics of an aviation gas turbine engine is the development of methods for troubleshooting, i.e., indicating the places and causes of their occurrence [25]. Quick troubleshooting is necessary to identify and eliminate faulty units and system elements, adjust them in order to reduce the downtime of the aircraft.

Serviceable and many faulty states of the GTE form a set of its technical conditions. Checking the serviceability, operability, correct functioning, troubleshooting are special cases of the general problem of diagnosing the technical condition of an aviation GTE.

By checking malfunction, operability and correct functioning, two possible outcomes are revealed [21]. The first contains either only a good state (when checking the health), or, in addition to a good one, those faulty states are identified, being in which the GTE remains operable or correctly functioning. The second result contains either all faulty conditions (in the health check), or those in which the presence of which makes the engine inoperative or malfunctioning.

Troubleshooting results in results that can be categorized into groups of indistinguishable fault conditions. Their number determines the degree of detail of the locations and the composition of existing (or assumed) faults in the engine. In the theory of technical diagnostics, this degree of detail is usually called the depth of search, or the resolving power of diagnostics [20].

## 1.2 Direct and inverse problems of diagnostics

Direct problems of diagnosing the technical condition of a gas turbine engine are understood to be the determination of certain information about its technical condition from a given elementary check.

An elementary check is a test or operating impact on the engine and its response to this impact. When diagnosing a gas turbine engine under operating conditions, operating influences are used as a component of an elementary check, consisting in changing the position of all kinds of controls [18]. When diagnosing a gas turbine engine under test conditions, it is possible to use test influences by connecting engine components and systems to special devices. When developing a diagnostic system, a number of engine states can be taken for information obtained during an elementary check. matching this check.

To solve direct problems of diagnostics, it is necessary to first construct a mathematical model of a serviceable engine and to perform the necessary set of admissible elementary checks of supposed faults. The mathematical model of a serviceable engine should provide input into it of any of the possible malfunctions and the calculation of the result of an elementary check based on the known value of its effect.

Solving inverse problems of diagnostics makes it possible to analyze all admissible checks in order to select only the most effective or discriminating checks. If, for example, there is a single malfunction in the engine, then it can be detected by an elementary check with the fulfillment of the condition for its manifestation and transportation to control points.

The manifestation of a malfunction is the appearance of a value of one or more input, internal or output parameters of the engine, which differ from the values corresponding to its good condition.

A significant reduction in the amount of work in the development of a specific diagnostic system can be achieved by alternating the solution of direct and inverse diagnostic problems. In this case, first, using the ways of solving the partial direct and partial inverse problems of the analysis of the model of the diagnosed object, an elementary check is calculated that detects a certain malfunction or distinguishes a pair of malfunctions [18]. After that, based on the obtained elementary check, a more extended elementary check is determined by determining those input and internal parameters that were not used during the elementary check, and also by including all outputs of the diagnostic object in the checkpoints.

Then the direct problem of diagnostics is solved, i.e., all faults detected by the extended elementary check are determined. The calculation cycle is repeated for each new fault.

### 1.3 Characteristics of aviation gas turbine engine as an object of diagnosis

An aircraft gas turbine engine and its functionally related systems are an integral part of an operational diagnostic system. The choice of methods and means of technical 'diagnostics of the main units and systems of the engine under operating conditions is largely determined by the controllability, that is, the availability of their design and equipment for the possibility of obtaining reliable information necessary for an objective assessment of the technical condition without disassembly [17].

Special tests and operating practice indicate that an objective assessment of the technical condition of a well-mastered engine, depending on the complexity of its design, is possible by measuring and analyzing 20–100 parameters. The processing of such a number of parameters makes it possible to monitor the operability, correct functioning and determine the serviceability of the engine with a depth to the node. Under the conditions of engine fine-tuning, as well as when it is necessary to assess the technical state with a depth of up to an individual element, the measurement and analysis of 200-1000 parameters is required. At the same time, the methods of their processing become significantly more complicated.

The operation of a gas turbine engine is characterized by a complex interaction of its systems: fuel control, air bleed, control of the rotation of the blades of the compressor straighteners, power synchronization (for helicopter gas turbine engines), limitation of limiting parameters, lubrication, venting, starting, etc [21]. Therefore, an assessment of the technical condition of the engine is possible based on the measurement and analysis of parameters reflecting this relationship. These parameters are called basic parameters.

These include: thrust (effective power), hourly fuel consumption, rotor speed, gas temperature in front of the turbine, position of the lever for controlling fuel supply to the engine, parameters of functioning of the main engine systems.

The main group should also include the parameters of the environment, since the parameters characterizing the operation of the engine, when operating with them, are reduced to standard atmospheric conditions.

Different groups of parameters have different requirements for measurement accuracy. The main parameters are measured with a high degree of accuracy [17]. Auxiliary parameters that determine the performance of individual units or units of functional tasks under operating conditions can be measured with a lower degree of accuracy, since they are used in diagnostics with a depth to the unit or unit.

Particularly important in the conditions of use of the engine for its intended purpose is the measurement accuracy of emergency parameters, the failure of which outside the tolerance limits can lead to engine failure. Therefore, the monitoring of emergency parameters during engine operation is carried out continuously.

Difficulties in accurately determining the parameters for diagnostics lie in the fact that each mode of engine operation has its own parameters. This is due to the dynamism - the interaction of gas flows in the flow path of the engine and the rotating masses of the rotors, the thermal inertia of the engine.

Therefore, the development of effective methods for processing measurement results is of particular importance in the process of diagnosing the technical state of the engine.

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## 2 ANALYSIS AND STRUCTURE OF THE PROTOTYPE ENGINE

### 2.1 Analysis of the main technical data of the prototype engine

The TV3-117 engine was chosen as a prototype.

The TV3-117 engine is designed for civilian helicopters [1].

In terms of fuel economy and weight characteristics, the engine is among the world's best models.

The high level of design and high degree of smoothness of process of serial production provided to the engine high indicators of reliability and a big resource [2].

The main technical characteristics of the engine - prototype:

rated power under normal conditions 1,1 MWt;

the degree of increase in air pressure in the compressor 9,8;

gas consumption at the cut of the exhaust pipe 70 kg/s;

gas temperature at the cut of the exhaust pipe, 683 – 703 K;

the gas temperature in front of the turbine is calculated, 1150 K;

rated speed of the power turbine shaft 1000 rpm;

axial high pressure compressor, number of stages 12;

combustion chamber tubular-annular, the number of fire tubes 16;

axial high pressure turbine, number of stages 2;

low pressure turbine (power) axial, the number of stages 2

Direction of rotation of the rotor of the power turbine counterclockwise (left).

For the engine being designed, determine the gas temperature in front of the turbine $T`_{ch}$ = 1250 K, parameters of the main elements of the designed GTU are determined according to methodical recommendations (table. 1.1).

To determine the rational value of the degree of pressure increase in the compressor, we perform parametric optimization of the workflow within the change of the degree of pressure increase in the compressor from 10 to 30.

Table 1.1

Parameters of the main elements of the engine

| | |
|---|---|
| $\sigma_{in}$=0,98 | The ratio of the total pressure of the inlet device; |
| $\eta^*_{KBT} = 0{,}82$ | Efficiency HPC; |
| $\sigma_{кз}$=0,97 | The coefficient of recovery of total pressure in CCh; |
| $\eta^*_{TBT} = 0{,}89$ | Efficiency HPT; |
| $\eta^*_{THT} = 0{,}9$ | Efficiency LPT. |

## 2.2 Engine design

The structural layout of the engine includes an inlet device, a compressor, a combustion chamber, a compressor turbine, a free turbine and an outlet device [3].

The inlet device is a part of the helicopter fuselage that forms a smooth channel for the supply of air from the atmosphere to the compressor with minimal hydraulic losses. The inlet device is designed to supply air from the atmosphere to the compressor with the specified parameters. In the engine inlet device, the air flow is accelerated to the required speed due to the discharge created by the compressor during its operation.

Engine compressor

The compressor of the engine - axial, twelve-stage, high-pressure, highly mechanized with rotary blades of the entrance directing device and directing devices of the first four stages of the compressor, and also with two operated valves of air bypass because of the seventh stage of the compressor. The compressor is used to increase the air pressure due to the mechanical work supplied by the compressor turbine.

Combustion chamber

Combustion chamber - ring, direct flow. The combustion chamber is designed to organize the process of fuel combustion and the supply of heat released to the working fluid - air. In the combustion chamber there is a change in the chemical composition of the working fluid. Air is converted into a gas, which is a mixture of air and combustion products.

Compressor turbine

The compressor turbine is a jet, two-stage axial. The compressor turbine is designed to convert part of the gas enthalpy into mechanical work to drive the compressor and engine units.

Free turbine

Free turbine - jet, two-stage, axial. The free turbine is a converter of energy of a gas stream in mechanical work for creation of the power transferred through transmission and a reducer on rotation of bearing and steering screws of the helicopter, and also units established on the main reducer.

Engine output device

The output device of the engine is made in the form of an expanding oval pipe, reducing the speed of the gas flow and diverting it away from the axis of the engine in such a way as to prevent hot gases from entering the structural elements of the helicopter.

The system of start of the TVZ-117B engine – independent [2]. The starting system is intended for reliable repeated start of engines in all conditions of operation, performance of false start and scrolling of a rotor of the turbo compressor when performing preventive and regular works. The turbocharger rotor is promoted with the help of the SV-78BA air starter, which uses compressed air from the AI-9V auxiliary power unit, and the ignition of the fuel-air mixture is carried out by an electric ignition system.

## Conclusions

The analysis of the basic technical data of the engine-prototype TV3-117 is carried out. The parameters of the working process of the engine being designed are determined and a description of its design was made. Also was described GTE main units.

# 3 MATHEMATICAL MODEL THAT ALLOWS TO EVALUATE THE LEVEL OF DIAGNOSTIC DEVIATIONS DEPENDING ON THE MEASURED PARAMETERS

Direct problems of diagnosing the technical condition of a gas turbine engine are understood to be the determination of certain information about its technical condition from a given elementary check [20].

An elementary check is a test or operating impact on the engine and its response to this impact. When diagnosing a gas turbine engine under operating conditions, working influences are used as a component of an elementary check, consisting in changing the position of all kinds of controls. When diagnosing a gas turbine engine under test conditions, it is possible to use test influences by connecting engine components and systems to special devices [21]. When developing a diagnostic system, a number of engine states can be taken for information obtained during an elementary check. matching this check.

To solve direct problems of diagnostics, it is necessary to first construct a mathematical model of a serviceable engine and to perform the necessary set of admissible elementary checks of supposed faults. The mathematical model of a serviceable engine should provide input into it of any of the possible malfunctions and the calculation of the result of an elementary check based on the known value of its effect.

## 3.1 Thermodynamic calculation of GTE

The purpose of thermodynamic calculation is to determine the main parameters of the working fluid in the characteristic cross sections of the flow part of the gas turbine [11], specific power and specific fuel consumption.

Output data:

GTE power at takeoff mode $N_e$ =1.6 МВт;

gas temperature $T`_{ch}$ =1250 К;

pressure ratio into the compressor $\pi'_c$= 9,8;

inlet parameters of GTE:

$T_n$= 288.15 K;

$P_n$= 101325 Pa;

adiabatic index for air: $k$ = 1,4;

gas table for air: $R$ = 287,3 J/(kg · K);

adiabatic index for gas $k_{ch}$ = 1,33;

gas table for gas: $R_{ch}$ = 288 J/(kg · K);

Determination of air parameters at the inlet to the GTE.

Air temperature:

$$T'_n := T_n + \frac{V}{2 \cdot \frac{k}{k-1} \cdot R} \qquad T'_n = 288.15$$

Air pressure:

$$P'_n := P_n \cdot \left(\frac{T'_n}{T_n}\right)^{\frac{k}{k-1}} \qquad P'_n = 1.013 \times 10^5$$

The coefficient that takes into account the loss of total pressure in the inlet device is accepted $\sigma_{in}$=0,96 and determine $T`_{in}$ and $P`_{in}$:

$$T`_{in} = 288.15 \text{ K}$$

$$P'_{in} := P'_n \cdot \sigma_{in}$$

$$P`_{in} = 9.727 \cdot 10^4 \text{ Pa}$$

In accordance with the recommendations, we accept compressor stage efficiency $\eta'_{st} := 0.88$ and determine compressor efficiency by formula:

$$\eta'_c := \frac{\pi'_c{}^{\frac{k-1}{k}} - 1}{\pi'_c{}^{\frac{k-1}{k \cdot \eta'_{st}}} - 1} \qquad \eta'_c = 0.837$$

The temperature and air pressure at the outlet of the compressor are calculated by formulas:

$$P'_c := P'_{in} \cdot \pi'_c \qquad P`_c=953.3 \text{ kPa}$$

$$T'_c := T'_{in} + \frac{L_c}{\frac{k}{k-1} \cdot R} \qquad T`_c=604.5\text{K}$$

Determine the work of air in compressor:

$$L_c := \frac{k}{k-1} \cdot R \cdot T'_{in} \cdot \left( \pi'_c{}^{\frac{k-1}{k}} - 1 \right) \cdot \frac{1}{\eta'_c}$$

$$L_c = 3.182 \cdot 10^5 \text{ J/kg}$$

Taking the full pressure recovery factor in CC $\sigma_{кз}$ = 0,96 determine the gas pressure at the outlet of CC:

$$P'_{ch} := P'_c \cdot \sigma_{ch} = 9.151 \times 10^5$$

$$P`_{ch} = 9.151 \cdot 10^5 \text{ Pa}$$

According to the recommendations, the average heat capacity of gases in CC is calculated using the dependence:

$$C_{P.ave} := 878 + 0.208 \cdot \left(T'_{ch} + 0.48 \cdot T'_c\right)$$

$$C_{P.ave} = 1.198 \times 10^3 \text{ K}$$

The relative fuel consumption is found by setting the combustion coefficient $\eta_г$=0,98 and taking the value of the lower heat of combustion of the fuel:

$H_u=42.5 \cdot 10^6$ J/kg

$$g_t := \frac{C_{P.ave} \cdot \left(T'_{ch} - T'_c\right)}{\eta_{ch} \cdot H_u}$$

$$g_t = 0.019$$

For gaseous fuel can be taken:

$$l_0 := 14.7$$

The total coefficient of excess air in CC:

$$\alpha := \frac{1}{g_t \cdot l_0} \qquad \alpha = 3.663$$

In accordance with the recommendations we accept:

relative air flow rate for cooling turbine parts $q_{cool}$ = 0,03;

mechanical efficiency;

$$\eta_m := 0.985$$

efficiency of HPT $\eta`_{th}$=0.98

and calculate the parameters behind the HPT:

The temperature and air pressure at the outlet of the compressor are calculated by formulas:

$$T'_{th} := T'_{ch} - \frac{k_{ch} - 1}{k_{ch}} \cdot \frac{L_{th}}{R_{ch}}$$

$$T`_{th}=968.333K$$

$$P'_{th} := P'_{ch} \cdot \left(1 - \frac{T'_{ch} - T'_{th}}{T'_{ch} \cdot \eta'_{th}}\right)^{\frac{k_{ch}}{k_{ch}-1}}$$

$$P`_{th}=2.822 \cdot 10^5 \text{ Pa}$$

In accordance with the recommendations, we accept the efficiency of LPT as $\eta`_t$=0.89 and calculate the parameters for LPT:

Assuming that the PT is fully expanded, we calculate the pressure on the PT:

$$P'_t := 1.05 \cdot P_n$$

$P`_t$=1.064·10$^5$ Pa

In accordance with the recommendations, we accept the efficiency of PT $\eta`_t$=0.89 and calculate the work of PT:

$$L_t := \frac{k_{ch}}{k_{ch}-1} \cdot R_{ch} \cdot T'_{th} \cdot \left[1 - \left(\frac{P'_t}{P'_{th}}\right)^{\frac{k_{ch}-1}{k_{ch}}}\right] \cdot \eta'_t$$

$L_t$=2.15·10$^5$ J/kg

Determine temperature behind the PT:

$$T'_t := T'_{th} - \frac{k_{ch}-1}{k_{ch}} \cdot \frac{L_t}{R_{ch}}$$

$T`_t$=783.087 K

Setting the given speed $\lambda_t$= 0.5 at the outlet of the free turbine, find the gas velocity and static parameters of the gas behind the turbine according to the formulas:

$$C_t := \lambda_t \cdot \sqrt{2 \cdot \frac{k_{ch}}{k_{ch}+1} \cdot R_{ch} \cdot T'_t}$$

$C_t$=253.708 m/s

$$T_t := T'_t \cdot \left(1 - \frac{k_{ch}-1}{k_{ch}+1} \cdot \lambda_t^2\right)$$

$T_t$=755.36 K

$$P_t := P'_t \cdot \left(1 - \frac{k_{ch}-1}{k_{ch}+1} \cdot \lambda_t^2\right)^{\frac{k_{ch}}{k_{ch}-1}}$$

$P_t$=9.2·10$^4$ Pa

If $P_t$ lower than $P_n$, it means that behind turbine flow part of outlet unit has diffuser form, where speed decreased, and static pressure increased from $P_t$ to $P_n$.

Let's determine speed and temperature of gas flowing from outlet unit by the formulas:

$$C_c := \varphi_c \cdot \sqrt{2 \cdot \frac{k_{ch}}{k_{ch}-1} \cdot R_{ch} \cdot T'_t \cdot \left[1 - \left(\frac{P_n}{P'_t}\right)^{\frac{k_{ch}-1}{k_{ch}}}\right]}$$

**where $\varphi_c$=0.975

$C_c$=144.203 m/s

$P_c$=$P_n$=$1.013 \cdot 10^5$ Pa

$$T_c := T'_t - \frac{k_{ch}-1}{k_{ch}} \cdot \frac{C_c^{\,2}}{2R_{ch}}$$

$T_c$=774.129 K

Using determined parameters lets calculate main specific parameters of out turboshaft engine:

Specific effective power (onto second shaft) and specific fuel consummation determined by formulas:

$L_e := L_t$ $L_e=2.15 \cdot 10^5$ j/kg

$$N_{e.s} := L_e \cdot (1 + g_t)$$

$N_{e.s}=2.19 \cdot 10^5$ J/kg*N

$$C_e := \frac{3600 \cdot g_t \cdot (1 - g_{cool})}{N_{e.s}}$$

$C_e=2.961 \cdot 10^{-4}$ kg/h

$$g_t := \frac{C_{P.ave} \cdot \left(T'_{ch} - T'_c\right)}{\eta_{ch} \cdot H_u}$$

$g_t$=0.019

Calculate the flow of air through GTE:

$$G_{air} := \frac{N_e}{N_{e.s}}$$

$G_{air}$=7.305 kg/s

Internal efficiency of GTE determined by formula:

$$\eta_e := \frac{L_e}{g_t \cdot H_u \cdot \left(1 - g_{cool}\right)}$$ $\eta_e$=0.281

Based on the results of thermodynamic calculation, we construct the dependences of the change in total pressure and total temperature on the engine path (Fig. 3.1) [12].

### 3.2 Gas-dynamic calculation of GTE

The purpose of gas-dynamic calculation is to determine the size in the characteristic cross sections of the flow part of the gas turbine, the number of rotors and their speeds, the number of stages of the compressor and turbine, the distribution of compression (expansion) between stages and stages, clarification of gas turbine parameters [13].

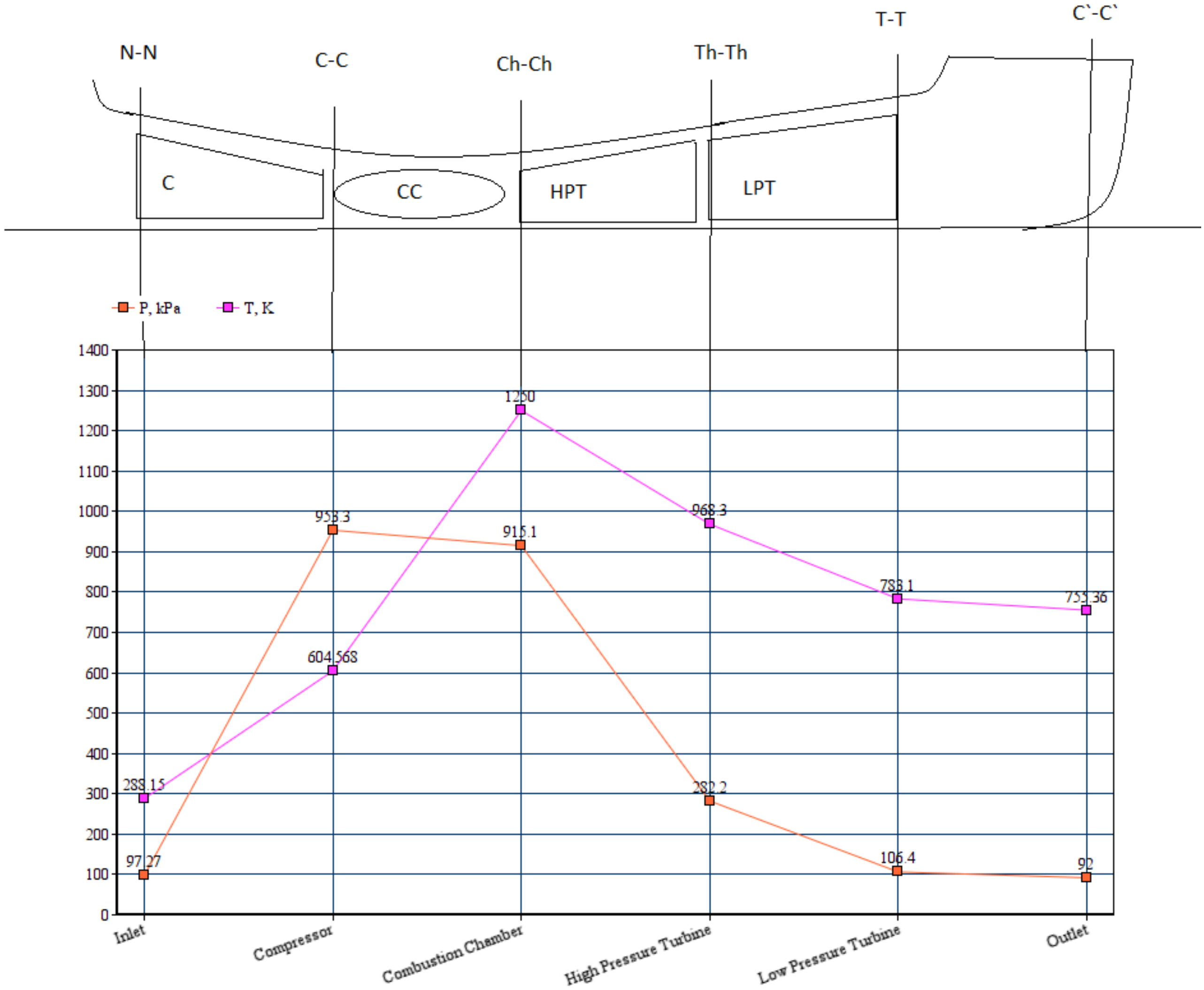


Figure 3.1 - Temperature and pressure during the GTE flowpath.

The results of thermodynamic calculation of GTU are used as initial data.

When profiling the working blade of the first stage of the subsonic compressor in accordance with the recommendations determine the axial flow rate at the inlet to the first stage of the compressor $C_{1a}$= 150 m/s.

Determination of sizes of inlet compressor section:

Reduced speed of compressor blades $\lambda_{1a}$ and related flow density $q(\lambda_{1a})$ determined by formula:

$$\lambda_{1a} := \frac{C_{1a}}{18.3\sqrt{T'_{in}}} \qquad \lambda_{1a} = 0.483$$

$$q(\lambda_{1a}) := 0.688$$

The cross-sectional area at the entrance to the compressor is determined on the basis of the results of thermodynamic calculation of air flow, accept that mass of air equal to 0.040348 kg:

$$F_{in} := \frac{\left(G_{air} \cdot \sqrt{T'_{in}}\right)}{m_{air} \cdot P'_{in} \cdot q(\lambda_{1a})}$$

$F_{in}$=0.046 m$^2$

We accept the relative diameter of the sleeve (according to the prototype) $d_1$=0.5 m·

The final diameter of the compressor at the inlet is determined by the ratio:

$$D_{1c} := \sqrt{\frac{4 \cdot F_{in}}{\pi \cdot \left(1 - d_1\right)^2}}$$

$D_{1c}$=0.484 m.

The diameter of the sleeve at the entrance to the compressor is determined by the formula:

$$D_{1b} := \sqrt{D_{1c}^2 - \frac{4 \cdot F_{in}}{\pi}}$$

$D_{1b}$=0.419 m.

Blade height at the first stage of compressor:

$$h_{bl} := \frac{D_{1c} - D_{1b}}{2}$$

$h_{bl}$=0.032 m.

Determination of sizes of outlet compressor section:

Reduced speed of compressor last stage blades $\lambda_{1a}$ and related flow density $q(\lambda_{1a})$ determined by formula:

$$\lambda_{ac} := \frac{C_c}{18.3 \cdot \sqrt{T'_c}}$$

$\lambda_{ac} = 0.32$

$q(\lambda_{ac}) := 0.4835$

The cross-sectional area at the exit of the compressor is determined on the basis of the results of thermodynamic calculation of air flow:

$$F_c := \frac{G_{air} \cdot \sqrt{T'_c}}{m_{air} \cdot P'_c \cdot q(\lambda_{ac})}$$

$F_c$=0.009 $m^2$.

The final diameter of the compressor at the outlet is equal to inlet diameter:

$D_c$=$D_{1c}$=0.484 m.

The diameter of the sleeve at the entrance to the compressor is determined by the formula:

$$D_{b.c} := \sqrt{D_c^2 - \frac{4 \cdot F_c}{\pi}}$$

$D_{b.c}$=0.471 m.

Blade height at the first stage of compressor:

$$h_{bl} := \frac{D_{1c} - D_{b.c}}{2}$$

$h_{bl}$=0.0064 m.

$$d_{b.c} := \frac{D_{b.c}}{D_c}$$

$d_{b.c}$=0.973 m

To reduce $d_{b.c}$ at outlet of compressor lets reduce diameter $D_c$ of the last stages to 0.4 m. Than:

$$D_{b.c} := \sqrt{0.4^2 - \frac{4 \cdot F_c}{\pi}} = 0.384 \text{ m}$$

$$h_{bl} := \frac{(0.4 - 0.384)}{2} = 8 \times 10^{-3} \text{ m}$$

$$d_{b.c.} := \frac{0.384}{0.4} = 0.96 \text{ m}$$

So, at inlet of compressor we have $D_c$=0.484 m, $D_b$=0.419 m, $h_{bl}$=32 mm, and at outlet of compressor we have $D_c$=0.4 m, $D_b$=0.384 m, $h_{bl}$=8 mm.

For calculation of diameter parameters of HPT, we need to calculate work and number of stages of HPT:

Using work of compressor calculated in thermodynamic calculation determine work of HPT by formula:

$$L'_{th} := \frac{L_c}{(1 + g_t)(1 - g_{cool}) \cdot \eta_m}$$

$L`_{th}$=326.9 kJ/kg.

Approximately determine, at which peripheral speed of HPT we can get work $L_{th}$=326.9 kJ/kg.

Let y`=0.55, then if there is one stage turbine (z=q, $\eta`_t$=0.89), we get:

$$u_{th.ave} := y' \cdot \sqrt{\frac{2 \cdot L_{th}}{z \cdot \eta'_{th}}}$$

$U_{th.ave}$=471.428 m/s.

This angle speed can’t exist, so let z=2:

$$u_{th.ave} := y' \cdot \sqrt{\frac{2 \cdot L_{th}}{z \cdot \eta'_{th}}}$$

$U_{th.ave}$=333.35 m/s.

Therefore, we can accept two-stage HPT.

Work of turbine $L_{th}$ we distribute with difference in 10% as:

$L_{st1}$=179.8 kJ/kg;

$L_{st2}$=147.1 kJ/kg.

Let's choose the angle of flow exit from nozzle $\alpha_1$=20° and determine flow speed of gas from nozzle:

$$C_1 := \frac{L_{st1}}{u_{th.ave} \cdot \cos(\alpha_1)}$$

$C_1$ = 574.026 m/s.

$$\lambda_1 := \frac{C_1}{18.15 \cdot \sqrt{T'_{ch}}}$$

$$\lambda_1 = 0.895$$

$q(\lambda_{1ca})$ = 0.9866 – using gasdynamic function table from training manual.

Pressure and consumption of gas at nozzle outlet determined by formulas:

$$G_{ch} := G_{air} \cdot (1 + g_t) \cdot (1 - g_{cool})$$

$G_{ch}$ = 7.218 kg/h.

$$P'_{ca} := P'_c \cdot \sigma_{ch} \cdot \sigma_{ca}$$

$P`_{ca}$ = 89.23 kPa

Section area at nozzle outlet determine by formula:

$$F_{1ca} := \frac{G_{ch} \cdot \sqrt{T'_{ch}}}{m_{ch} \cdot P'_{ca} \cdot q_{\lambda 1ca} \cdot \sin(\alpha_1)}$$

$F_{1ca}$ = 0.021 $m^2$.

Accept $D_{t.ave}$ = 0.484, then:

$$h_1 := \frac{F_{1ca}}{\pi \cdot D_{t.ave}}$$

$h_1$ = 0.014 m.

$$D_t := D_{t.ave} + h_{bl}$$

$D_t = 0.498$ m.

Determine the diameter of HPT bushing by formula:

$$D_b := \sqrt{D_t^2 - \frac{4 \cdot F_{1ca}}{\pi}} = 0.47$$

So, at the inlet of HPT we have $D_{th} = 0.498$ m, $D_b = 0.47$ m and $h_{bl} = 0.014$ m.

Speed of gas at HPT inlet section determine by formula:

$$C_{1a} := C_1 \cdot \sin(\alpha_1)$$

$C_{1a} = 196.293$ m/s.

Stress in dangerous sections of the blades from the action of centrifugal forces determine by formula:

$$\sigma_p := 2 \cdot \rho \cdot K_\phi \cdot u_{th.ave}^2 \cdot \frac{h_{bl} \cdot 10^{-5}}{D_{t.ave}}$$

$\sigma_p = 258.98$ MPa.

Using the table from Appendix 5 in the manual materials [11], we find that the strength of HPT blades can be ensured when using alloy ЭИ-617 for the manufacture of blades and intensive cooling of the blades to a temperature of 950 K. Under these conditions, $\sigma_{100} = 330$ and a margin of safety:

$$n := \frac{\sigma_\tau}{\sigma_p} = 1.274$$

Working HPT blades satisfy the strength conditions.

Determination of diameter parameters at outlet section of HPT.

Gas parameters at HPT outlet determined by formulas:

$$T'_{th} := T'_{ch} - \frac{L_{th}}{\frac{k_{ch} \cdot R_{ch}}{k_{ch} - 1}}$$

$T`_{ch}$ = 968 K.

$$P'_{th} := P'_{ch} \cdot \left(1 - \frac{T'_{ch} - T'_{th}}{T'_{ch} \cdot \eta'_{th}}\right)^{\frac{k_{ch}}{k_{ch}-1}}$$

$P`_{th}$ = 282.2 kPa.

Set the reduced velocity λ = 0.55, which corresponds to the axial component of the gas velocity at the exit from HPT: $C_{2a}$ = 0.55 · 18.15 $\sqrt{T`_{th}}$ =310.636 m/s. From the tables of gas dynamic functions, we find:

$q(\lambda_{2a})$ = 0.7623

Considering that part of the cooling air enters the gas flow and mixes with it, we take $g_{cool}$ = 0.03 and find the gas flow rate at the outlet from HPT:

$$G_{ch} := G_{air} \cdot (1 + g_t) \cdot (1 - g_{cool})$$

$G_{ch}$ = 7.218 kg/h.

Section area at outlet of HPT determine using formula:

$$F_{th} := \frac{G_{ch} \cdot \sqrt{T'_{th}}}{m_{ch} \cdot P'_{th} \cdot q_{\lambda 2a}}$$

$F_{th}$ = 0.026 m$^2$.

Allow $D_{t.ave}$ = 0.484 and determine the blade height of the second stage of HPT (by trailing edge):

$$h_{bl} := \frac{F_{th}}{\pi \cdot D_{t.ave}}$$

$h_{bl}$ = 0.017 m.

Then:

$$D_{th} := D_{t.ave} + h_{bl}$$

$D_{th} = 0.501$ m.

Accepting $D_{th} = 0.5$ m and determining $D_{b.th}$ by formula:

$$D_{b.th} := \sqrt{D_{th}^2 - \frac{4 \cdot F_{th}}{\pi}}$$

$D_{b.th} = 0.466$ m.

In order to make sure that the dimensions obtained are acceptable, we draw on a scale the flow path of a two-stage high-pressure turbine and find that the broadening angle of the flow path does not exceed 20 (up to 30 is allowed). Therefore, the diametrical dimensions of the high-pressure turbine can be taken as final.

Determination the quantity of compressor stages.

The work of first stage of compressor determined by formula, allowing lattice density $(v/t_1) = 2$:

$$\Delta W_{u1.b} := C_{1a} \cdot \frac{1.55}{1 + 1.5 \cdot \frac{t_b}{v_1}}$$

$\Delta W_{ul.b} = 173.86$ m/s.

$$u_{1b} := u_{th.ave} \cdot \frac{D_{1b}}{D_{t.ave}}$$

$u_{1b} = 288.69$ m/s.

$$L_{bl1} := u_{1b} \cdot \Delta W_{u1.b}$$

$L_{bl1} = 36.87$ kJ/kg.

The work of last stage of compressor determined by formula, allowing lattice density $(v/t_1) = 1.8$:

$$\Delta W_{u2.b} := C_{2a} \cdot \frac{1.55}{1 + 1.5 \cdot \frac{t_b}{v_2}}$$

$\Delta W_{uz.b} = 121.917$ m/s.

$$u_{zb} := u_{th.ave} \cdot \frac{D_b}{D_{t.ave}}$$

$u_{zb} = 323.639$ m/s.

$$L_{bl2} := u_{zb} \cdot \Delta W_{u2.b}$$

$L_{blz} = 39.46$ kJ/kg.

The average work of the stage will be:

$$L_{ave} := 0.5 \cdot (L_{bl1} + L_{bl2})$$

$L_{ave} = 38.16$ kJ/kg.

The quantity of stage determined using formula:

$$z_c := \frac{L_c}{L_{ave}}$$

$z_c \approx 9$

Comparing with the prototype engine TB3-117, we choose the number of blades equal to 12.

The power balance of the compressor and high-pressure turbine is checked using the formula:

$$N_c := G_{air} \cdot L_c$$

$N_c = 2324$ kWt,

$$N_{th} := G_{ch} \cdot L_{th}$$

$N_c = 2360$ kWt.

$$\eta_m := \frac{N_c}{N_{th}} = 0.985$$

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

$$n_c := 60 \cdot \frac{u_c}{\pi \cdot D_c}$$

$$n_{th} := 60 \cdot \frac{u_{th.ave}}{\pi \cdot D_{t.ave}}$$

$n_c$ = 13160 rpm, $n_{th}$ = 13160 rpm.

Determination the quantity of stages and work distribution by LPT stages.

Taking into account that the gas temperature is $T`_{th}$ = 968.33 K < 1200 K at the inlet and therefore the LPT not need to be cooled, and all the air cooling the elements of the high-pressure turbine is mixed with the gas flow, we get:

$$G_{ch.t} := G_{air} \cdot (1 + g_t) \cdot (1 - g_{cool.t})$$

$G_{ch.t}$ = 7.441 kg/s.

$L_t$ = 215 kJ/kg.

Using scale scheme of engine choosing $D_{t.ave}$ = 0.5 m, then:

$$u_{t.ave} := y' \cdot \sqrt{\frac{2 \cdot L_t}{z \cdot \eta'_{th}}}$$

$u_{t.ave}$ = 270.338 m/s.

Loading parameter y` determined if z = 2:

$$y' := u_{t.ave} \cdot \sqrt{\frac{z \cdot \eta'_t}{2 \cdot L_t}} = 0.55$$

Therefore, a two-stage turbine can be used. The distribution of work on the stages with difference between stages in 10%:

$L_{bl1}$ = 118.3 kJ/kg,

$L_{bl2}$ = 96.76 kJ/kg.

Determination of diameter parameters at the LPT outlet section.

Gas parameters at LPT outlet section determined by:

$$T'_t := T'_{th} - \frac{L_t}{\frac{k_{ch}}{k_{ch}-1} \cdot R}$$

$T`_t$ = 782.636 K.

$$P'_t := P'_{th} \cdot \sigma_{per} \cdot \left(1 - \frac{T'_{th} - T'_t}{T'_{th} \cdot \eta'_t}\right)^{\frac{k_{ch}}{k_{ch}-1}}$$

$P`_t$ = 103.5 kPa.

At outlet section of LPT axial gas velocity equal $C_{1a} = C_1 \cdot \sin(\alpha_1)$ = 159.188 m/s. Set the reduced speed at the outlet of the LPT: $\lambda_{at}$ =0.6, which corresponds $C_{at}$ = 340 m/s. Using gas-dynamic functions table determining $q(\lambda_{at})$ = 0.8109 [26]. The cross-section area at LPT outlet determining by formula:

$$F_t := \frac{G_{ch} \cdot \sqrt{T'_t}}{m_{ch} \cdot P'_t \cdot q_{\lambda at}}$$

$F_t$ = 0.061 $m^2$.

Accepting $D_t$ = 0.55 m and finding bushing diameter and height of blade:

$$D_{bt} := \sqrt{D_t^2 - \frac{4 \cdot F_t}{\pi}}$$

$D_{bt}$ = 0.474 m

$$h_{bl} := \frac{D_t - D_{bt}}{2}$$

$h_{bl}$ = 0.038 m.

So, at the LPT outlet section we have: $D_t$ = 0.55 m, $D_{bt}$ = 0.474 m, $h_{bl}$ = 0.038 m.

We draw the flow path of the LPT on a scale and find that the geometric dimensions are acceptable. Therefore, it is possible to realize LPT with two stages.

Rotating frequency of LPT rotor determine by formula:

$$n_t := \frac{60 \cdot u_{t.ave}}{\pi \cdot D_{t.ave}}$$

$n_t$ = 10330 rpm.

Determination of nozzle diameter parameters.

The outflow from the nozzle is subcritical, the expansion is complete, since:

$$\frac{P'_t \cdot \sigma_{per}}{P_n} = 0.995$$

which is lower than $\pi_{cr}$ = 1.85.

Outflow speed from nozzle equal $C_c$ =144.203

$$\lambda_{ca} := \frac{C_c}{18.15 \cdot \sqrt{T'_t}} = 0.284$$

$q(\lambda_{ca})$ = 0.4313

Determine the area and diameter of nozzle outlet:

$$F_n := \frac{G_{ch.t} \cdot \sqrt{T'_t}}{m_{ch} \cdot P'_t \cdot \sigma_{ca} \cdot q_{\lambda ca}}$$

$F_n$ = 0.121 $m^2$.

$$D_n := \sqrt{\frac{4 \cdot F_n}{\pi}}$$

$D_n$ = 0.392 m.

Specific fuel consumption determined by formula:

$$C_e := \frac{3600 \cdot g_t \cdot (1 - g_{cool})}{L_t}$$

$$C_e = 0.000301 \text{ kg/(N·h)}.$$

The obtained engine parameters coincide with the results obtained in thermodynamic calculation [13].

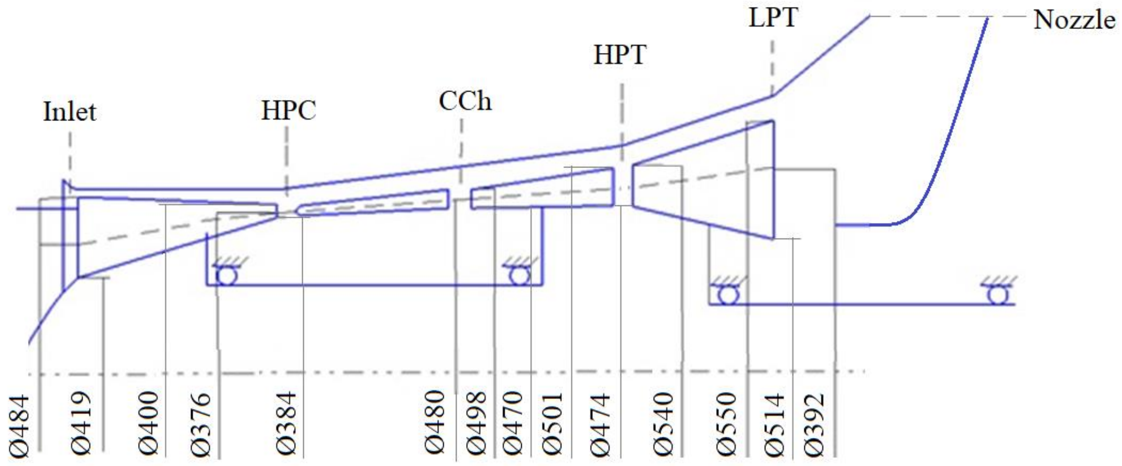


Figure 3.2 – Diameter dimensions in the main crossings of the engine

### 3.3 Mathematical model of GTE work process

The task of the mathematical model of the GTU workflow is to calculate the parameters of the gas turbine in throttle, in particular, engine speed, temperature, pressure, power and fuel consumption for primary diagnostic information processing is to obtain signs of the vehicle, which depend mainly on the vehicle and may contain measurement errors [24].

One of the purposes of the mathematical model of the working process is to obtain the dependences of the measured parameters of the working process on the relative consolidated speed of the rotor of the turbocharger at constant parameters of the air at the inlet to the gas turbine.

All calculations of GTE parameters are performed in accordance with the guidelines.

The initial parameters for the calculation choose the calculated parameters in the process of thermogas-dynamic calculation, which is assigned the index "r" (calculated).

The purpose of the report is to minimize the impact of working conditions on the results of diagnosis. For this purpose methods of the theory of similarity of modes of work of GTE are used [12]. At the same time it is necessary to use the dependences received from a condition of similarity of operating modes of the engine.

After determining the output parameters, select the value of the relative speed of the rotor $n_r$ in the range: 0.85; 0.9; 0.95; 1.0; 1.05; 1.1.

The inlet temperature is taken equal to the atmospheric temperature:

$T` = T`_n = 288$ K.

Тиск на вході приймаємо: $P`_n = 101325$ Pa.

Reduced value of the rotor speed using following formula:

$$n_{red_i} := n_{r_i} \cdot \sqrt{\frac{288}{T'_i}}$$

The relative degree of pressure increase in the compressor is found by the formula:

$$\bar{\pi}_к^* = \bar{n}_{зв}^a,$$

where $a = \pi_{кр}^{*\,0,2}$ – degree indicator;

$\pi_{кр}^*$ – the total degree of pressure increase in the compressor is calculated.

Then the degree of pressure increase is determined by the formula:

$$\pi_к^* = \pi_{кр}^* \cdot \bar{\pi}_к^*.$$

Relative efficiency of the compressor (efficiency):

$$\bar{\eta}_к^* = \bar{n}_{зв}^в,$$

where $в = \pi_{кр}^{*\,0,1}(\bar{n}_{зв} - \bar{n}_{зв}^2)$ – degree indicator.

Then the efficiency will be equal to:

$$\eta_к^* = \eta_{кр}^* \cdot \overline{\eta}_к^* .$$

The operation of the compressor is found by the formula:

$$L_k = \frac{kRT_в^*}{k-1}(\pi_k^{*(k-1)/k} - 1)\frac{1}{\eta_k^*} ,$$

where $k$ =1,4 – adiabatic index;

$R$ = 287,3 $J/kg \cdot К$ – gas coefficient.

The temperature of the compressor is determined by the formula:

$$T_к^* = T_в^* + L_k / [kR/(k-1)].$$

Combustion chamber pressure:

$$P_Г^* = P_H \pi_к^* \sigma_{кзр} \sigma_{вхр} ,$$

where $\sigma_{кзр} = 0{,}97$ – the coefficient of recovery of total pressure in the combustion chamber;

$\sigma_{вхр} = 0{,}98$ – a factor that takes into account the loss of total pressure in the inlet device.

The temperature behind the combustion chamber:

$$T_Г^* = T_{Гр}^* \cdot L_k / L_{kp} ,$$

where $T_{Гр}^*$ – the temperature behind the combustion chamber is calculated;

$L_{kp}$ – the work of the compressor is calculated.

The average heat capacity of gases in the short circuit is calculated using the dependence:

$$C_{кз} = 878 + 0{,}208(T_Г^* + 0{,}48 T_к^*) .$$

We find the relative fuel consumption using the dependence:

$$g_{пал} = C_{кз} \cdot (T_Г^* - T_к^*)/(H_u \cdot \eta_{Гр}),$$

where $g_{fuel}$ = $H_u$ = 42.5 · $10^6$ J/kg – the value of the lower heat of combustion of the fuel;

$\eta_{Гр} = 0{,}97$ – combustion coefficient.

The operation of the compressor turbine is determined by the formula:

$$L_{TK} = \left[\frac{L_K}{(1+g_{пал})(1-g_{ох.р}-g_{в.р})\eta_{T.р}}\right],$$

where $g_{ох.р.} = 0{,}04$ – relative air flow for cooling turbine parts;

$\eta_{T.р.} = 0{,}99$ – mechanical efficiency of the turbine.

The temperature behind the compressor turbine is found by the formula:

$$T_T^* = T_Г^* - \cdot L_{TK} \cdot \frac{k_g - 1}{k_g \cdot R_г},$$

where $k_g = 1{,}33$ – adiabatic index for gas;

$R_g = 288$ *Дж/кг·К* – gas table for gas.

The pressure behind the compressor turbine is found by the formula:

$$P_T^* = P_Г^*(1 - \frac{T_Г^* - T_T^*}{T_Г^* \cdot \eta_{T.к.р.}^*})^{\frac{k_г}{k_г - 1}},$$

where $\eta_{Tкр} = 0{,}91$ – Turbine efficiency.

The operation of a free turbine is calculated by the formula:

$$L_{BT} = \frac{k_г R_г T_T^*}{k_г - 1}\left[1 - (\frac{P_{Tр}^*}{P_T^*})^{\frac{k_г - 1}{k_г}}\right] \times \eta_{Tкр},$$

We find the temperature behind the free turbine:

$$T_{BT}^* = T_T^* - \frac{L_T}{\frac{k_г}{k_г - 1} \cdot R_Г \cdot \eta_{BT}^*}.$$

where $\eta_{BT} = 0{,}9$ – Efficiency of a free turbine.

Assuming that the free turbine is fully expanded, we calculate the pressure behind it:

$$P_{BT}^* = 1{,}05 \cdot P_H^*$$

Calculate the specific power by the formula:

$$N_{e.п} = L_{BT} \cdot \eta_{мср}(1 + g_{пал}),$$

where $\eta_{мср} = 0{,}992$ – mechanical efficiency of a free turbine.

We calculate air flow through the gas turbine:

$$G_к = G_{кр} \frac{P_Г^*}{P_{Гр}^*} \sqrt{\frac{T_{Гр}^*}{T_Г^*}} .$$

The values of the rotational frequencies of the rotors are determined by formulas:

$$n_{НТ} = \bar{n} \cdot n_{НТр}; \quad n_{ВТ} = \bar{n} \cdot n_{ВТр} .$$

Fuel consumption is found using the dependence:

$$G_{пал} = G_к \cdot g_{пал} \cdot 3600 .$$

The specific fuel consumption is determined by dependence:

$$C_e = 3{,}6 \cdot g_{пал} / N_{e.n}$$

Power is determined by the formula:

$$N_e = 10^{-3} \cdot N_{e.n} \cdot G_к$$

All calculations are summarized in the form of table. 3.1.

Table 3.1

The results of the calculation of the working process of the GTU when changing the mode of its operation in standard atmospheric conditions

| Parameter and calculation formula | Value | | | | | |
|---|---|---|---|---|---|---|
| $\bar{n}$, | 0,85 | 0,9 | 0,95 | 1 | 1.05 | 1,1 |
| $T_в^* = T_H, K$ | 288 | 288 | 288 | 288 | 288 | 288 |
| $P_H$, Pa | 101325 | 101325 | 101325 | 101325 | 101325 | 101325 |
| $\bar{n}_{зв} = \bar{n}\sqrt{\frac{288}{T_в^*}}$ | 0.85 | 0.9 | 0.95 | 1 | 1.05 | 1.1 |
| $\bar{\pi}_к^* = \bar{n}_{зв}^a$, where $a = \pi_{кр}^{*\ 0,2}$ | 0.774 | 0.847 | 0.922 | 1 | 1.08 | 1.162 |
| $\pi_к^* = \pi_{кр}^* \cdot \bar{\pi}_к^*$ | 7.583 | 8.298 | 9.038 | 9.8 | 10.585 | 11.391 |

| | | | | | | |
|---|---|---|---|---|---|---|
| $\overline{\eta}_{\kappa}^{*}=\overline{n}_{зв}^{в}$, де $в=\pi_{кр}^{*\,0,1}(\overline{n}_{зв}-\overline{n}_{зв}^{2})$ | 0.974 | 0.988 | 0.997 | 1 | 0.997 | 0.987 |
| $\eta_{\kappa}^{*}=\eta_{кр}^{*}\cdot\overline{\eta}_{\kappa}^{*}$ | 0.816 | 0.828 | 0.835 | 0.837 | 0.835 | 0.826 |
| $L_{k}=\frac{kRT_{в}^{*}}{k-1}(\pi_{k}^{*(k-1)/k}-1)\frac{1}{\eta_{k}^{*}}$, J/kg | 2.782·10$^{5}$ | 2.906·10$^{5}$ | 3.038·10$^{5}$ | 3.18·10$^{5}$ | 3.339·10$^{5}$ | 3.518·10$^{5}$ |
| $T_{\kappa}^{*}=T_{в}^{*}+L_{k}/[kR/(k-1)]$, К | 567.708 | 577.041 | 590.08 | 604.253 | 620.008 | 637.827 |
| $P_{Г}^{*}=P_{H}\pi_{\kappa}^{*}\sigma_{кзр}\sigma_{вхр}$, Pa | 7.376·10$^{5}$ | 8.072·10$^{5}$ | 8.791·10$^{5}$ | 9.533·10$^{5}$ | 1.03·10$^{6}$ | 1.108·10$^{6}$ |
| $P_{Г}^{*}=P_{H}\pi_{\kappa}^{*}\sigma_{кзр}\sigma_{вхр}$, Pa | 7.081·10$^{5}$ | 7.749·10$^{5}$ | 8.44·10$^{5}$ | 9.151·10$^{5}$ | 9.884·10$^{5}$ | 1.064·10$^{6}$ |
| $T_{Г}^{*}=T_{Гр}^{*}\cdot L_{k}/L_{kр}$, К | 1093 | 1142 | 1193 | 1849 | 1312 | 1382 |
| $C_{кз}=878+0,208(T_{Г}^{*}+0,48T_{\kappa}^{*})$, J/(kg·K) | 1162 | 1173 | 1185 | 1198 | 1213 | 1229 |
| $g_{пал}=C_{кз}\cdot(T_{Г}^{*}-T_{\kappa}^{*})/(H_{u}\cdot\eta_{Гр})$ | 0.015 | 0.016 | 0.017 | 0.019 | 0.020 | 0.022 |
| $L_{TK}=\left[\frac{L_{K}}{(1+g_{пал})(1-g_{ох.р}-g_{в.р})\eta_{T.р}}\right]$, J/(kg·K) | 2.87·10$^{5}$ | 2.994·10$^{5}$ | 3.126·10$^{5}$ | 3.268·10$^{5}$ | 3.425·10$^{5}$ | 3.603·10$^{5}$ |
| $T_{T}^{*}=T_{Г}^{*}-L_{TK}(k_{г}-1)/(k_{г}\cdot R_{г})$, К | 845.877 | 883.876 | 924.084 | 967.826 | 1016 | 1072 |
| $P_{T}^{*}=P_{Г}^{*}(1-\frac{T_{Г}^{*}-T_{T}^{*}}{T_{Г}^{*}\cdot\eta_{T.к.р.}^{*}})^{\frac{k_{г}}{k_{г}-1}}$, Pa | 2.172·10$^{5}$ | 2.381·10$^{5}$ | 2.597·10$^{5}$ | 2.822·10$^{5}$ | 3.054·10$^{5}$ | 3.295·10$^{5}$ |
| $L_{BT}=\frac{k_{г}R_{г}T_{T}^{*}}{k_{г}-1}\left[1-(\frac{P_{Tр}^{*}}{P_{T}^{*}})^{\frac{k_{г}-1}{k_{г}}}\right]\times$, J/kg $\times\eta_{Tкр}$ | 1.469·10$^{5}$ | 1.706·10$^{5}$ | 1.949·10$^{5}$ | 2.203·10$^{5}$ | 2.473·10$^{5}$ | 2.765·10$^{5}$ |
| $N_{e.п}=L_{CT}\cdot\eta_{мср}(1+g_{пал})$, Wt/(kg/s) | 1.468·10$^{5}$ | 1.707·10$^{5}$ | 1.953·10$^{5}$ | 2.211·10$^{5}$ | 2.485·10$^{5}$ | 2.784·10$^{5}$ |

| | | | | | | |
|---|---|---|---|---|---|---|
| $G_{К} = G_{Кр} \dfrac{P^*_{Г}}{P^*_{Гр}} \sqrt{\dfrac{T^*_{Гр}}{T^*_{Г}}}$, kg/s | 6.044 | 6.473 | 6.895 | 7.307 | 7.703 | 8.076 |
| $C_e = 3{,}6 \cdot g_{пал} / N_{e.п}$, kg/(kWt·h) | $3.614 \cdot 10^{-4}$ | $3.355 \cdot 10^{-4}$ | $3.164 \cdot 10^{-4}$ | $3.022 \cdot 10^{-4}$ | $2.917 \cdot 10^{-4}$ | $2.84 \cdot 10^{-4}$ |
| $n_{НТ} = \bar{n} \cdot n_{НТр}$, rpm | 8777 | 9294 | 9810 | 10330 | 10840 | 11360 |
| $n_{ВТ} = \bar{n} \cdot n_{ВТр}$, rmp | 11190 | 11850 | 12510 | 13160 | 13820 | 14480 |
| $G_{пал} = G_{к} \cdot g_{пал} \cdot 3600$, kg/h | 376.009 | 405.834 | 437.919 | 473.435 | 513.698 | 560.235 |
| $N_e = 10^{-3} \cdot N_{e.п} \cdot G_{К}$, kWt | 887.4 | 1105 | 1347 | 1615 | 1914 | 2248 |
| $\bar{C}_e = C_e / C_{e.p}$ | 1.198 | 1.112 | 1.049 | 1.002 | 0.967 | 0.942 |
| $\bar{N}_e = N_e / N_{e.p}$ | 0.555 | 0.691 | 0.842 | 1.01 | 1.197 | 1.405 |

Based on the calculation of the mathematical model of the working process of the gas turbine, we plot the dependences of the parameters of the gas turbine (temperature, pressure in different sections of the engine, hourly fuel consumption) on the speed of the high pressure rotor [14]. We have obtained linear functions, so we will carry out the approximation of the values by the method of the nearest squares. As a result, we obtain our dependences of the parameters on the rotor speed in the form of a parabolic function (Fig. 3.3 - 3.6).

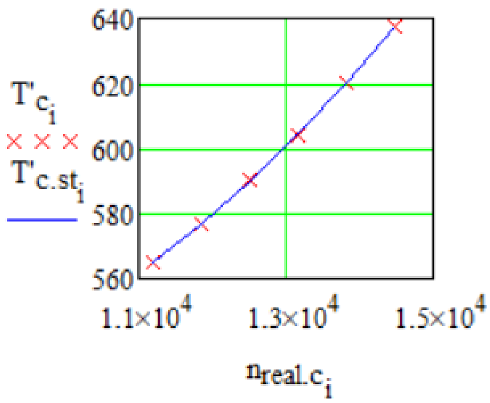


Figure 3.3 - Dependence of frequency and temperature on the high pressure compressor from the rotational speed of the high-pressure rotor

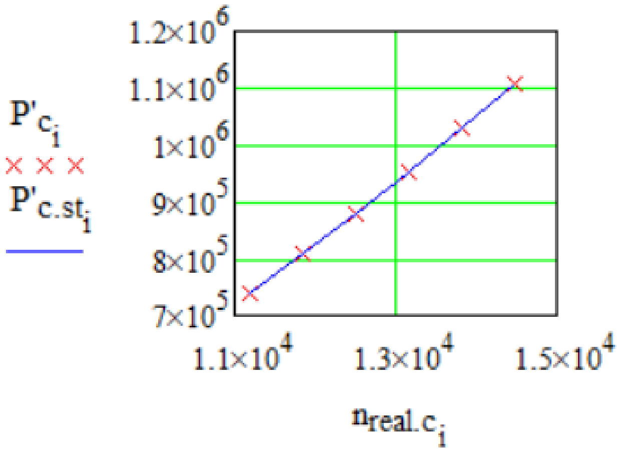


Figure 3.4 - Dependence of pressure on the compressor on the speed of the high pressure rotor

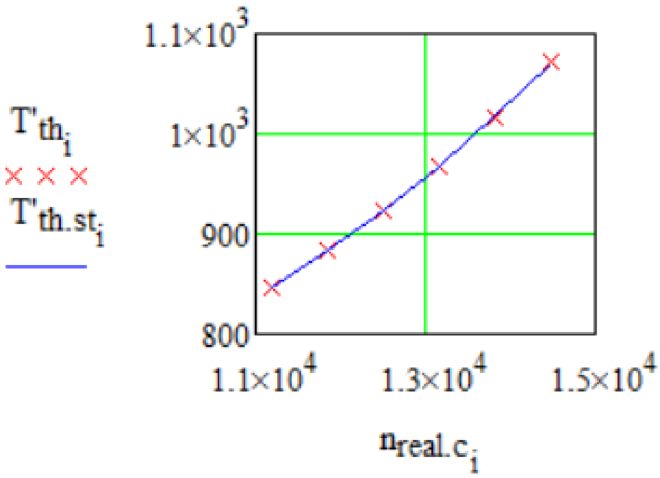


Figure 3.5 – Dependence of temperature on a high-pressure turbine on the speed of the high-pressure rotor

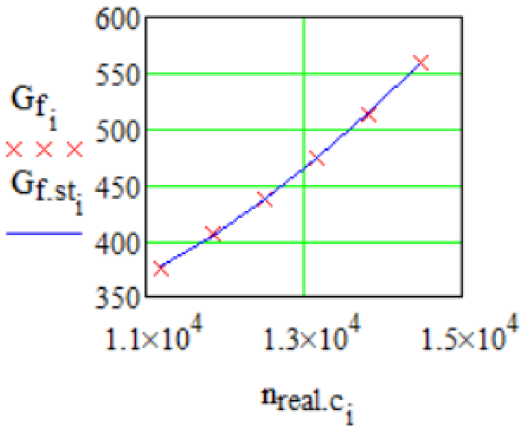


Figure 3.6 – Dependence of fuel consumption on the rotor speed high pressure

After analyzing the graphs, it is seen that almost all the studied parameters, such as temperature in different sections of the gas turbine engine, high pressure compressor pressure, hourly fuel consumption, engine power, increase when throttling on a clear increasing almost straight line.

## 3.4 Methods of engine diagnostic

The development of diagnostic methods for aircraft gas turbine engines is currently based on the methods developed for determining the technical condition of piston engines and radio electronic devices. However, due to the specific nature of the GTE, the practical application of these developed and tested diagnostic methods is difficult [16].

An objective determination of the technical state of a gas turbine engine requires the solution of specific problems and the development of special methods and diagnostic tools. In the general case, the structure of diagnostics of the technical state of a GTE can be represented as follows [3]: development of a classification of engine states; assessment of the diagnostic value of the selected signs of conditions; substantiation of the selected criteria of technical condition and their assessment; selection (development) of a method for mathematical description of a GTE as an object of diagnostics; substantiation of a diagnostic method or a method for detecting a malfunction.

A gas turbine engine in the process of developing a resource has many states. Therefore, when solving problems of diagnostics, it is first necessary to choose for analysis a finite number of characteristic classes of states in terms of characteristic features or parameters that express it.

For example, one class of states includes damage to parts of the engine flow path by foreign objects, destruction of parts washed by oil, etc. In the first case, the vibration level can be taken as a sign, and in the second, the appearance of chips in the oil.

The development of a classification of GTE states is difficult because of the need to process a significant amount of a priori information, which, in turn, causes prolonged controlled operation of engines. In addition, due to the significant mutual influence of the parameters of the gas turbine engine, it is difficult to identify and control the essential features of states, by which one can divide these states into classes [17]. It is often almost impossible to establish boundaries between different classes of states, since they can be characterized by the same characteristics. In the process of diagnosing a gas turbine engine, it is not always possible to objectively list the signs that characterize a specific state of the engine; it is impossible to have a priori information about random states.

### 3.4.1 Diagnostics of the state of GTE by functional parameters meters of oil system

Diagnostics of the state of GTE by functional parameters meters of the oil system, the functional parameters of the oil system of modern serial helicopter GTEs subject to continuous monitoring are the oil pressure in the pumping part of the oil system and the oil temperature / m at the outlet (inlet) of the engine.

Since the GTE has a significant rotor speed (20,000 rpm and more), its bearings and other rubbing surfaces must be continuously and efficiently lubricated. The oil consumption for lubrication of individual bearings or mating surfaces is determined by the section of the outlet nozzles and the magnitude of the pressure and depends on the thermal and mechanical loads of the unit being lubricated.

For each mode of GTE operation, the instructions for its operation set a certain value of pm. A drop in the oil pressure below the established limits leads to a significant increase in the wear of the mating parts, as well as to an increase in the thermal state, which reduces their mechanical strength. Consequently, the pm parameter indirectly determines the technical state of the GTE at the moment of its operation, but does not indicate the presence of any specific defect [15].

The most common defects that cause a drop in oil pressure can be: wear of oil pump parts; fuel ingress into the oil system through the seals of the fuel system units; clogging of filters, disruption of the ventilation system; changes in the physical and chemical properties of the oil; destruction of oil seals; destruction of oil pipelines, formation of air locks in the system, "jamming" of the oil pump's pressure reducing valve in the open position due to falling under its chamfer of solid particles in the oil.

Operational experience shows that the most common cause of a drop in oil pressure is the “sticking” of the oil pump pressure reducing valve. It is practically difficult to determine the probability of a solid particle falling under the pressure reducing valve on serial engines without introducing additional control.

A change in the technical state of the engine in the process of developing a technical resource has an insignificant effect on pressure, since the mass flow of the injection pump significantly exceeds the required pumping of oil through the system and the reduction valve maintains a constant value of pm. Therefore, the `oil pressure 'parameter does not have a large diagnostic value for determining the accumulation of failures by the engine. He can only determine the critical state of the engine, when, due to insufficient lubrication, it is destroyed. rubbing knots.

Each operating mode of the GTE must correspond to a certain value of the oil temperature. When using mineral oil, its temperature at the engine inlet is set within strictly defined limits. A temperature rise beyond these limits leads either to a large thickening of the oil and insufficient penetration into the gaps of the rubbing surfaces (with a decrease in temperature), or to excessive dilution and deterioration of the lubricating ability of the oil, as well as to the deterioration of heat transfer to the oil and overheating of rubbing surfaces (with increasing temperature). Violation of the temperature regime of the oil ultimately leads to increased wear of the rubbing pairs.

### 3.4.2 Vibroacoustic diagnostics of GTE

Vibration level. In the practice of operating aircraft gas-turbine engines, there are malfunctions that, when the engine is running, can be detected by the vibration level. The reasons for the increased vibration level can be surging phenomena in the compressor, wear of parts of the gas-air duct, destruction of compressor and turbine blades, destruction of bearings of rotor supports, disruption of the normal operation of the automatic control system for the rotation of the compressor straighteners (if the engine is equipped with a mechanism for turning the AC, misalignment of shafts and transmission of the engine and power plant. Diagnostics of the state of GTE by vibration level provides detection of malfunctions based on the analysis of vibrations generated by a running engine and associated units and systems.

Vibration control equipment. The set of on-board equipment designed to control vibration accelerations of aircraft engines includes vibration sensors, a filter unit and an indicating device [19].

Vibration sensors operate on the principle of using a seismic element that includes a mass tn, a spring with stiffness C, and a damper D with a proportionality coefficient K between the velocity of the mass m and the viscous friction force.

Vibration sensors installed to measure the vibration of aircraft and helicopter GTEs differ in the way they pick up signals proportional to the movement of the seismic mass. Inductive capacitive, ohmic, electromagnetic and other elements are used as displacement sensors.

Schematic of the MV-25 sensor, which is a balanced mass made in the form of a permanent magnet and placed inside a housing. The coil is located in the housing.

The permanent magnet is installed in the housing via rolling bearings. In the outer bearing cage, three steel thrust bearings are fixed by means of bushings and loaded with cylindrical springs at an angle of 120 ° to each other. The axes of the sectors rest on the thrust bearings, centering the inner race of the rolling bearing. The inner cage is rigidly connected to the moving system of the sensor (permanent magnet) by a screw. The outer bearing race is screwed to the sensor housing.

The middle position of the permanent magnet in the direction of the sensor axis, which coincides with the direction of measurement of vibration parameters, is provided by two cylindrical springs [19].

Under the action of an exciting force in the direction of the measurement axis of the sector, swinging in the thrust bearings, the permanent magnet is allowed to move relative to the sensor body. Since the moving system (magnet - springs) is much lower ", the magnet will practically remain at rest. The magnetic flux of the permanent magnet passes through two air gaps and is closed through the steel body of the sensor. A cylindrical coil is placed in the air gap. Both ends of the sensor coil are connected to the terminals of the plug connector. In the case of relative motion of the magnet, induction currents are induced in the coil, which, when interacting with the main flux, will damp out the natural vibrations of the moving system of the sensor.

The sensor is rigidly mounted on special motor flanges (at the vibration measurement point) with two screws without installing any gaskets.

The reliability of operation and the accuracy of measuring the vibration level is achieved by the correct installation of the equipment on the aircraft and strict adherence to the operating rules established by the manufacturer.

Vibration control equipment is tested before the flight. To do this, before starting the engine with the power supply turned off, the position of the arrows of the indicating devices is checked, which should be against the zero mark. If necessary, the arrow is set to this position using a corrector located on the front side of the instrument case. After turning on the power source and warming up the equipment, pressing the button for turning on the built-in control should cause the signal lamps to light up and the arrows of the indicating devices deviate into the built-in control zone, which indicates the serviceability of all units of the equipment.

After starting the engine, the crew must make sure that the equipment is in good working order by shifting the arrows from zero [20]. During the flight, the crew visually controls the amount of vibration accelerations on the engines using the indicating instruments. When the maximum permissible acceleration on the engine is reached, the signal lamp lights up, and the arrow of the indicating device should be at the level of the mechanical indicator or exceed it. In this case, the aircraft crew should make sure that the readings are correct using the built-in monitoring equipment and take measures in accordance with the flight manual for this type of aircraft.

Control in rotation and helicopter GTE [25]. The increased vibration level of a helicopter GTE in comparison with an aircraft one is explained by the impossibility of accurately setting the alignment of the engine and gearbox shafts, the presence of a long transmission with the use of cardan elements, the difficulty of synchronizing the operating modes of engines operating at a common load, etc.

An increased vibration level can cause various malfunctions. The occurrence of malfunctions of components and systems of the engine due to an increased level of vibration occurs due to the excess of the maximum permissible amplitude of the movement of individual structural elements, the maximum permissible stresses in parts and fatigue of materials.

Vibration measuring equipment is used to control the vibration level (vibration velocity) of engines and transmissions in helicopters. Thus, for example, the IV-200G vibration measuring equipment is installed on the Mi-6 and Mi-10 helicopters.

The set of measuring equipment consists of four sensors, two two-channel electronic units, two indicating devices (one with a scale of 0-100 mm / s, the other with a scale of O-200 mm / s), two signal lamps (installed on the dashboard of a flight technician) , two redundant signal lights (located on the middle dashboard of the cockpit), control buttons for checking the operability of the equipment and switches indicating devices for sequential control of vibration of the left and right engines. One two-channel unit serves one motor.

Each engine of the power plant has vibration sensors: one on the compressor inlet casing, the other on the rear transmission casing. In this case, a vibration sensor mounted on the inlet housing of the compressor is connected to the first channel of the electronic unit, and another vibration sensor mounted on the transmission housing to the second channel of the same electronic unit.

By means of a manual switch, indicating devices can be connected in turn to the corresponding channel of one or another electronic unit: a device with a scale of 0-100 mm / s and indicating the level of vibration of the engine is connected to the first, a device with a scale of 0-200 mm / c, showing the vibration level of the engine transmission. The permissible vibration levels of the D-25V engines on the Mi-6 and Mi-10 helicopters at the compressor inlet casing are 50 mm / s, and on the engine transmission casing - 150 mm / s.

Continuous monitoring of the vibration level allows the helicopter crew to judge the engine and transmission serviceability and, if the permissible vibration level is exceeded, make a decision on further operation of the power plant.

In flight with a normally operating power plant in all modes, the warning lamps should not light up, and the readings of the instruments should be: the first channel (the level of vibration of the engine

lei) - not more than 50 mm / s, the second channel (the level of vibration - Z transmission) - not more than 150 mm / s. If the vibration level * exceeds the permissible value, the warning lamps light up [24]. In this case, it is necessary to determine a specific place of increased vibration using a switch and indicating devices. If the vibration of the engines exceeds the permissible value (50 mm / s), then it is necessary to use the `step-gas' lever to lower the operating mode of the engines to a level at which the vibration value will be within the permissible limits. With absence

external signs of abnormal operation of the engines, it is necessary to continue the flight in this regime. If a decrease in the operating mode of the engines does not lead to a decrease in vibration and the vibration level continues to increase, then the engine should be turned off and switch to single-engine flight.

### 3.4.3 Methods for collecting and summarizing information on the technical condition of the GTE Non-automated method of collecting information

One of the acute problems in the development of diagnostic systems is to obtain a sufficient amount of reliable information about the technical condition of the engine. Currently, when diagnosing a gas turbine engine by changing the functional diagnostic parameters, manual and automated collection and analysis of information about the state of the engine is mainly used. The main goal of the manual method of collecting the necessary information is to obtain redundant information for detecting and determining malfunctions in engine systems that are not washed by oil, i.e., compressor units ^

combustion chambers, turbines, etc., as well as the use of experience in recording information for the development of systems for automated monitoring of the technical condition of the engine.

Registration of the necessary information can be carried out both in the process of testing the engine on the ground and during the flight. Moreover, at present, there is a tendency to collect diagnostic information in flight as more reliable. In this case, the registration of information should be carried out in a previously selected certain mode without turning on the anti-icing system on special tear-off blanks by the flight engineer, flight mechanic or navigator. The information obtained by a special program is converted into a dimensionless form for comparison with the normalized characteristics of a known working engine, which were obtained during its bench tests at the same power, thrust, or pressure ratio. To eliminate the error in technical diagnostics using this method, it is necessary to plot the deviations of the obtained data from the reference data in percent and average about the first 10 deviations. In this way, the deviation level of the corresponding parameter for a particular motor is set. The smoothed values of the parameter make it possible to graphically analyze its drift in recent flights.

An analysis of the increase or decrease in the parameter drift from the initial values makes it possible to reveal the reasons for the deviation of the parameters and to develop appropriate recommendations for the further operation of the engine. To obtain an objective diagnostic result when a significant drift of the corresponding parameter appears, it is necessary to use additional information on the technical state of the engine obtained by various monitoring methods. For example, in BEAD [35] the physical method was used to find a number of engine malfunctions at the initial stage of their development, which could not be detected by other methods and means. The efficiency of this method for recording diagnostic information is largely determined by the coordinated actions of the crew.

Recent advances in diagnosing the state of a gas turbine engine make it possible to process punched cards with information recorded by the crew using a computer, which increases the objectivity of the diagnostic results.

The main disadvantages of monitoring the state of the engine according to the data of manual registration of parameters are: limited modes in which diagnostic information is recorded. The practice of operating GTEs shows that not all of their defects manifest themselves to the same extent in different regimes.

### 3.4.4 Least squares method

The least squares method is a mathematical method used to solve various problems, based on minimizing the sum of the squares of the deviations of some functions from the desired variables. It can be used to "solve" overdetermined systems of equations (when the number of equations exceeds the number of unknowns), to find a solution in the case of ordinary (not overdetermined) nonlinear systems of equations, to approximate the point values of some function [22]. OLS is one of the basic regression analysis methods for estimating unknown parameters of regression models from sample data.

To bring the obtained parameters as a result of gas-dynamic calculations, as well as to calculate the throttling parameters, we will use the method of least squares, which will allow us to more accurately determine the graphs of the change in the measured parameters.

## 3.5 Features of building a mathematical model of a gas turbine engine

Optimization of methods for constructing algorithms for diagnosing complex objects in the general case is possible if there is a formal description of them in serviceable and faulty states.

Such a formal description or graphical-analytical representation of the main properties of objects under diagnostics is usually called diagnostic mathematical models. They can be given by differential equations, logical relationships, tables, diagrams, or other form, either explicitly or implicitly [24].

The clear model is a set of formal descriptions of a healthy object and each of its faulty states under consideration. An unclear model contains any one formal description of an object, mathematical models of its faults, and rules for obtaining all other possible states from them. The most expedient is the construction of a mathematical model of the healthy state of the object, according to which it is possible to build the corresponding models of its faulty states. The latter should describe the object of diagnosis with a sufficient degree of accuracy. Implicit models, moreover, should be convenient for obtaining the required reliable descriptions of the object.

The compilation and study of a mathematical model of an aviation GTE will make it possible to divide the set of its states into two subsets, i.e., operable and inoperable states, to obtain a criterion for assessing the degree of operability, and to establish signs of emerging malfunctions. The choice of methods for the mathematical description of the processes occurring in a gas turbine engine for diagnosing the technical state of its main structural units can be based on the following provisions.

1. In the process of developing the resource of a gas turbine engine, an inevitable deterioration of its economic and power parameters occurs, which is explained by a change in the loss coefficients reflecting the technical state of the engine flow path. The reasons for the change in the loss coefficients are mechanical and thermal effects on units and parts, which lead to a change in the geometric characteristics of the elements of the engine flow path.

2. A change in the geometric characteristics of the engine elements, its misalignment during operation leads to an increase in the unevenness of the flow in the inlet device, compressor, combustion measurement, etc., velocity fields and pressure fields. An increase in the unevenness of flows leads to overheating of the engine, the appearance of stall and oscillatory modes of operation, and an increase in vibration in the engine components.

4. The technical condition of the combustion chamber, injectors, fuel of the control equipment affects the quality of the mixture of formation and the combustion process. The deterioration of mixture formation in the combustion chambers and afterburners occurs due to the formation of coke in the fuel injectors, their clogging, and the regulation of the fuel control equipment. These defects reduce the completeness of fuel combustion, which leads to an increase in the specific and hourly fuel consumption at a constant operating mode of the engine [25].

In the mathematical description of the processes occurring in the gas turbine engine, it is necessary to take into account that an increase in hydraulic losses in various elements of the engine flow path leads to the same consequences. Thus, an increase in hydraulic losses in the combustion chamber, turbines, afterburner, jet nozzle (output device) leads to an increase in the temperature of the gases in front of the turbine, a shift in the line of operating modes to the surging boundary, deterioration of the economic performance of the engine, etc. The traction (power) characteristics may change slightly.

## 3.6 Mathematical calculation of diagnostic deviations based on processing a set of parameters

### 3.6.1 Selecting the sensors

Select sensors for receiving the main parameters, taking into account the obtained maximum values from the previous calculation of the throttle parameters and the measurement area.

The first sensor we will use is in the inlet unit of the engine. Taking into account the parameters that we calculated in the gas dynamic calculation, the operating temperature at the inlet will be approximately 288 K, therefore we choose the ПП90-Т sensor [4]. The operating temperature of this sensor is approximately 213 - 343 K and the device error is in the range of 1%.

The next sensor we want to select is the engine inlet pressure sensor. The pressure on this at this section is considered equal to one atmosphere or 101325 Pa. In this section, we put a ЗАП526-20.00 [6] sensor with a working area from 0 to 2 bar, which equals from 0 to 0.2 MPa, the error of this device is also about 1%.

The next sensor that we will select is the rotor speed sensor. Taking into account the parameters of our calculation, the maximum rotor speed is approximately 15,000 rpm. Here we select the ДЧВИ-14 sensor [5]. The working area of this sensor is from 500 to 17000 rpm and a measurement error of 1.5%.

The next step is to measure the pressure parameter in the downstream section of the compressor. Using the parameters of the thermo and gas-dynamic calculation, we take the maximum pressure value of 1.2 MPa and use here the SML-20.0 [5] sensor with a working pressure measurement area from 0 to 1.6 MPa.

The next sensor that we need is a temperature measurement sensor. It will be installed downstream of the compressor. The maximum temperature here from thermo gas-dynamic calculations is about 700 K, so here we will use the ТХК-1192 [9] sensor, which is made in the form of a chromel-copel thermocouple with an operating temperature of 233 to 873 Kelvin and with an error of 1.5% [10].

Next in line is the temperature measurement sensor in front of the working turbine. The maximum temperature in this area is 1100 K according to thermodynamic calculations. In this area, we will use a T74-T sensor [4] with a working area from 573 to 1173 K and with an error of 3%.

The last selectable sensor will be the mass flow sensor. The maximum value of the mass fuel consumption according to the thermodynamic calculation is 600 kilograms per hour. Therefore, we choose a TCM 0650 [7] sensor with a working area from 0 to 650 kilograms per hour of fuel and with an error of about 0.3%.

### 3.6.2 Accounting for external conditions, operating mode and parameter measurement errors

For the subsequent construction of a graph of diagnostic predictions and dependencies, we need a set of 4 main parameters. Such as the temperature and pressure behind the compressor, the temperature in front of the working turbine, also the mass flow rate [23].

We use the previously written set of formulas to determine these four parameters based on 3 climatic parameters, such as pressure and ambient temperature, rotor speed in percent.

For these three parameters, we substitute the conditional 300 random values in the normal operating limit [14]. We define them using the Mathcad software according to a random law.

Thus, this data is automatically calculated.

Now, based on the obtained data and values, we will determine the normal value that we would receive by removing these parameters from the sensors by adding deviations to the given value, taking into account the error of the measuring instruments of the sensors distributed according to the normal law.

Diagnosis of GTE is performed according to the normalized diagnostic deviations of the parameter values measured during the operation of GTE from the reference values.

Variable limits of monitored parameters can be used alone or as an addition to detection of fixed limits and serve to validate data before recording by assessing deviations from previous records and monitoring the recording of certain parameters that change over a wide range during flight. This allows you to exclude the recording of points where the parameter value changed little in comparison with the previous recording. When using variable limits, the tolerances of the controlled parameters are set relative to the last recorded point [25].

To adequately recognize TS, the neural network must be trained using data obtained for the conditions and operating modes at which diagnosis will be made. In this case, the object operation in all diagnostic modes should be presented in the

$$R_j = \hat{f}_{uni}(R_j^{min}, R_j^{max}),$$

same way. Then the value of they-th regime parameter of the model will be:
where $R_j^{min}$, $R_j^{max}$ are the minimum and maximum values of the *j*-th regime parameter in diagnostic modes.

Errors and gross errors of measurement are the last factor that can be taken into account when forming sets for training neural networks.

The following formula describes how to determinate measurement deviation based on measure sensor error and the full value of the parameter read from the sensor:

$$\Delta\hat{R}_j = \hat{f}_{norm}\left(0, {\Delta R_j^{max}}/{3}\right), \quad j = 1, n_r,$$

$$\hat{\mathbf{R}} = \mathbf{R} + \Delta\hat{\mathbf{R}},$$

where $R_j^{min}$, $R_j^{max}$ are the minimum and maximum values of the *j*-th regime parameter in diagnostic modes and $n_r$ is the number of regime and diagnostic parameters, respectively.

Using our set of values for every parameter, which we have, determine normal measurement value [14]. For this purpose, we use software Mathcad. Create graphic dependence for every of our 4 main parameters (pressure after the compressor $P`_c$ (figure 3.7), temperature after compressor $T`_c$ (figure 3.8), temperature before working turbine $T`_t$ (figure 3.9) and mass fuel consumption $G_f$ (figure 3.10) to rotating of rotor and number of parameters:

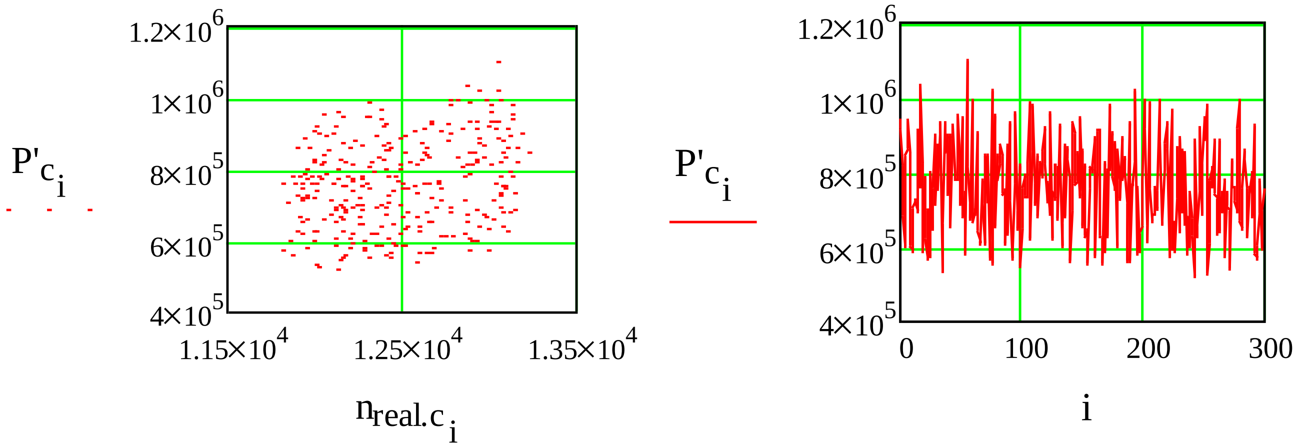


Figure 3.7 Normal measured values of pressure after compressor during different operation regime with accounting measuring errors.

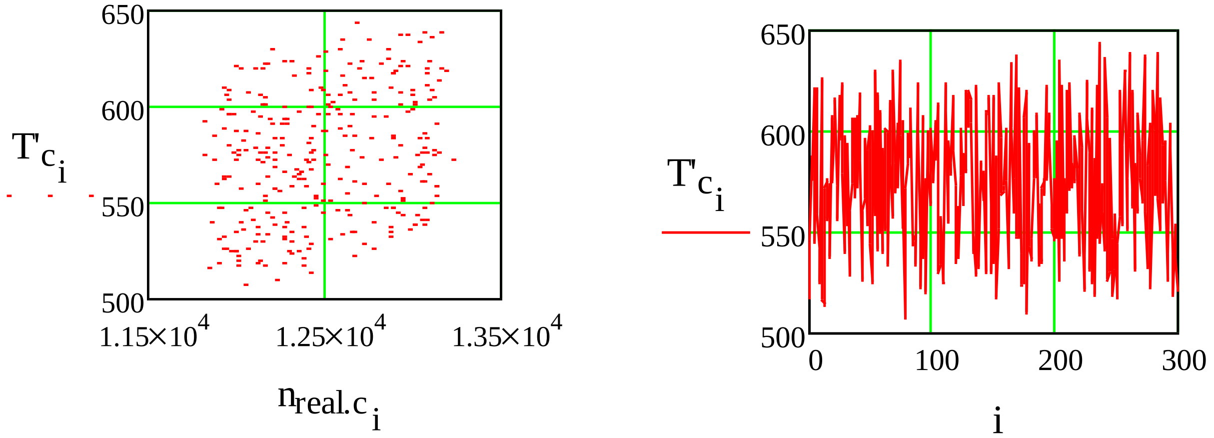


Figure 3.8 Normal measured values of temperature after compressor during different operation regime with accounting measuring errors.

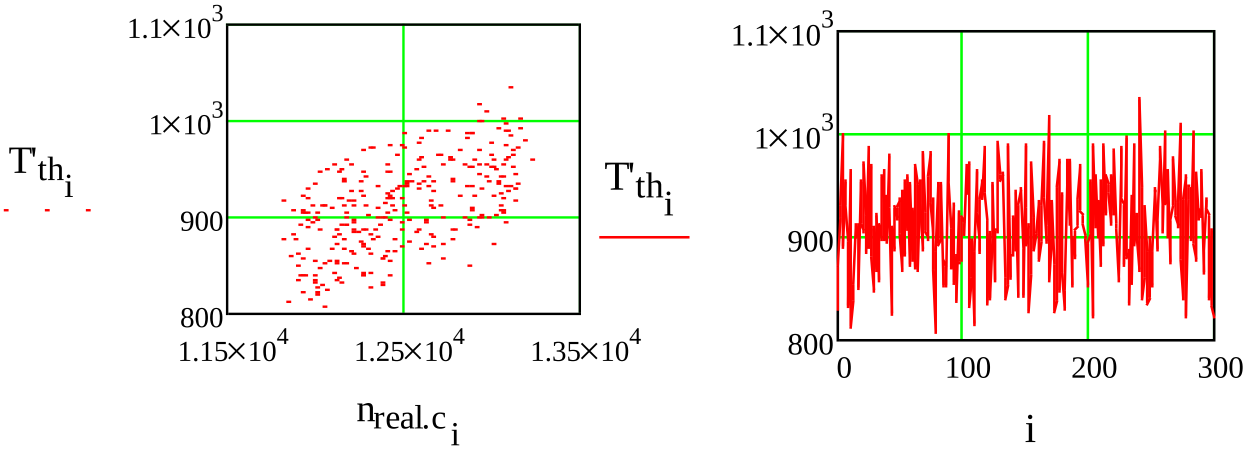


Figure 3.9 Normal measured values of temperature before working turbine during different operation regime with accounting measuring errors.

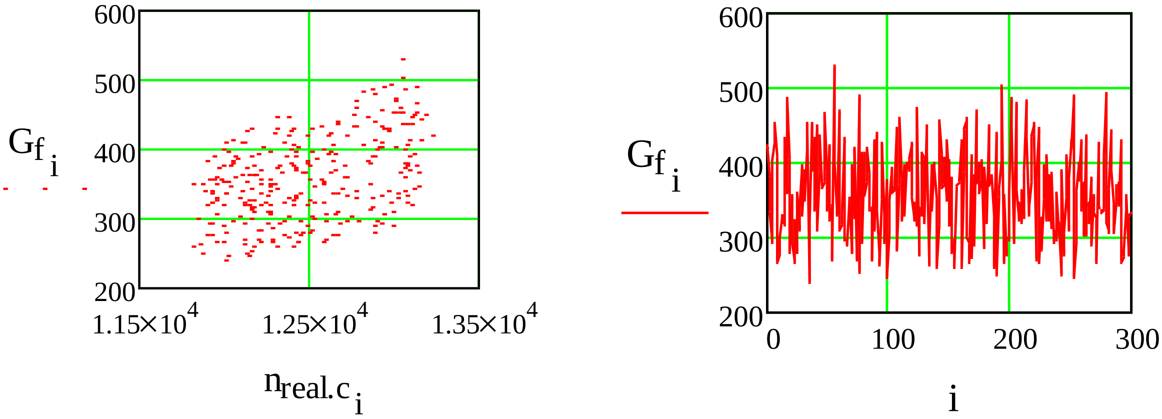


Figure 3.10 Normal measured values of mass fuel consumption during different operating regime with accounting measuring errors.

Diagnosis of GTE is performed according to the normalized diagnostic deviations of the parameter values measured during the operation of GTE from the reference values.

To calculate the reference values of the parameter should use the dependence of the reduced to standard atmospheric conditions of the braking pressure on the compressor on the reduced frequency of the rotor of the average engine:

$$P^{*\,\text{ет}}_{\text{к зв}} = a_0 + a_1\, n_{\text{зв}} + a_2\, n^2_{\text{зв}} + a_3\, n^3_{\text{зв}}$$

where $n_{\text{зв}}$ - consolidated rotor speed,%; $a_0 - a_3$ - dependence coefficients calculated using throttling formulas with set of 300 parameters variation unique for every of our 4 main parameters.

By supplementing the results of the analytical solution with experimental data, it is possible to refine the numerical values of the influence coefficients, establish whether all factors influencing the process under consideration are taken into account in the calculations, evaluate the errors and errors in the values of the calculated influence coefficients in comparison with the values calculated from the experimental characteristics.

We will make an approximation of the obtained data by the least squares method and draw a graph of the dependence of the normal obtained data and ideal values to the operating mode of the rotor and the measurement number (figure 3.11 – 3.14).

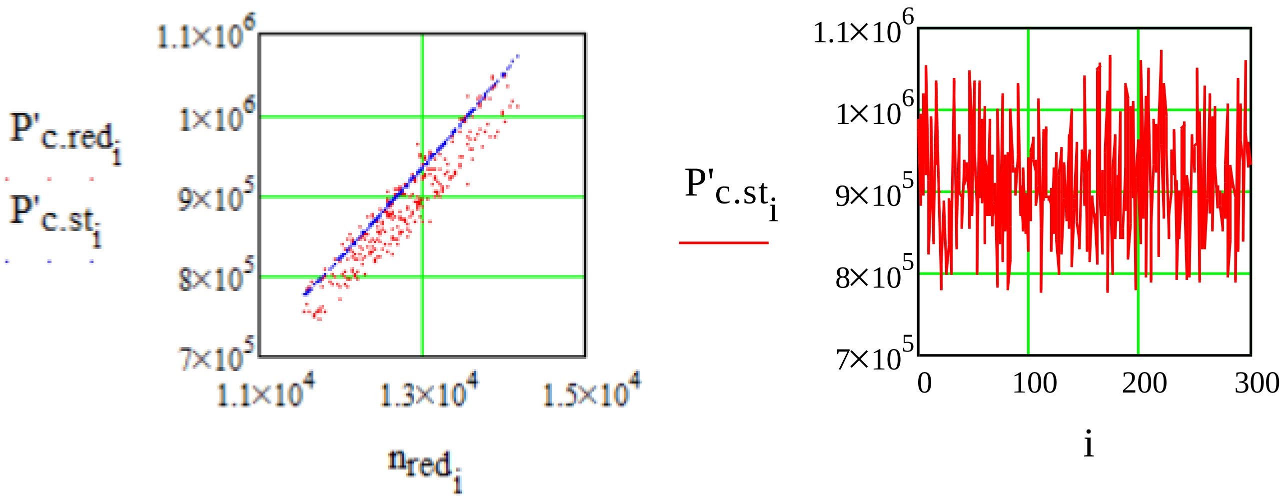


Figure 3.11 Comparison of normal measured pressure after compressor and ideal measured parameter ($P`_{c.red}$ – normal, $P`_{c.st}$ - ideal).

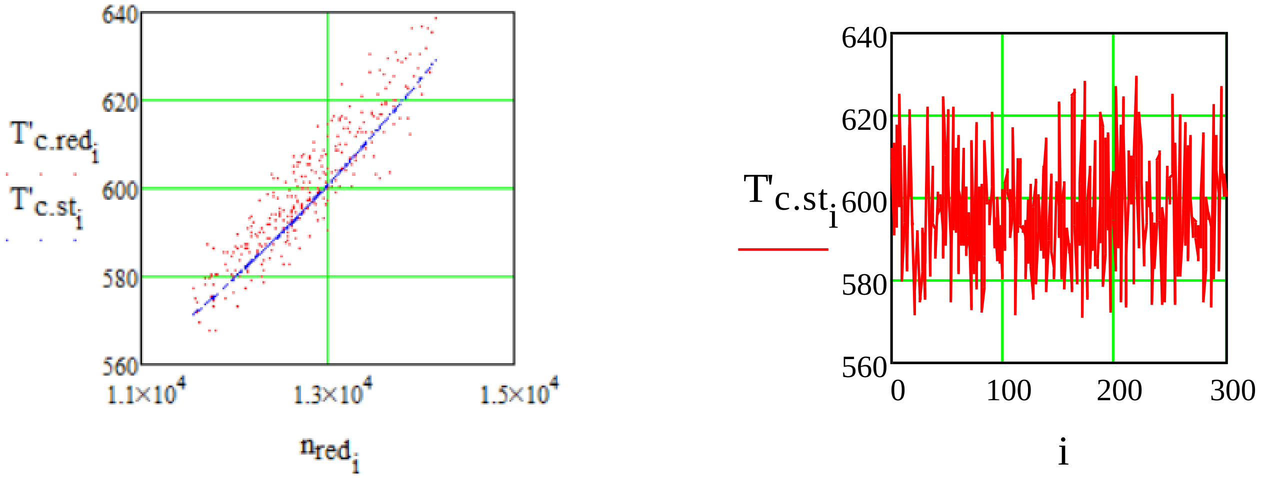


Figure 3.12 Comparison of normal measured temperature after compressor and ideal measured parameter ($T`_{c.red}$ – normal, $T`_{c.st}$ - ideal).

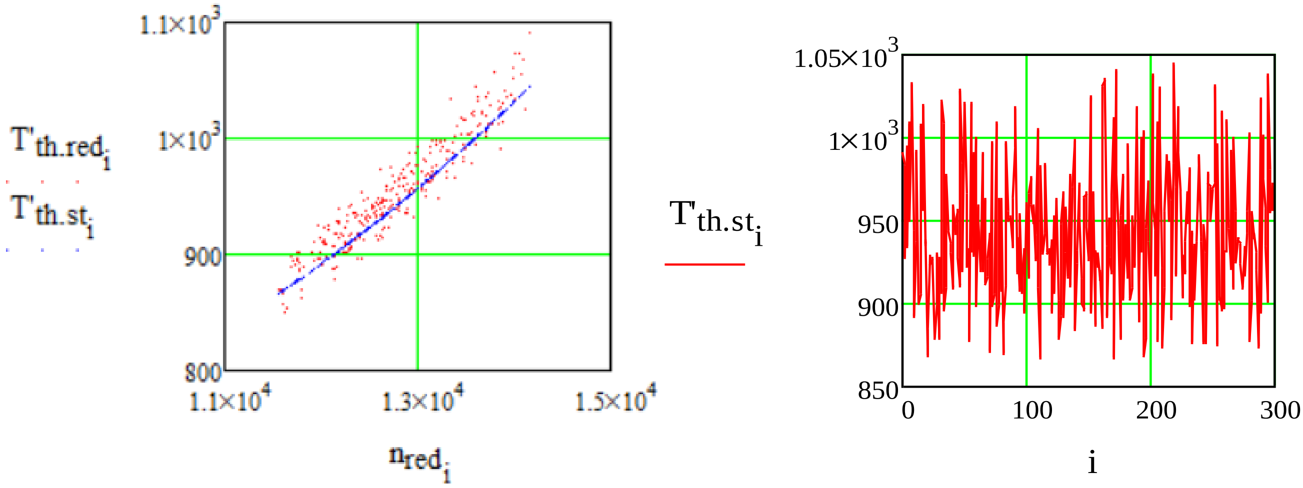


Figure 3.13 Comparison of normal measured temperature before working turbine and ideal measured parameter ($T`_{th.red}$ – normal, $T`_{th.st}$ - ideal).

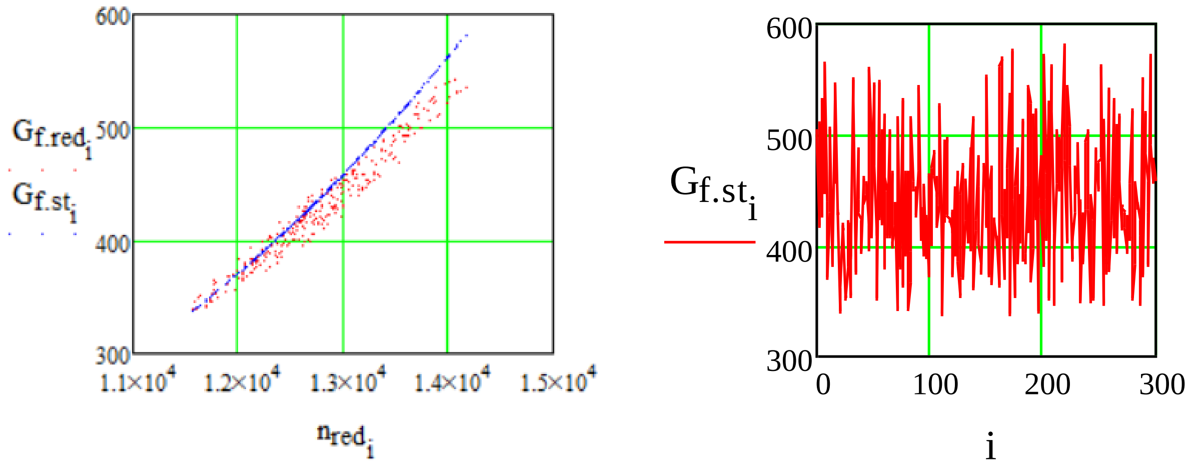


Figure 3.14 Comparison of normal measured mass fuel consumption of GTE and ideal measured parameter ($G_f$ – normal, $G_f$ – ideal).

Next, the values of the diagnostic deviations of the consolidated parameters for each of the calculated parameters were calculated. Determine using following formulas:

$$\Delta T'_{c_i} := T'_{c.red_i} - T'_{c.st_i}$$

$$\Delta P'_{c_i} := P'_{c.red_i} - P'_{c.st_i}$$

$$\Delta T'_{th_i} := T'_{th.red_i} - T'_{th.st_i}$$

$$\Delta G_{f_i} := G_{f.red_i} - G_{f.st_i}$$

where Δx – is deviation from ideal measured value, $x_{red}$ – is normal measured parameter and $x_{st}$ – is ideal measured value, which wre reduced to standard atmospheric conditions.

By constructing graphs of the dependences of the obtained parameter deviations on the engine operating time and comparing the values from the deviations at different operating time, one can obtain valuable information about its technical condition.

Apply these measured parameters deviation dependence from numerical number of taken point to graphic using Mathcad (figures 3.15 – 3.18):

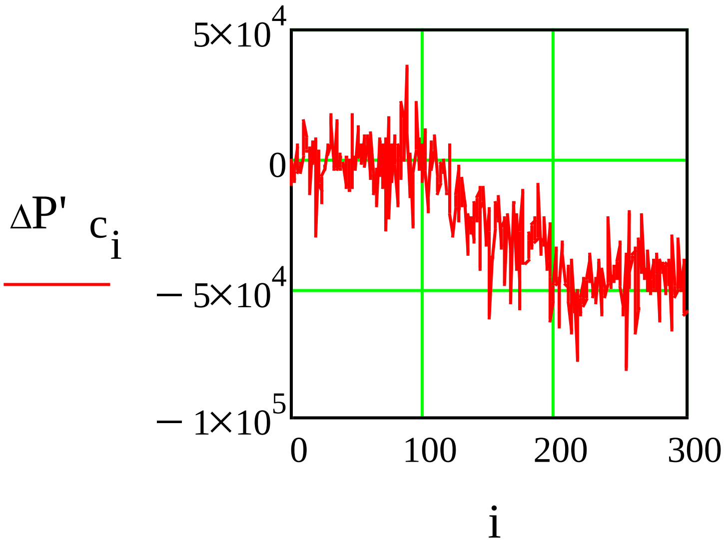


Figure 3.15 Pressure after compressor measured parameter deviation.

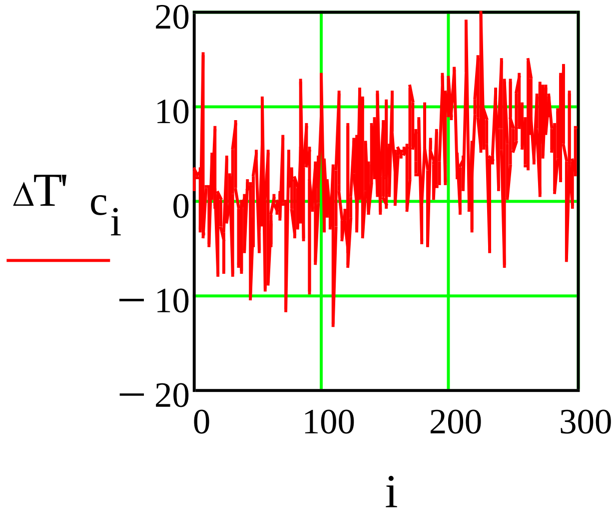


Figure 3.16 Temperature after compressor measured parameter deviation.

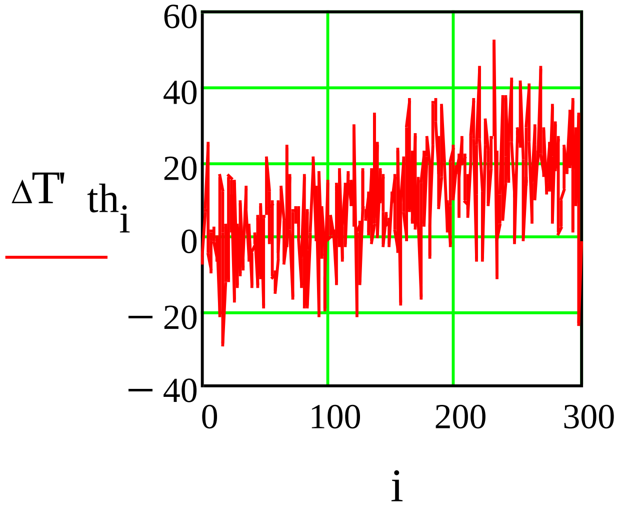


Figure 3.17 Temperature before working turbine measured parameter deviation.

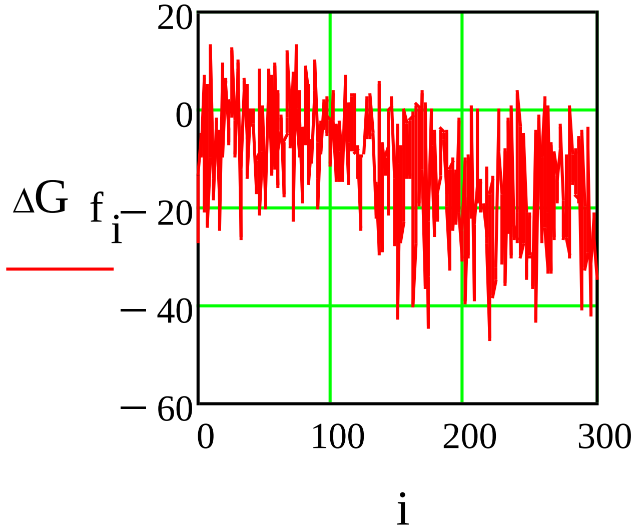


Figure 3.18 Mass fuel consumption measured parameter deviation.

### 3.7 Measured parameters deviation comparison with variance due to measurement errors and inadequacy of reference models.

To compare the magnitude of the deviation for each specific measurement point, for each individual parameter with a spread associated with measurement errors and inadequacy of ideal models, we will normalize the obtained diagnostic deviations [22]. To do this, calculate the value of the Δnorm, the value behind which the standardization of the deviation is carried out. The parameter value is calculated as the standard deviation behind the first set of points, in our case we will take an area of 30 points. For our first parameter, pressure after compressor we use formula:

$$\Delta P'_{c.norm} := \sqrt{\frac{\sum_{i=0}^{29} \left(\Delta P'_{c_i} - \Delta P'_{c.ave}\right)^2}{30-1}}$$

To calculate the value for which the normalized deviation is carried out, we need to calculate the average value of the diagnostic deviation calculated from the first 30 points using formula:

$$\Delta P'_{c.ave} := \frac{\sum_{i=0}^{29} \Delta P'_{c_i}}{30}$$

Now, when we have calculated the parameters of the diagnostic deviation and the scatter associated with measurement errors and inadequacy of ideal engine models, to further determine the presence of a trend change in the diagnostic deviation we can normalize the obtained diagnostic deviations by formula:

$$\Delta P'_{c.n_i} := \frac{\Delta P'_{c_i}}{\Delta P'_{c.norm}}$$

For another our parameters, like temperature after compressor ($T`_c$), temperature before working turbine ($T`_{th}$) and mass fuel consumption ($G_f$) calculate average value of the diagnostic deviation calculated from the first 30 points and normalize the obtained diagnostic deviations use formulas for $T`_c$:

$$\Delta T'_{c.ave} := \frac{\sum_{i=0}^{29} \Delta T'_{c_i}}{30}$$

$$\Delta T'_{c.norm} := \sqrt{\frac{\sum_{i=0}^{29} \left(\Delta T'_{c_i} - \Delta T'_{c.ave}\right)^2}{30-1}}$$

$$\Delta T'_{c.n_i} := \frac{\Delta T'_{c_i}}{\Delta T'_{c.norm}}$$

Also determine average value of the diagnostic deviation calculated from the first 30 points and normalize the obtained diagnostic deviations use formulas for $T`_{th}$:

$$\Delta T'_{th.ave} := \frac{\sum_{i=0}^{29} \Delta T'_{th_i}}{30}$$

$$\Delta T'_{th.norm} := \sqrt{\frac{\sum_{i=0}^{29} \left(\Delta T'_{th_i} - \Delta T'_{th.ave}\right)^2}{30-1}}$$

$$\Delta T'_{th.n_i} := \frac{\Delta T'_{th_i}}{\Delta T'_{th.norm}}$$

Average value of the diagnostic deviation calculated from the first 30 points and normalize the obtained diagnostic deviations use formulas for $G_f$:

$$\Delta G_{f.ave} := \frac{\sum_{i=0}^{29} \Delta G_{f_i}}{30}$$

$$\Delta G_{f.norm} := \sqrt{\frac{\sum_{i=0}^{29} \left(\Delta G_{f_i} - \Delta G_{f.ave}\right)^2}{30-1}}$$

$$\Delta G_{f.n_i} := \frac{\Delta G_{f_i}}{\Delta G_{f.norm}}$$

Let us construct a graphs of the dependence of the calculated above normalized parameters of the dependence of the diagnostic deviations from the measurement number and limit it to a region of up to 3 orders of deviation (figure 3.20 – 3.23):

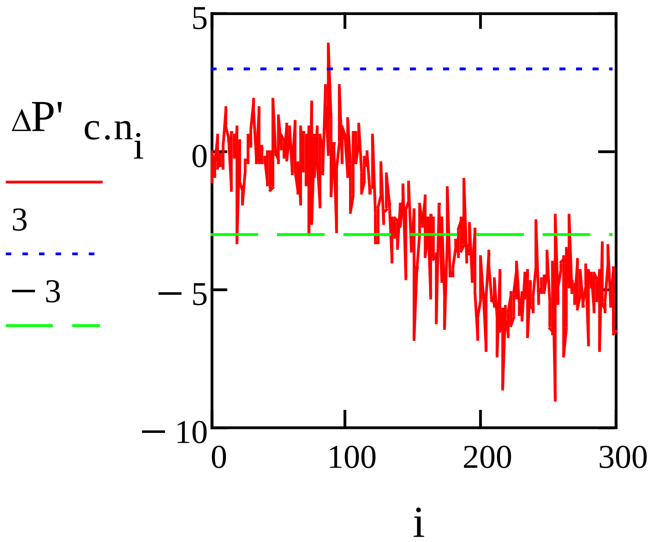


Figure 3.20 Normalized compressor pressure diagnostic deviation dependence from the measurement number.

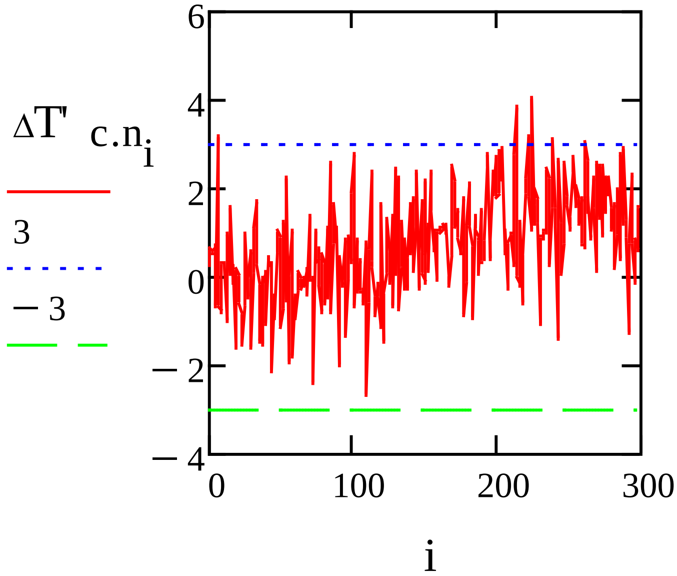


Figure 3.21 Normalized compressor temperature diagnostic deviation dependence from the measurement number.

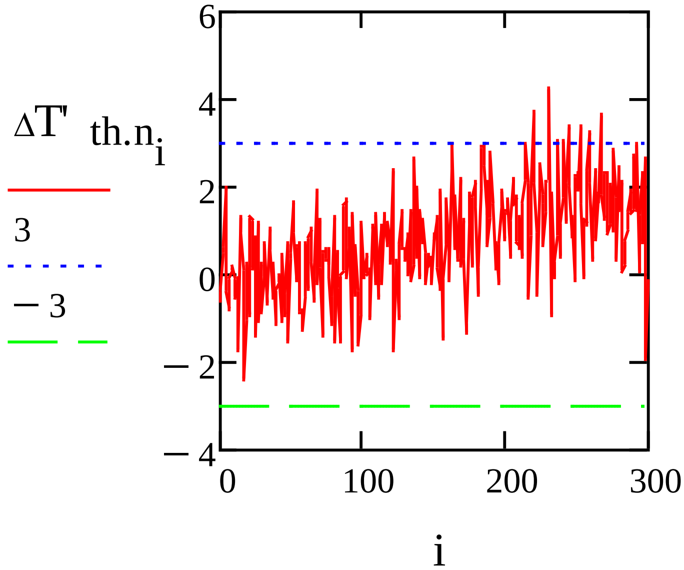


Figure 3.22 Normalized turbine temperature diagnostic deviation dependence from the measurement number.

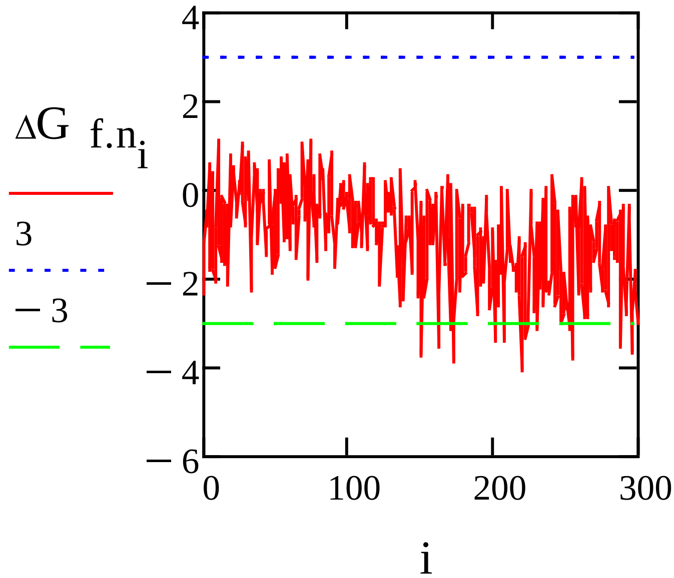


Figure 3.23 Normalized mass fuel consumption diagnostic deviation dependence from the measurement number.

Let's check the presence of a time series of signs of a technical condition and the presence of a trend [14]. Trend temporal gradual change in the diagnostic deviation can be caused by gradual degradation processes that occur in the nodes. For example, this can include abrasive wear of compressor blades, high-temperature corrosion and seal wear, and many others. To determine the trend, it is necessary to determine whether the value of the correlation coefficient really differs from zero from the diagnostic deviation and the time parameter. checking the presence of a trend is carried out for each separately taken area at 30 points, considered as units of time.

To check the presence of a trend, we need to calculate the value of the mathematical expectation M and root mean square deviation for two sections, our section of 30 units and the section that lies behind it. Calculate it using the formulas:

$$M_{p_j} := \frac{\sum_{i=j}^{j+L-1} \Delta P'_{c.n_i}}{L} \qquad M_{i_j} := \frac{\sum_{i=j}^{j+L-1} i}{L}$$

$$M_{t_j} := \frac{\sum_{i=j}^{j+L-1} \Delta T'_{th.n_i}}{L} \qquad M_{t_j} := \frac{\sum_{i=j}^{j+L-1} \Delta T'_{c.n_i}}{L}$$

$$M_{g_j} := \frac{\sum_{i=j}^{j+L-1} \Delta G_{f.n_i}}{L}$$

where $M_p$, $M_t$, $M_g$ - mathematical expectations of our range and $M_i$ - mathematical expectation our of our range.

$$\Delta S_{p_j} := \sqrt{\frac{\sum_{i=j}^{j+L-1} \left(\Delta P'_{c.n_i} - M_{p_j}\right)^2}{L-1}} \qquad \Delta S_{i_j} := \sqrt{\frac{\sum_{i=j}^{j+L-1} \left(i - M_{i_j}\right)^2}{L-1}}$$

$$\Delta S_{t_j} := \sqrt{\frac{\sum_{i=j}^{j+L-1} \left(\Delta T'_{c.n_i} - M_{t_j}\right)^2}{L-1}} \qquad \Delta S_{i_j} := \sqrt{\frac{\sum_{i=j}^{j+L-1} \left(i - M_{i_j}\right)^2}{L-1}}$$

$$\Delta S_{t_j} := \sqrt{\frac{\sum_{i=j}^{j+L-1} \left(\Delta T'_{th.n_i} - M_{t_j}\right)^2}{L-1}} \qquad \Delta S_{i_j} := \sqrt{\frac{\sum_{i=j}^{j+L-1} \left(i - M_{i_j}\right)^2}{L-1}}$$

$$\Delta S_{g_j} := \sqrt{\frac{\sum_{i=j}^{j+L-1} \left(\Delta G_{f.n_i} - M_{g_j}\right)^2}{L-1}} \qquad \Delta S_{i_j} := \sqrt{\frac{\sum_{i=j}^{j+L-1} \left(i - M_{i_j}\right)^2}{L-1}}$$

where $\Delta S_p$, $\Delta S_t$, $\Delta S_g$ – root mean square deviation of our range and $\Delta S_i$ – root mean square deviation out of our range.

Also, to determine correlation coefficient we need calculate correlation moment depending on our mathematical expectation by formula:

$$\mu_j := \frac{\sum_{i=j}^{j+L-1} \left[\left(i - M_{i_j}\right) \cdot \left(\Delta P'_{c.n_i} - M_{p_j}\right)\right]}{L}$$

$$\mu_j := \frac{\sum_{i=j}^{j+L-1} \left[\left(i - M_{i_j}\right) \cdot \left(\Delta T'_{c.n_i} - M_{t_j}\right)\right]}{L}$$

$$\mu_j := \frac{\sum_{i=j}^{j+L-1} \left[\left(i - M_{i_j}\right) \cdot \left(\Delta T'_{th.n_i} - M_{t_j}\right)\right]}{L}$$

$$\mu_j := \frac{\sum_{i=j}^{j+L-1} \left[\left(i - M_{i_j}\right) \cdot \left(\Delta G_{f.n_i} - M_{g_j}\right)\right]}{L}$$

Now we can calculate the correlation coefficient using the formula:

$$\rho_j := \frac{\mu_j}{\Delta S_{p_j} \cdot \Delta S_{i_j}} \qquad \rho_j := \frac{\mu_j}{\Delta S_{t_j} \cdot \Delta S_{i_j}}$$

$$\rho_j := \frac{\mu_j}{\Delta S_{t_j} \cdot \Delta S_{i_j}} \qquad \rho_j := \frac{\mu_j}{\Delta S_{g_j} \cdot \Delta S_{i_j}}$$

Having the correlation coefficient, we can calculate the statistics that obeys the Student's distribution at a significance level of 0.01 and the amount of the degree of freedom k = L – 2 by the formula same for every parameter:

$$T_j := \rho_j \cdot \frac{\sqrt{L-2}}{\sqrt{1-(\rho_j)^2}}$$

Now we can find the critical point, the line T cr in our case, using the Mathcad software, determined the line T critical by the formula same for every parameter:

$$T_{cr} := qt\left(1 - \frac{0.01}{2}, N - 2\right)$$

Let's draw a graphs of the statistic dependence of the Student's distribution with the critical boundaries (figure 3.24 – 3.27). In cases where conditions T is greater than T cr the trend of the parameter is considered significant.

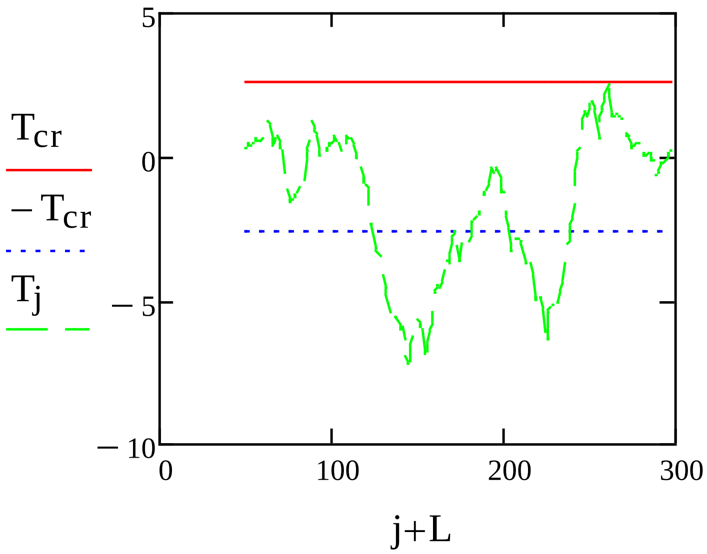


Figure 3.24 Statistic dependence of the Student's distribution with critical boundaries for pressure after compressor parameter.

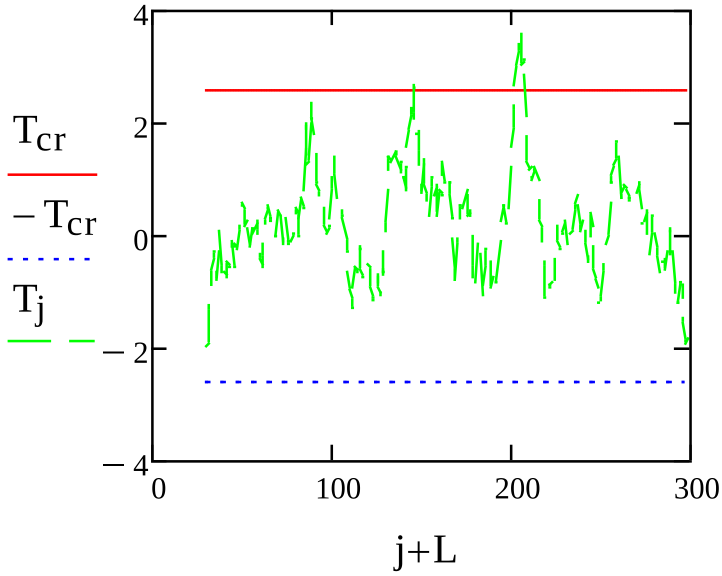


Figure 3.25 Statistic dependence of the Student's distribution with critical boundaries for temperature after compressor parameter.

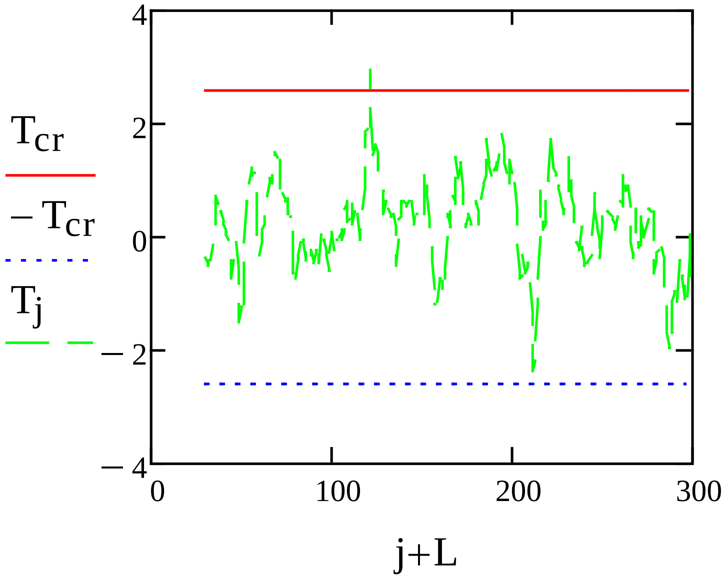


Figure 3.26 Statistic dependence of the Student's distribution with critical boundaries for temperature before working turbine parameter.

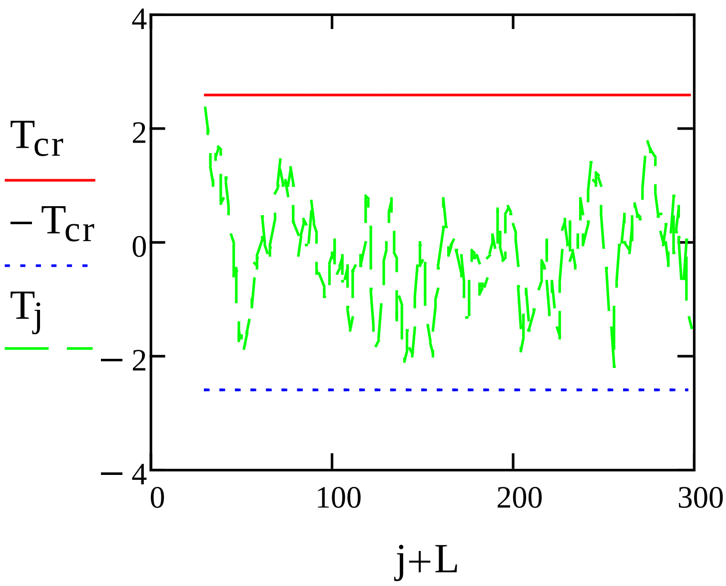


Figure 3.26 Statistic dependence of the Student's distribution with critical boundaries for mass fuel consumption parameter.

After analyzing the draw graphs, we come to the conclusion that the trend to change the diagnostic deviations takes place in all places that go beyond the boundary lines for our parameters [22].

### 3.8 Result analysis

Having considered the graph of the statistical dependence of the Student's distribution with critical boundaries, and specifically the first graph, Figure 3.24, of the pressure behind the compressor, we come to the conclusion that the trend takes place, since the graph clearly shows the two lower peaks going beyond the lower critical boundary [14].

Consider the following graph in Figure 3. 25 for the downstream temperature parameter. In this graph, one peak is seen that has gone beyond the upper critical boundary, which indicates that there is a trend for the temperature behind the compressor.

Let us study the following graph of the statistical dependence of the student distribution with critical boundaries, this time for the temperature parameters in front of the working turbine. On this graph, you can clearly see only one small place where the value goes beyond the critical point, which means that there is a trend in diagnostic deviations on this graph.

Let's consider the last remaining graph for the parameter of mass fuel consumption Figure 3.26. Let us analyze this graph of the statistical dependence of the student distribution with critical boundaries. Unlike all previous charts, this chart does not exceed the critical boundaries. This indicates that there is no trend towards a change in diagnostic deviations for the mass fuel consumption parameter.

## Conclusions

1. A mathematical model of the GTE workflow has been developed. The model allows to calculate the parameters of the gas turbine engine, sensors were selected to measure the main parameters for further measurement of the dependencies of the measured parameters at different engine modes based on the maximum values of the parameters. The model allows to calculate the rotating frequency of the high-pressure rotor.

2. The normal measured values of the parameters were calculated taking into account the errors of the sensors and graphs of the measured basic parameters were draw, such as the pressure behind the compressor, the temperature behind the compressor and before the working turbine, as well as the mass fuel consumption for further comparison with the ideal measured values.

3. A mathematical model has been developed to determine the parameters of diagnostic deviations, to check the presence of a trend, were calculated the correlation coefficient and statistics that obeys the Student's distribution at a significance level of 0.01 and the amount of the degree of freedom $k = L - 2$ and draw graphs of statistic dependence of the Student's distribution with critical boundaries for our measured parameters.

4. Were draw the and analyzed graphs for presence of measurement diagnostic trend. We can make a conclusion, that the trend of measurement deviation was found for almost all parameter except the mass fuel consumption.

# 4 ENVIRONMENTAL PROTECTION

## 4.1 Hazardous factors that occur during the operation of the GTE

According to the state standard, hazardous and dangerous factors by action and nature of influence are divided into four classes: physical, chemical, biological and psychophysiological.

During the operation of the gas turbine, the possible negative impact on the environment consists of several main factors: possible gas leakage and increased noise and vibration.

According to the state standard, hazardous and dangerous factors by action and nature of influence are divided into four classes: physical, chemical, biological and psychophysiological. Noise and vibration are physical pollutants, and gas leaks are chemical pollutants.

Noise is a set of different in strength and frequency of sounds that interfere with the perception of useful signals and adversely affect a person. The physical essence of sound is the oscillation of environmental particles that are perceived by human hearing as undesirable. During sound vibrations, areas of low and high pressure are formed, which act on the auditory analyzer (ear membrane). Vibration - the movement of a mechanical system, in which alternately increase and decrease over time the value of the quantity that characterizes this movement. Manifested in the form of mechanical oscillations of elastic bodies.

Hazardous factors that adversely affect the environment include:

– increased noise level during operation of the gas turbine engine;

– possible explosion of the gas-air mixture due to the dangerous concentration (5 - 15%) with air, formed due to gas leakage due to leakage in the joints, seals;

– chemical contaminants associated with possible gas leakage due to leaks in joints, seals;

– vibration during operation of GTE.

## 4.2 Environmental impacts assessment for TB3-117.

One of the forms of physical pollution of the atmosphere is noise, the body's adaptation to it is impossible. Noise is a set of sounds of different frequency and intensity that occur as a result of oscillating motion of particles in elastic media (solid, liquid, gaseous). Noise intensity of 30 ÷ 80 dB does not harm the human body. At the same time, noises with an intensity of 85 dB and more lead to physiological and psychological negative effects on the nervous system, sleep, emotions, performance. Today, the problem of noise pollution is very relevant, as it grows over time. Usually noise is an unpleasant or unwanted sound or a set of sounds that interfere with the perception of useful sound signals, disturb the silence, have a hazardous or irritating effect on the human body, reduce its efficiency. Elevated noise has an adverse effect on the human body. The degree of this action depends on the characteristics of the noise and individual characteristics of the person. Noise affects not only the hearing organs, but also the nervous system, causes an increase in blood pressure, decreased attention, leads to reduced productivity and increased injuries. Existing regulations provide for a maximum permissible sound level of 85 dB.

Noise adversely affects various body systems: cardiovascular, nervous, disturbs sleep, attention, increases irritability, depression, anxiety, irritation, can affect the respiratory and digestive systems; hearing impairment with temporary or permanent hearing loss; impaired ability to transmit and perceive the sounds of speech; distraction from normal activities; changes in human physiological responses to stress signals; effects on mental and physical health; effect on labor activity and labor productivity. Studies show adverse effects of noise on the central nervous, cardiovascular and digestive systems.

When the vibration of production mechanisms, their rapid oscillating and rotational movements are transmitted to objects in contact with them, including workers.

The cause of vibration disturbances are unbalanced force effects arising during operation of machines: shock loads; reciprocating movements; imbalance. The reasons for the imbalance are: the heterogeneity of the material; discrepancy of centers of masses and axes of rotation; deformation.

Vibration is a generally biologically hazardous factor that leads to occupational diseases - vibration diseases, the treatment of which is possible only in the early stages. The disease is accompanied by persistent disorders in the human body. The person partially or completely loses his ability to work. According to the method of transmission to humans, vibration is divided into general and local. General - acts through the supporting surfaces of the feet on the whole body. Local - on certain parts of the body. Prolonged exposure to vibration causes an occupational disease - vibration disease.

Methane is the second largest greenhouse gas after carbon dioxide in terms of total emissions and atmospheric content. The global warming potential of methane per unit volume for a hundred-year time horizon is 58 times higher than that of carbon dioxide. Methane is 21 times more efficient as a greenhouse gas than carbon dioxide per unit mass. The direct contribution of methane to the growth of the greenhouse effect has already exceeded 20%. However, its lifetime in the atmosphere (12 ± 3 years) is much shorter than that of carbon dioxide.

### 4.3 Calculation of emissions of hazardous substances by the engine

GTD are stationary organized sources of emissions of hazardous substances into the atmosphere. When drawing up and monitoring the implementation of environmental protection plans at gas industry enterprises, emissions of carbon monoxide (CO) and nitrogen oxides (NOx) are taken into account.Викиди ШР в атмосферу з відпрацьованими газами двигунів визначається їх емісійними характеристиками, режимами роботи, а також кількістю працюючих ГПА.

The mass of emissions of hazardous substances in the area of the compressor station for the three operating HPA in nominal mode is calculated as follows:

1. We accept working time at nominal mode for the year:

$$t_н = 270 \text{ day} = 6480 \text{ h.}$$

2. Determine the operating mode of the engines at rated mode:

$$T_н = t_н\, n,$$

where n is the number of operating units (n=2),

$$T_н = 2 \cdot 6480 = 12960 \text{ h.}$$

3. Determine the mass of fuel consumed by the unit during the period of operation:

$$G_T = G_{Tпит.}\, R_H\, T_H ,$$

where $G_{Tпит}$ = 0,183 kg/(kWt•h) -– specific fuel consumption at nominal mode, kg/h.

$R_H$ = 6,3 MВт. – unit power at rated mode (according to the technical characteristics of the engine).

$$G_т = 0{,}183 \cdot 6{,}3 \cdot 12960 = 14941 \text{ kg/year}$$

4. Calculate the mass of Mi annual emissions of carbon monoxide (CO), nitrogen oxides (NOx), for HPA in nominal mode:

$$M_i = к_i\, G_T ,$$

where $\kappa_i$ – emission factor of the i-th substance, when operating at nominal mode (emission index), kg.speed / kg.fuel.

For carbon monoxide $\kappa_{CO}$ = 0,0175 kg.sh/kg.fuel., for nitric oxide $\kappa_{NOx}$ = 0,0125 kg.sh/kg.fuel. (indicators ki are taken as average statistical data from running similar engines), than:

$$M_{co} = 0.0175 \cdot 14941 = 0.261 \text{ mSH/year}$$

$$M_{no} = 0.0125 \cdot 14941 = 0.187 \text{ mSH/year}$$

Averted environmental and economic damage that occurs during the year due to emissions into the atmosphere, for the source of pollution is determined by the formula:

$$Y = \gamma \cdot \sigma \cdot f \cdot M$$

where Y– averted ecological and economic damage (UAH / year);

*y* –- constant, the numerical value of which is equal to 2.4 when estimating annual emissions;

*б* – the value of which is determined in the calculations;

*f* – value, the value of which is determined in the following calculations;

*M* – the mass of the annual emission of pollutants from the source of pollutants is given.

For an organized source (exhaust pipe), height h> 10 m and an area of active pollution, which is a circle with a radius $z_{3A3}$ = 20 *xh*,

$$x = 1 + \frac{\Delta T}{75^{\circ}C},$$

where *x* – dimensionless correction for the rise of the emission flare, calculated by the formula;

$\Delta T$ – the average annual value of the temperature difference at the outlet of the source of pollution is equal to 15 $^{0}$C :

$$x = 1 + \frac{15}{75} = 1{,}2\,,$$

than

$$z_{ЗАЗ} = 20 \cdot 1{,}2 \cdot 10 = 240 \text{ м}.$$

The value of the relative danger of air pollution over the territory of the compressor station b = 4 (the territory of industrial enterprises).

The value of the factor f (correction, taking into account the nature of the scattering of impurities in the atmosphere) for gaseous impurities and light fine particles, we assume that:

$$f = \frac{100м}{100м + x \cdot h} \times \frac{4\,\frac{м}{с}}{1\,\frac{м}{с} + U\,\frac{м}{с}}\,,$$

where $U$ – average annual value of the wind speed modulus at the weather vane level, m / s; in cases where the value is unknown, it is taken equal to 3 m / s:

$$f = \frac{100}{100 + 1{,}2 \cdot 10} \cdot \frac{4}{1+3} = 0{,}89$$

The value of the reduced mass of the annual emission of pollutants into the atmosphere from the source is determined by the formula:

$$M = A_i\ M_i\,,$$

where $M_i$ – mass of annual emission of impurity of the i-th type t / year (for CO MSO = 0,392 t. SHR / year, for NOx - MNOx = 0,28 t. ShR / year.

$A_i$ – indicator of relative aggressiveness of the substance (for CO $A_{CO}$ =1):

$$M_{CO} = 0{,}392 \cdot 1 = 0{,}392 \text{ t.SHR / year.}$$

$$M_{NOx} = 0{,}28 \cdot 1 = 0{,}28 \text{ t.SHR / year.}$$

Averted environmental and economic damage:

$$Y_{CO} = 2{,}4 \cdot 4 \cdot 0{,}89 \cdot 392 = 3349{,}24 \text{ UAH / year}$$

$$Y_{NOx} = 2{,}4 \cdot 4 \cdot 0{,}89 \cdot 280 = 2392 \text{ UAH / year}$$

### 4.4 Measures to increase the environmental safety of the drive engine

Reduction of negative impact of GPA as a part of KS on environment during its work is provided by the following:

- compressed natural gas is used as fuel for the GTE drive, which reduces hazardous emissions of combustion products;
- at the site of installation of the GTE there are tanks for collecting sludge fuel (gas condensate), lubricants, technical fluids and pallets to prevent spillage of liquids when replacing components and units. This prevents soil contamination during maintenance and repair of the GPE drive, as well as during routine work on the unit.;
- provided places for washing at the sites of periodic maintenance and repair with the necessary communications;
- technical staff strictly adheres to the rules of maintenance in accordance with environmental requirements for the protection of nature from production factors;
- air intake and exhaust devices of the engine providing effective mufflers of lamellar-slot type, which reduces the noise level;
- the walls of all blocks are made using panels filled with sound-absorbing material;
- air corridors are located at a distance of at least 7 ÷ 8 km. from large settlements;

## Conclusions

The section addresses issues related to environmental protection:

– the analysis of ecological danger caused by the gas turbine drive of GTE is carried out;

– Emissions of hazardous substances by the HPA engine are calculated and the averted ecological and economic damage caused to the environment is determined;

– identified ways to increase the environmental safety of the designed GTE drive, the main purpose of which is to reduce the negative impact of GTE on the environment.

# 5 OCCUPATIONAL HEALTH

All productions of the gas industry are productions with a high level of danger. The level of occupational injuries of enterprises in the industry is stable. The majority of occupational injuries occur in ancillary enterprises. The nature and causes of occupational injuries do not change from year to year. The main reason is the unsatisfactory organization of work, the decline of production discipline, low staff skills. Therefore, the organization of labor protection in enterprises is one of the most important tasks and responsibilities of the administration. The administration of the enterprise is obliged to provide proper technical equipment of all workplaces and to create working conditions that comply with the rules of labor protection..

## 5.1 Analysis of harmful and dangerous production factors

Dangerous factor of production ─ a factor of production, the action of which on the worker in certain conditions leads to injury or other sudden sharp deterioration of health.

Harmful factor of production ─ a factor of production, the action of which on the worker in certain conditions leads to illness or reduced efficiency.

"Dangerous and harmful production factors" at the facility, such dangerous and harmful factors are possible:

– unprotected moving elements of GPA, lifting mechanisms and production equipment;

– vehicles for delivery of equipment units;

– increased slipperiness (due to ice, wetting and oiling of the installation surface;

– increased vibration;

– increased level of infrared radiation from the heated parts of the drive;

– increased noise (reduces productivity, quickly causes fatigue, may be the result of occupational diseases);

– increased levels of ultraviolet and thermal radiation;

– increased dust and gassiness in the GTE area;

– increased or decreased surface temperature of GTE equipment and materials;

– dangerous voltage level in the electrical network;

– physical overload (static and dynamic);

– neuropsychological (emotional).

Chemical hazardous and harmful production factors:

– by the nature of the action on the human body - general toxic and irritating;

– by penetration into the human body - penetrating through the respiratory system, gastrointestinal tract, skin and mucous membranes.

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.

Vibrations are mechanical oscillating movements, the sources of which in this case are gas and air pipelines, equipment, some types of hand tools. If the vibrating parts of the equipment touch the body of the worker, the vibration acts as an occupational hazard. The points of its application are most often the arms and legs. There is a local vibration, which is applied to a limited area of the body, it is exposed to workers with electric tools percussive and rotational action, and general, associated with the movement of the body in space. Vibrations cause irritation or obstruction to the work process.

Potentially dangerous and harmful production factors that may occur during the implementation of the technological process or operation of equipment are summarized in table 5.1.

Table 5.1

Analysis of potentially dangerous production factors

| Source of danger | Characteristics of potentially hazardous production factors are acceptable values |
|---|---|
| GTE | Increased sound pressureL = 100 дБА, f = 63 Гц<br>ГДР L = 80 дБА, f = 63 Гц |
| Gassiness | Exceeding concentrations by 2.2 times |
| Electrical equipment | I = 10 A, U = 380 B, f = 50 Hz |
| Arc | High level of ultraviolet radiation72 (measures year) / m2 at l = 280 nm<br>GDR 60 (measures year) / m2 at l = 280 nm |
| Vessels under pressure | pressure in the gas pipeline - 55 atm |

| | |
|---|---|
| Excess noise in the premises of the CC and on the site of the APO | Noise level of 86 - 100 dBA is created in the premises;<br>The noise level at the APO site is 83 - 86 dBA |

Most of the work is performed under visual control (observation of the operation of mechanisms, devices, readings of measuring instruments and during production operations). Thus the human body carries this or that degree of loading and experiences pressure that under certain conditions leads to fatigue of an organ of sight and the general fatigue of an organism. Insufficient light affects the degree of eye fatigue, which depends on the degree of intensity of the processes that accompany the visual perception of objects in the outside world. Such processes include accommodation, convergence and adaptation. Visual acuity (the ability of the eyes to distinguish the details of objects) and permanent vision depend on the level of illumination.

Table 5.2 lists the toxic and harmful substances used in the enterprise.

Table 5.2

Characteristics of harmful substances

| Name of the substance or material | MPC, mg / m3 | | First aid for poisoning |
|---|---|---|---|
| | In the work area | В атмосфері | |
| Methanol | 5 | 1,0 | Gastric lavage, disinfection with a solution of manganese, drinking 5% saline solution |
| Diethylene glycol | 45 | 0,1 | Inpatient treatment |
| Gasoline | 85 | 3 | Fresh air, heat, 20 ... 30 drops of valerian |
| Condensate | 5 | 3 | Fresh air, tea |
| Oil | 6 | 1 | Wash your hands with warm soapy water |
| Diesel fuel | 300 | 3 | Fresh air, 20-30 drops of valerian, |

| | | | |
|---|---|---|---|
| Acids | 0,3 | 0,01 | Fresh air, rinsing the skin with water |
| Acetone | 200 | 0,35 | Fresh air, elevated legs, strong sweet tea or coffee |
| Benzene | 1,5 | 0,02 | Fresh air, rinsing the skin with water. |
| Sulfuric acid | 30 | 0,3 | Fresh air, inhalation of soda solution. |

## 5.2 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 5.3 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 5.3
- geometric dimensions of the compressor hall;

- the amount of gas emitted in the room.

Table 5.3

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, ie

Based on the data obtained, choose the type of fan.

Fan performance can be calculated by the following formula:

$$L = n \cdot V_{np},$$

where $n -$ multiplicity of air exchange;

$V_{np}$ – volume of the room.

The volume of the room is determined by the following formula:

$$V_{np} = (1 - 0{,}3) \cdot V_{ГПА},$$

where $V_{ГМК}$ –об'єм зали ГПА, 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 GPA.

The 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 GPA 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:

$$L = 40 \cdot 380{,}8 = 15231{,}9 \frac{м^3}{год}.$$

According to this performance, choose a centrifugal fan type

C 4-70 № 8 with productivity limits 15 ÷ 23.3 thousand m3 / hour, in the amount of 8 pcs.

### 5.2.1 Fire and explosion safety during operation of the compressor station

Compressor stations must be equipped with devices and means of control of automation and signaling on gas pipelines and units.

Serviceability and correctness of indications of control and measuring devices are checked:

– once per shift (regular staff) according to the schedule of inspection of technical condition;

– gas analyzers for compliance with the established parameters are checked 2 times a year with a mixture.

Work on regulation and repair of automation systems, emergency protection and alarm systems in conditions of gassiness is prohibited.

Maintenance and repair of measuring instruments, automation and alarm systems must be performed by specially trained personnel who have passed the knowledge test and successfully passed the tests.

Devices removed for repair or inspection must be replaced immediately.

Prior to the replacement of gas analyzers, the control of gas pollution of the premises must be carried out by portable gas analyzers (constantly).

It is forbidden to arrange basements and semi-basements in the building of the compressor shop.

It is forbidden to install in the shops any devices or equipment that are not structurally or technologically connected with the compressors.

The service personnel of the compressor shop must systematically monitor:

tightness, strength of gas pipeline connections, stuffing box seals of equipment and apparatus;

serviceability of emergency drain and overflow lines from oil tanks (tanks for emergency drain should be serviceable and empty, management of cranes on drain lines - reliable);

serviceability of thermal insulation of the heated surface of GPA, flues and air ducts;

serviceability of ventilation systems and automatic means of switching on emergency electric lighting.

In the compressor shop and other buildings it is forbidden:

- to lay temporary electric networks;

- use the body of machines, pipelines and metal structures of buildings as grounding devices of equipment units;

- use flammable flammable liquids for washing and cleaning parts;

- to dry overalls on central heating devices, hot surfaces of units and gas communications.

It is not allowed to perform any repair work on existing units, devices and pipelines.

It is forbidden to clean the pipelines with steel tinder and other devices that can cause sparks.

Service personnel must know the layout of all communications, as well as their purpose, unmistakably block (open) them in case of accidents and fires.

According to DSTU of Ukraine 2273-93 «SSPB Fire equipment. Terms and definitions "fire extinguishers are portable or mobile equipment for extinguishing fires due to the release of a spare extinguishing agent.

### 5.2.2 The main requirements for compliance with the rules of labor protection during operation of the designed engine

Maintenance of the equipment, including its start-up, stop and regulatory issues, must be carried out in accordance with the requirements of the technical instructions of the manufacturer. Operation of the gas turbine with parameters that deviate from the values specified in the operating instructions is not allowed.

After installation of the main and auxiliary equipment during commissioning, when the compressor station concentrates construction, installation, operation and commissioning equipment, special attention should be paid to compliance with safety rules. Before supplying gas to the compressor station, all personnel of construction, installation, commissioning and other organizations involved on the site must be instructed in safety, which must be documented.

When installing the gas turbine should pay attention to the following:

- lifting the turbine unit should be performed using a special traverse;
- lifting of other units (suction chamber, oil cooler unit, exhaust device, muffler, etc.) must be performed in accordance with the insurance schemes and in accordance with the recommendations set out in the technical documentation at the GTE.

All leaks and crevices must be eliminated in the joints of the gas turbine units, the oil tank lids must be installed tightly. On the non-functioning unit of the blinds of the air cleaning device, the air intake compartment of the engine must be closed, the inlet diffusers of the fans of the oil cooler unit are covered.

Commissioning, repair and operation of gas turbines must be carried out in accordance with the requirements of the "Safety Rules for the installation of equipment of compressor stations of main gas pipelines".

Service personnel who have undergone special training, passed exams and are admitted to their maintenance and operation in accordance with the established procedure are allowed to operate and repair gas turbine units.

Before starting the gas turbine, it is necessary to make sure that the sound signal is triggered by pressing the "Start" button. Starting of the unit without protections and covers on the rotating details and on the knots which are at height no more than 2 m from floor level (fans of the block of cooling of oil, the coupling of starting pumps) or their removal during unit operation is not allowed.

During operation of the gas turbine is prohibited:

- enter the engine compartment when starting and running the engine;
- perform work on the engine when the gas turbine system is under current;
- perform work in the suction chamber and exhaust shaft of the unit during start-up or when the engine is running;
- work with open doors of the engine compartment, supercharger, POP and suction chamber.

The air in the oil tank should be checked daily for the content of flammable gases in it with an entry in the log. When the content of combustible gases in the oil tank of the unit is more than 1%, the operation of the HPA is not allowed.

It is not allowed for service personnel to be near the working unit without personal protective equipment against noise, more than one hour during one work shift.

The permissible vibration level of the gas turbine, measured by standard equipment, should not exceed 30 mm / s.

The airtight bulkhead between the engine and supercharger compartments must be maintained in such a way that air from the supercharger compartment does not enter the engine compartment. When supplying hot air from the engine to heat the compartments of the unit, the personnel working in the compartments must be notified. Protective gloves should be worn when handling hot air valves.

When the electricity is cut off, it is necessary to use station portable lights, voltage 12V in explosive design.

In winter, GTU service areas should be periodically cleared of snow.

Emergency shutdown of the unit must be performed in the following cases:

- at threat of safety of service personnel;
- at breakdown of the unit;
- with the appearance of metal knocks and shocks;
- severe oil or gas losses;
- ignition of oil or gas;
- surge phenomena in the unit.

- All engine adjustment work can only be performed when
- stopped unit. Regular and repair work on the engine should be performed only after cooling of its external surfaces to a temperature of 450C. During assembly and disassembly of the unit it is necessary to use serviceable special tools and devices that guarantee safe work.

  It is forbidden:

- use faulty lifting mechanisms and devices for lifting the engine, supercharger cover, rotor and other prefabricated units of the unit;
- leave the parts suspended on the lifting mechanisms;
- operate lifting mechanisms at temperatures below - 20 0C.

Lifting mechanisms that work in pairs should be loaded evenly to avoid breakage and injury to personnel.

Fire-retardant technical detergents should be used when decontaminating and washing parts.

It is forbidden to store kerosene, gasoline and other flammable materials in the shelters of the GTU or near them.

Operation of the fire extinguishing system is inadmissible if the service life of cylinders has expired, and also the defects excluding a guarantee of safe work of installation are revealed. It is forbidden to transport the installation in the presence of extinguishing agent in cylinders. It is allowed to enter the compartments of the engine and supercharger after the operation of the fire extinguishing system without a gas mask only after thorough ventilation and sampling of gassiness in the room.

To determine the content of harmful substances in the air of the working area should be performed control measurements by sampling at least once a year.

Doors must be marked on the doors of the engine compartment, intake chamber and air purifier with the words "Do not enter when operating the GTE".

## 5. 3 Occupational Safety Instruction

### 5.3.1 General safety requirements

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 one once every 12 months (when running in engines running on leaded gasoline once every 12 months);

- repeated briefings: on labor safety - at least one 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 (SB) 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.
after being briefed at the workplace. 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.

### 5.3.2 Safety requirements before starting work

8. Before starting work, the tester must:

a) check by external examination the serviceability, put on overalls and other personal protective equipment installed for this type works;

b) receive a task from the master to perform work and when performing new types of work or changes in working conditions get from the master description of the technological process and instruction on labor protection (before when performing work with increased danger, undergo targeted instruction with a receipt in the work permit);

c) inspect the workplace, remove foreign objects, release passages, check for safety signs;

d) if present on the floor, decking, etc. water, oil products and other clean, remove, wipe dry and sprinkle with sand (sawdust) if necessary;

e) check the serviceability of equipment, protective covers, transport trolleys, tools, lifting equipment and mechanisms;

f) inspect the reliability of fastening the braking device, the coupling guard and the tested engine to the foundation plate (frame), as well as the reliability of the connection of the piping system, electrical harnesses to the engine;

g) make sure that there are no foreign objects and tools on the engine, in the braking device, as well as in the absence of leaks in the connectors and connections of fuel, oil and water systems, tightness air and gas pipelines;

h) when testing gas turbine engines, check the serviceability bench fuel system, open the flap on the exhaust gas outlet pipe, inspect the bench, engine inlet and outlet ducts, make sure there are no foreign objects;

i) transport the engine on a trolley at a speed not more than 5 km / h and a brigade of at least two people;

j) when performing slinger work and with increased danger have an admission order and the corresponding certificate of right performing these works.

9. Before work on hydraulic and pneumatic testing systems and devices:

a) remove all flammable and combustible materials from the area testing;

b) post warning signs and install place fences hydraulic and pneumatic tests;

c) prepare standard equal-strength plugs for testing systems.

### 5.3.3 Safety requirements during work

10. The tester is obliged:

a) observe all safety measures, monitor the serviceability and safe condition of the equipment and tools used in the work, special clothing and footwear, as well as hands must be dry;

b) maintain order at the workplace, avoid cluttering up with materials, equipment and production waste, prevent spillage of fuels and lubricants and water (in case of spillage of oil products and other liquids, immediately clean up and wipe dry spill);

c) during work, be attentive, not distracted or distracted from the work of other workers, monitor the good condition and safety of protective equipment, cleanliness of overalls;

d) carry the tool only in specially equipped for these purposes in bags, boxes, cases (do not leave the tool in working position during breaks in work, put it in bags, cases or boxes);

e) with the engine running, monitor the normal operation of ventilation and all systems serving the stand;

f) with a short stay in the test room the stand (with the engine running), use personal protective equipment against noise (identify defects and inspect the working internal combustion engine at a minimum stable crankshaft speed);

g) carry out all work on adjusting the gas turbine engine only after stopping the engine (entering the box with the engine running allowed in exceptional cases to determine a defect, if this, the engine must run at low gas, and a master must be at the control panel);

h) stop the engine if a leak is detected in the fuel and oil systems, a sharp increase in the coolant temperature or oil, as well as exhaust gases from the engine outlet;

i) use portable lamps to inspect the engine voltage not higher than 12 V.

11. When performing work using hoisting machines:

a) load slinging (strapping) of the cargo only if there is a slinger certificate and the requirements of the security instructions are met labor for the slinger;

b) use serviceable and timely tested hoisting machines and hoisting devices of appropriate carrying capacity, with the established markings;

c) during the work on lifting and moving the cargo, warn and, if necessary, remove people from the danger zone (near the cargo, along the path of movement and in places of installation (storage), in time of movement of the load to be aside and move behind the load;

d) do not leave the load in a suspended state and do not produce on it work prior to installation in place;

e) when removing the engine from the trolley or test bench, do holding it (about 1 minute) in a suspended state at a height of 5 - 10 cm from the upper plane of the trolley or installation frame and only after this delay continue to raise the engine to the required height;

f) when stowing the load, place it on a solid, level base, excluding the possibility of falling after removing the slings.

12. The tester is prohibited from:

a) violate the requirements of explosion and fire safety (carry out work in strict accordance with the technological documentation and compliance with the established safety measures);

b) work in faulty personal protective equipment installed for this type of work;

c) perform assembly and disassembly work on a suspended engine;

d) work with faulty equipment and faulty tools;

e) work with faulty or insufficient lighting;

f) pass and stay under the raised load;

g) be near the engine when it is initially started;

h) start the engine by means not provided for by the technological documents (instructions);

i) start the engine with the intake manifolds folded back exhaust gas removal systems, as well as when ventilation is inoperative;

j) turn the engine crankshaft by hand with the fuel supply;

k) leave the control panel and the inspection window of the tester's cabin while the engine is running;

l) perform work on troubleshooting, wiping and tightening of connections (fasteners) on a running engine;

m) when testing a gas turbine engine, enter the box with the engine running.

**5.3.4 Safety requirements in emergency situations**

13. In case of an accident or violation of the operating mode of the test station (stand) the tester is obliged:

a) stop work and warn workers about the danger;

b) take measures to stop the engine, take the equipment out of operation by turning off the test bench and turning off the fuel supply;

c) take measures to eliminate the emergency in compliance with safety requirements and immediately notify the master (head of the site) about the incident;

d) in case of an accident with another employee or a sharp deterioration

If he feels well, he must receive first aid immediately.

**5.3.5 Safety requirements at the end of work**

14. The tester is obliged:

a) stop the engine, turn off the taps on the fuel and oil systems, turn off the power supply of the stand apparatus (equipment), carry out (if necessary) dismantle the engine and pipelines from subsequent installation of standard plugs (while avoiding the spill of flammable materials);

b) check the technical condition of the equipment and systems of the test station and prepare it for further operation;

c) tidy up the workplace and equipment, clear the aisles, put the tools in the toolbox (cabinet), hand over the electric lamps to the tool pantry, garbage and dirty take out the rags to the designated place;

d) close equipment and mechanisms, install fences and signs safety in the necessary places and make sure that none of those working together stayed at the station, turn off the lights;

e) inform the master about all the identified malfunctions during engine and system testing.

## Conclusion

This section 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.

## GENERAL CONCLUSIONS

1. A mathematical model of the GTE workflow has been developed. The model allows to calculate the parameters of the gas turbine engine, sensors were selected to measure the main parameters for further measurement of the dependencies of the measured parameters at different engine modes based on the maximum values of the parameters.

2. The normal measured values of the parameters were calculated taking into account the errors of the sensors and graphs of the measured basic parameters were draw and compare.

3. A mathematical model has been developed to determine the parameters of diagnostic deviations, presence of tendencies of gradual change (trend) of the measured parameters to check the presence of a trend, were calculated the values of the correlation coefficient and statistics that obeys the Student's distribution at a significance level of 0.01 and the amount of the degree of freedom $k = L - 2$ and draw graphs of statistic dependence of the Student's distribution with critical boundaries for our measured parameters.

4. Were analyzed graphs for presence of measurement diagnostic trend.

5. Issues related to environmental protection and labor protection are considered. The analysis of ecological danger caused by the gas turbine drive of GPA is carried out. Emissions of harmful substances by the engine are calculated and the averted ecological and economic damage caused to the environment is determined. Ways to increase the environmental safety of the designed GTE have been identified.

6. The dangerous and harmful production factors that arise during the operation and repair of the designed gas turbine, organizational, design and technological measures to reduce the level of action of dangerous and harmful

production factors are analyzed. Fire and explosion safety during maintenance of GTE is considered. The basic requirements for observance of rules on labor protection at operation of the designed GTE are listed.

## REFERENCES


1. http://engine.aviaport.ru
2. http://www.motorsich.com/rus/products/aircraft/turboshaft/tv3-117vm/
3. http://www.airwar.ru/enc/engines/tv3-117.html
4. http://ep-3.ru/termometri_1_7/
5. https://www.priborist.net/upload/iblock/
6. http://madeintatarstan.com/
7. https://tricorflow.com/tricor-coriolis-meter-tcm-0650/
8. https://domavia.ru/library_ati/detail/194886
9. http://teplomehanika.ru/teplopribor_tha_thk.htm
10. http://www.measurement.ru/AION/preobr_Cr.htm
11. Шпакович Н.И. Термогазодинамический расчет авиационных газотурбинных двигателей [Текст]: навч. посібник / В.В. Забобин, Н.А. Иванов, В.А. Конев, Г.И. Никитина. – Київ : КИИГА, 1992. – 68 с.
12. Гай, Л.Д. Термодинамічний та газодинамічний розрахунки компресорів та ГТУ [Текст]: методичні вказівки до дипломного проектування / Гай Л.Д., Шпакович М.І., Моца В.Г., та інші. - К.: «НАУ-друк», 2002 – 79 с.
13. Терещенко, Ю.М. Теорія теплових двигунів. Термогазодинамічний розрахунок газотурбінних двигунів [Текст] : навч. посібник / Ю. М. Терещенко. М.С. Кулик, Л.Г. Волянская та ін. – Київ: Вид-во Нац. Авіац. Уні-ту «НАУ-друк», 2009. – 328 с.
14. О. С. Якушенко Діагностика газотурбінних установок і компресорів: методичні рекомендації до виконання курсової роботи / уклад.: О. С. Якушенко, П.О.Власенко, П.В.Корольов. – К.: НАУ, 2016. – 23 с.
15. Авиационный турбовинтовой двигатель ТВ2-117А и редуктор ВР-8А. Ру ководство по эксплуатации. М., Машиностроение, 1976. 183 с.

16. Ахмедзянов А.М., Юлдыбаев Л.Х. Вопросы технической диагностики состояния авиадвигателей. — В кн.: Испытание авиационных двига телей. Уфа, изд. УАИ, 1977, № 5, с. 17—28.
17. Кеба И.В. Авиационный турбовинтовой двигатель ТВ2-117А. М., Машиностроение, 1977. 173 с.
18. Мозгалевский А.В., Гаскаров Д.В. Техническая диагности ка. М., Высшая школа, 1975. 206 с.
19. Окороков В.С., Воробьев В.Я. К вопросу виброакустической диагностики авиационных ГТД.— Труды ГосНИИГА, 1976, 131. 67 с.
20. Основы технической диагностики. Под ред. П.П. Пархоменко. М., Энергия, 1976. 464 с.
21. Сиротин Н.Н. Техническая диагностика авиационных двигателей. — В кн.: Воздушный транспорт. Итоги науки и техники. М., ВИНИТИ, 1976, № **5,** с. 106—147.
22. Черкез А.Я. - Инженерные расчеты газотурбинных двигателей методом малых отклонений. М., Машиностроение, 1975. 108 с.
23. Тюрин Ю.А. Выбор параметров для оценки технического состояния авиадвигателя и определение их диагностической ценности. — Труды ГосНИИГА, 1968, № 47, с. 76—107.
24. E. I. Lovescy. The helicopter — some ergonomic factors. «Applied Ergonomies», 1975, N 3.
25. John A. Murphy. Diagnostic system reguirements for Helicopter propulsion systems. «A1AA pap» 1977, N 889.
26. Шулекин В.Т. Теория авиационных двигателей [Текст]: навч. посібник / Шулекин В.Т., Медведев В.В. – Москва : МГТУГА, 2008. – 95 с.