

Exhaust gas temperature measurements in diagnostic examination of naval gas turbine engines

Part I Steady-state processes

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The article presents a possible method of detecting failures in the flow section and supply system of a naval gas turbine engine based on the exhaust gas temperature measured behind the gas generator. This temperature is a basic diagnostic parameter use for evaluating the technical state of the turbine engine in operation, and is monitored during engine start-ups, accelerations and decelerations of rotor units, and steady-load states.

ABSTRACT

The first part of the article is limited to the presentation of the results of diagnostic examination of a three-shaft engine with a separate power turbine, operating in steady-load states. The here presented diagnostic analyses and syntheses based on a simplified mathematical model of thermal and flow processes taking place in the combustion chamber, which was used for deriving the equation describing the average steady-state temperature of the exhaust gas flow at the outlet cross-section of the chamber.

Keywords: technical diagnostics; naval turbine engines; exhaust gas temperature; steady-state processes

INTRODUCTION

A basic control parameter of naval turbine engine operation is the temperature of the exhaust gas flow behind the combustion chamber, measured at engine steady-load states, during the start-up process, and during intermediate time intervals between consecutive steady states (acceleration and deceleration of rotor units). It results from the performed operational (diagnostic) examination of the engine that this parameter, which as a rule is the arithmetic average of the values shown by circumferentially situated thermocouples, provides opportunities for detecting places in which largest energy losses are observed in the operating processes realised by the engine. When the measured (static and dynamic) values of the exhaust gas temperature exceeds the set operating tolerance limits, it is a signal of inadmissible disturbances in the energy conversion processes realised in the engine, which threat with engine break-down (for instance unstable operation of the compressor) [2, 4, 8, 11]. It is also possible to identify and localise known and detectable failures of sub-assemblies and structural elements of the engine flow section and the system of fuel supply for the combustion chamber during engine operation [1, 7].

EXHAUST GAS TEMPERATURE

The exhaust gas temperature is the output parameter of the combustion chamber, which in the reliability aspect is

the most vulnerable element of the entire turbine engine [13]. High dynamics of the realised thermal and flow processes is the source of heavy thermal and gasodynamic loads acting on the components of its structure. No matter how complicated the structural form of the combustion chamber is, and how complicated is the aerodynamics of the primary and secondary air flow coming from the compressor [3], the temperature of the exhaust gas leaving KS can be calculated from the equations of mass and energy balance in the gas space accumulating the energy and substance of the flowing thermodynamic medium, at continuous inflow of the supply fuel – Fig.1 [2, 7, 8, 11, 12].

Inn the simplest zero-dimensional form of the model, the combustion chamber dynamics can be described by a set of differential equations of the thermal and flow processes realised with respect to time τ as the independent variable:

$$\frac{dm_{KS}}{d\tau} = \dot{m}_{pow} + \dot{m}_{pal} - \dot{m}_{spal} \quad (1)$$

$$\frac{dU_{KS}}{d\tau} = \dot{H}_{pow}^* + \dot{Q}_{pal} - \dot{H}_{spal} - \dot{Q}_M \quad (2)$$

$$\frac{dU_M}{d\tau} = \dot{Q}_M - \dot{Q}_{ot} \quad (3)$$

where:

m_{KS} and U_{KS} – substance and energy of the thermodynamic medium accumulated in the KS gas space,

- U_M – internal energy accumulated in the constructional material of the walls limiting the KS gas space,
- $\dot{m}_{pow}, \dot{m}_{pal}, \dot{m}_{spal}$ – mass flow rates of the air and fuel delivered to KS, and the exhaust gas discharged from KS,
- \dot{H}_{pow}^* – enthalpy flux of the air delivered from the compressor,
- \dot{H}_{spal} – enthalpy flux of the exhaust gas discharged from KS,
- \dot{Q}_{pal} – heat flux delivered with the fuel,
- \dot{Q}_M, \dot{Q}_{ot} – heat fluxes, respectively, passed from the thermodynamic medium to the wall limiting the KS gas space, and from the KS walls to the surroundings.

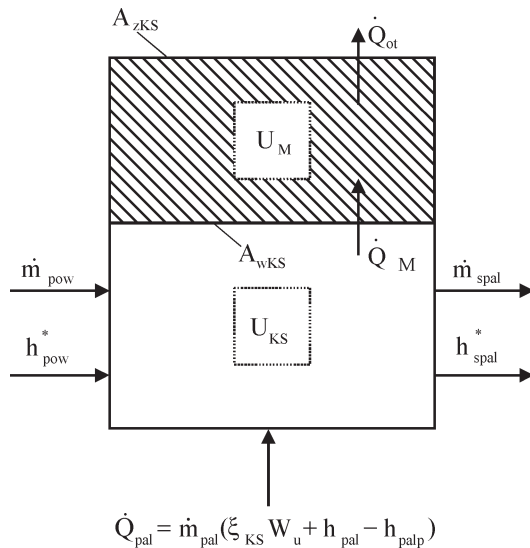


Fig. 1. Physical model of thermal and flow processes in the turbine engine combustion chamber

We can derive the following form of the equation describing changes of the exhaust gas temperature behind the combustion chamber:

$$T_{spal}^* = \frac{\dot{H}_{pow}^* + \dot{Q}_{pal} - \frac{dU_{KS}}{d\tau} - \dot{Q}_M}{\dot{m}_{spal} c_{pspal}(T_{spal}^*)} \quad (4)$$

In steady states, in which the processes of energy and substance accumulation (alternatively dissipation) are neglected and the time derivatives of mass and internal energy of the medium in KS are equal zero, we can write the formula describing changes of the exhaust gas temperature behind KS in a much simpler form:

$$T_{spal}^* = \frac{\dot{m}_{pow} c_{ppow}(T_{pow}^*) T_{pow}^* + \dot{m}_{pal} (\xi_{KS} W_u + h_{pal} - h_{palp}) - \alpha_{wKS} A_{wKS} (T_{spalKS} - T_{MKs})}{\dot{m}_{spal} c_{pspal}(T_{spal}^*)} \quad (5)$$

where:

- ξ_{KS} – coefficient of heat emission in KS,
- W_u – net caloric value of the fuel,
- h_{pal} – specific enthalpy of the fuel delivered to KS at the temperature equal to 293K,
- h_{palp} – specific enthalpy of the fuel delivered to KS at the temperature T_{spalKS} (heat lost for heating the fuel up to the temperature T_{spalKS}).
- α_{wKS} – coefficient of the convective heat-transfer from the exhaust gas to the walls limiting the KS space,
- A_{wKS} – convective heat transfer area,
- T_{spalKS}, T_{MKs} – temperature of, respectively, the exhaust gas and the inner KS wall surface,
- $c_{pspal}(T_{spal}^*)$ – mean specific heat of the exhaust gas at constant pressure, within the gas temperature range characteristic for KS combustion.

Comprehensive discussion of particular terms of the equation (5) in the context of designing control systems and controlling gas turbine engine load can be found in refs. [3, 4, 12], while their analysis and synthesis taking into account energy losses in thermal and flow processes, done for the purpose of diagnostic inference about the technical state of the engine, are given in refs. [6, 7, 9].

High requirements concerning outputs and economic indicators of the naval turbine engines force their permanent development. New, more complicated constructional forms appear, in which the combustion chamber is moved above the high-pressure compressor. Such a design leads to the reversion of the working medium flow direction, and considerable reduction in the engine length. A scheme of the working medium flow in this combustion chamber, complemented with approximate values of local flow velocities (in m/s) around the flame tube is shown in Fig. 2.

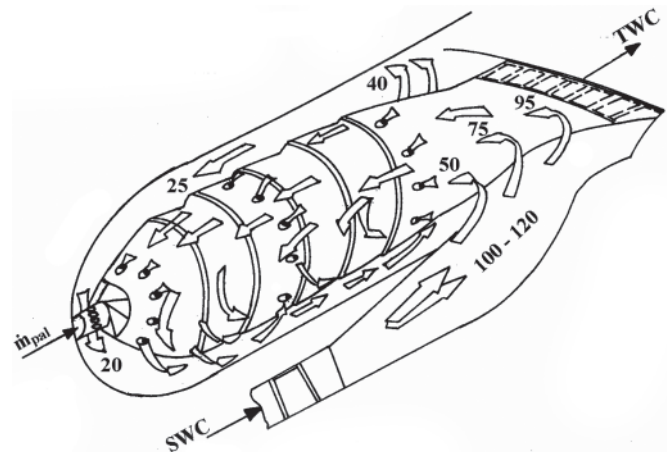


Fig. 2. Scheme of the structural form of the combustion chamber in the reversal-flow turbine engine, with marked local air flow velocities in m/s

Even without any comment, the presented figure clearly shows that the thermal and flow processes realised inside the combustion chamber, and in particular inside each flame tube, are extremely complicated. In states of unsteady engine operation the course of these energy conversion processes is even more complicated, making it impossible to verify experimentally the methods of mathematical modelling (numerical simulations) conventionally used for evaluating the exhaust gas temperatures for diagnostic purposes. Therefore the basic and, most frequently, the only method of determining diagnostic relations of defect-symptom type for those engines, taking into account the exhaust gas temperature, are experimental investigations (passive and active) done on a real object [3, 7, 16].

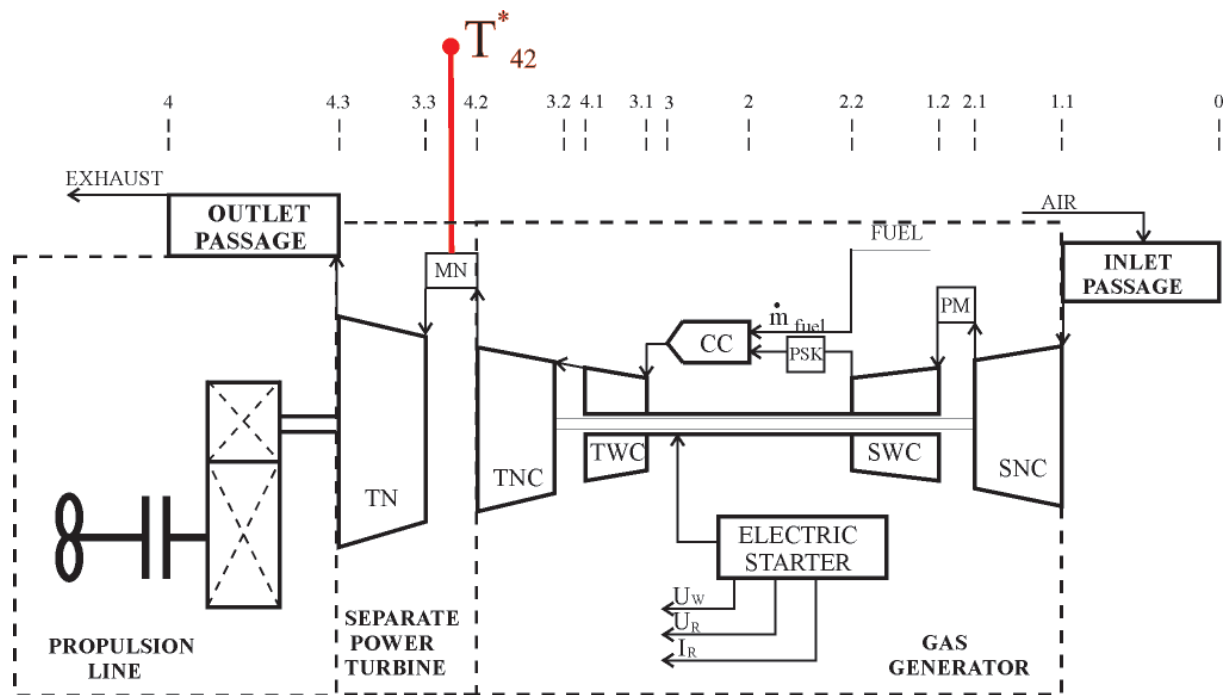


Fig. 3. Schematic diagram of the naval gas turbine engine with the marked control section for measuring the exhaust gas flow temperature behind the gas generator T_{42}^* . SNC, SWC – low-pressure and high-pressure compressor; TWC, TNC, TN – high-pressure turbine, low-pressure turbine and power turbine; KS – combustion chamber; PM, PSK, MN – space, respectively, between SNC and SWC, between SWC and KS, and between TNC and TN; U_w, U_R, I_R – excitation voltage, starting voltage and starting current

MEASUREMENT OF EXHAUST GAS FLOW TEMPERATURE

During gas turbine engine operation, the stagnation temperature of the exhaust gas flow is most frequently measured using thermocouples [2, 12]. The analysis of the recorded results should take into account that these measurements are burdened with errors resulting from the following reasons:

- temperature field disturbance caused by the thermocouple,
- thermal inertia of the thermocouple joint and cover,
- accelerated ageing and changes in the chemical composition and physical-and-chemical properties of the thermocouple wires due to their operation at high temperatures, (re-crystallisation, oxidation and diffusion in the surface layers of the wires close to the thermocouple's measuring joint may result in thermoelectric voltage changes exceeding ten percent, after 1000 hours of engine operation) [12,14,15].

Due to remarkable unsteadiness of thermal and flow processes in the combustion chamber and resultant pulsations of the exhaust gas flow, as well as the nonuniformity of the circumferential distribution of the exhaust gas temperature in the combustion chamber outlet section, its selective averaged measurement is done in serial engines in the flow passage control section situated at a distance from the combustion chamber [12,15] – most frequently behind the gas generator (at inlet to the separate power turbine) - Figs. 3 and 4.

Noteworthy is also the durability of the traditionally used thermocouples, which is higher when the measured exhaust gas temperatures are low [14].

Moving the thermocouples further from the combustion chamber also results from the need for maximal reduction of possible mechanical damage of the thermocouple, the broken parts of which usually cause vast damages in the blade system of the turbine part of the engine.

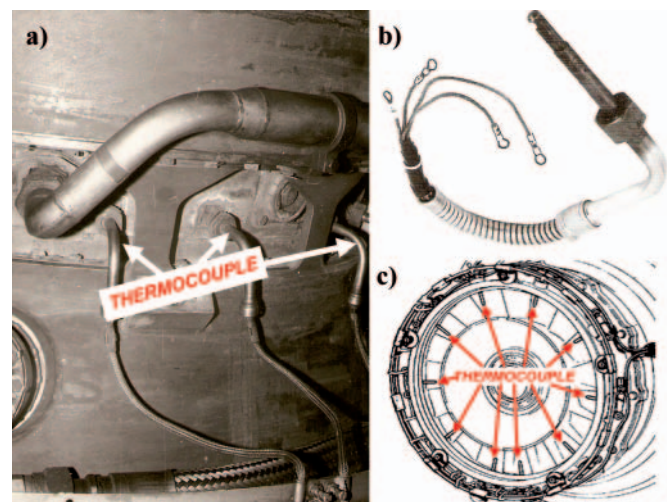


Fig. 4. Installing thermocouples in the flow section behind the turbine engine gas generator. a) outside view of the engine, b) chromel-alumel thermocouple TXA-1368, c) engine cross-section

Steady load states

The relative increase of the exhaust gas temperature for a turbine engine in operation is the measure of decrease of efficiency of energy conversion processes realised in individual fluid-flow machines (compressors and turbines) and in the combustion chamber, as a result of flow passage fouling (or wear) (Fig. 5), or disturbances in functioning of the fuel supply system (rate of fuel delivered to the combustion chamber) – Fig. 6.

To evaluate precisely the technical state of the flow section of an engine in operation, it should be divided into smaller parts in characteristic cross-sections, and the energy balance for these parts is to be done [5, 6, 7, 16]. The obtained thermodynamic relations which capture basic gasodynamic parameters of the engine provide opportunities for calculating temperature characteristics of the flow section based on operating measurements of engine control parameters [2, 7] – Fig. 5.

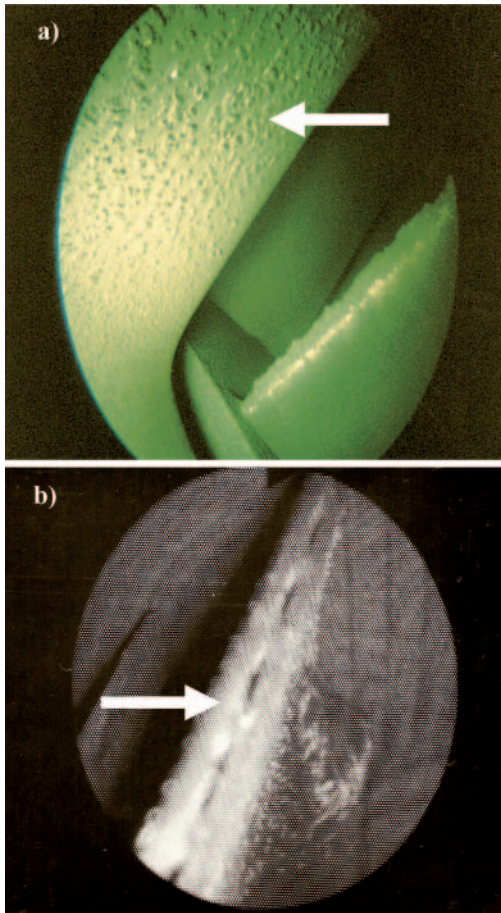


Fig. 5. Deposits of impurities: **a)** on compressor stage 1 stator blades, **b)** in the area of cooling air outlet openings at the high-pressure turbine rotor trailing edge

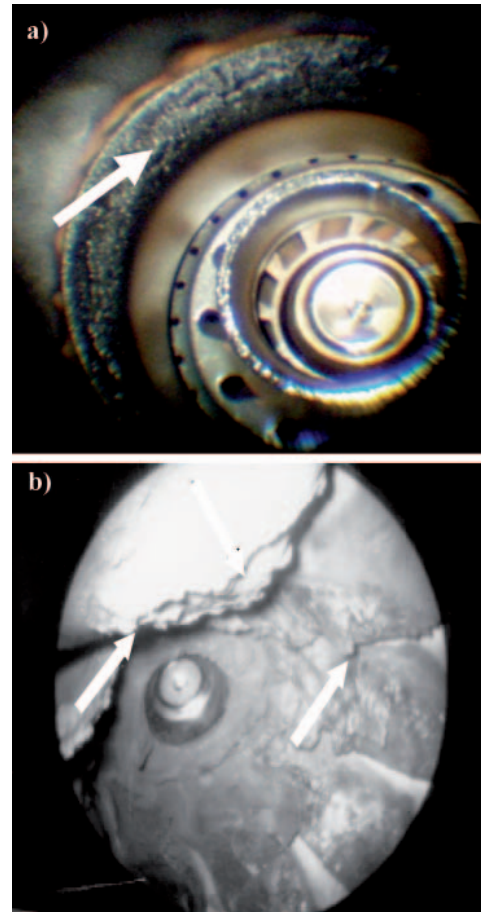


Fig. 6. Carbon deposits resulting from incomplete fuel combustion in the combustion chamber: **a)** on the injector seat surface, **b)** on the flame tube swirl vane blades

During engine operation, the state of the engine is systematically evaluated based on trends observed in the temperature characteristic of its flow section [6, 7, 8, 16]. It is represented by the distribution of the working medium stagnation temperature along the flow passage $T_{X-X}^* = f(L)$, worked out for a steady load range, most frequently equal to $1.0 P_{nom}$. The so-called lamination rate of the temperature profile in particular engine control cross-sections x-x, determined using systematic experimental examination, is the measure of the generalised diagnostic parameter calculated from the relation [7]:

$$\Delta T_{X-X}^* = T_{X-X(pom)}^* - T_{X-X(o)}^* \quad (6)$$

The distributions of changes of the average working medium stagnation temperature in particular control cross-sections of the flow passage, given in Fig. 7, refer to a new engine (solid line) and the same engine before and after washing the flow passage (dashed lines).

Figure 8 shows a sample diagnosis done based on the average exhaust gas temperature measured behind the gas generator of a three-shaft gas turbine engine with a separate power turbine. The engine control programme keeps the mass flow rate of the delivered fuel constant, $\dot{m}_{pal} = const$, within the set load range related to the rotational speed of the high-pressure rotor n_{wc} . The relative increase of the exhaust gas temperature behind the engine's low-pressure turbine (behind the gas generator – Fig.3) is expressed as:

$$\Delta T_{42}^* = T_{42pom(zr)}^* - T_{42o(zr)}^* \quad (7)$$

Figure 9 presents the courses of changes of the exhaust gas temperature behind the gas generator depending on the

rotational speed of the high-pressure rotor, calculated from relation (7), complemented by the relative values of this increase calculated from the formula:

$$\delta(\Delta T_{42}^*) = \frac{\Delta T_{42}^* \text{ "AFTER WASHING" } - \Delta T_{42}^* \text{ "BEFORE WASHING" }}{\Delta T_{42}^* \text{ "BEFORE WASHING" }} \Big|_{n_{wc} = idem} \quad (8)$$

Having analysed the numerical data shown in Fig. 9 we can conclude that washing the flow passages resulted in the decrease of the relative temperature δT_{42}^* by 16.1%. This is a quantitative indicator of the efficiency of the performed preventive service. Comparing the temperatures for the new engine and before washing still reveals remarkable deflections from the calculated value (about 30 K). This fact confirms the need for washing the flow passage several times in order to reconstruct fully the technical state of the engine [7]. When the experimental investigations were performed, additional increase of the hourly fuel consumption accompanied by the increased power of gas generator turbines was observed, which was connected with the decreased average temperature in the control section 4.2. All this testifies to the increased mass flow rate of the air delivered to the combustion chamber, i.e. some improvement in the efficiency of the working medium compression and decompression processes in the engine.

A characteristic gasodynamic feature of the turbine engine is remarkable circumferential nonuniformity of the temperature distribution in the flow of the exhaust gas before the (hot) turbine part of the flow passage. Reliable engine diagnosing based on changes of the average exhaust gas temperatures needs complementing it by a so-called temperature field nonuniformity coefficient. This coefficient makes the basis

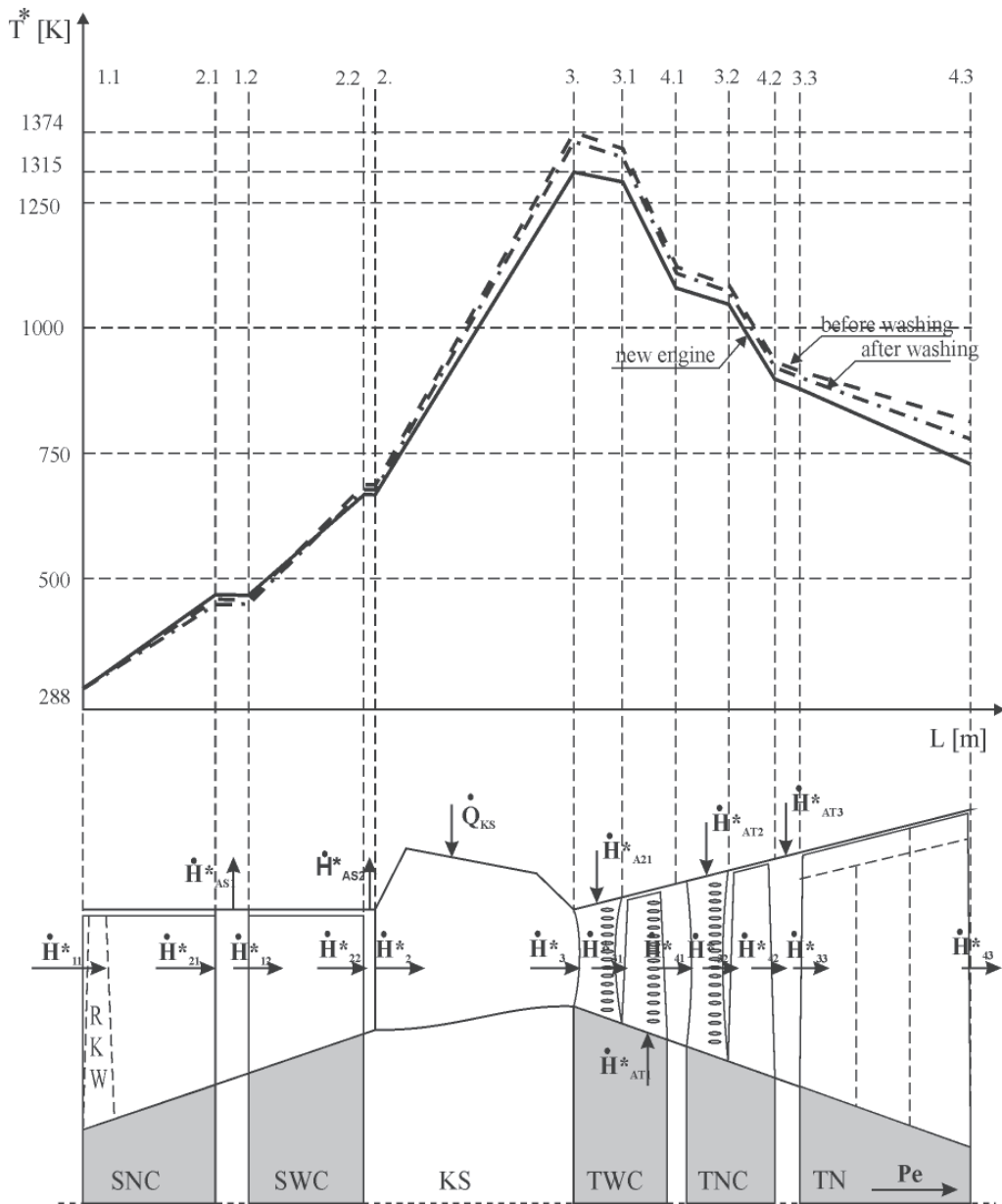


Fig. 7. Distribution of the working medium stagnation temperature in characteristic control cross-sections of the flow passage in a three-shaft engine with a separate power turbine for nominal load

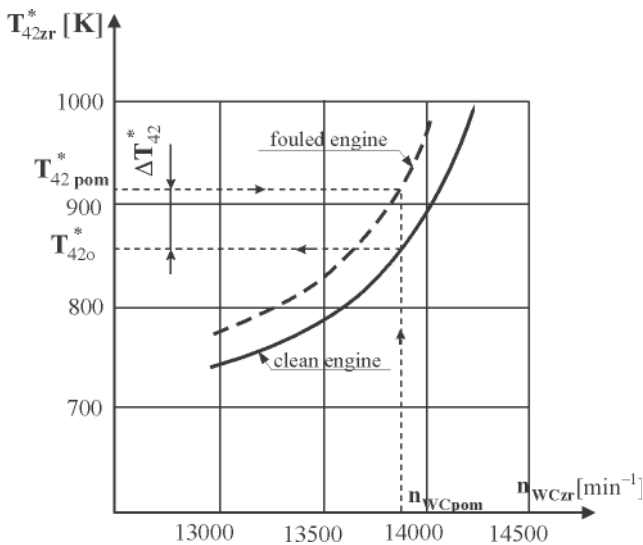


Fig. 8. Temperature characteristic $T^*_{42} = f(n_{WC})$ for a three-shaft engine with a separate power turbine

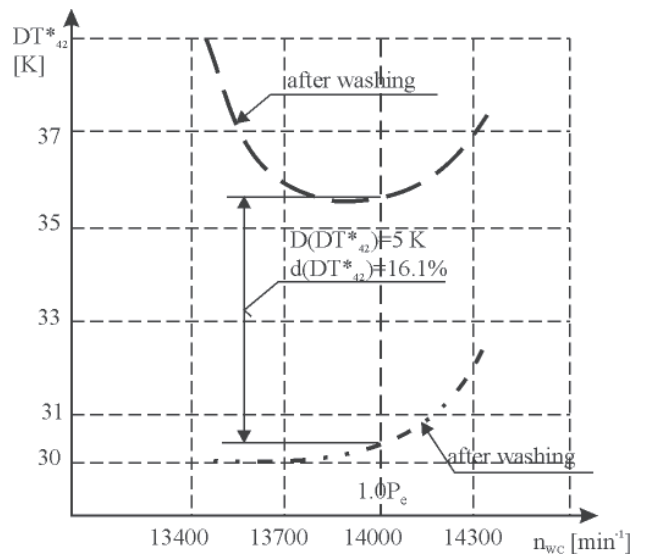


Fig. 9. Temperature increment behind the gas generator vs. high-pressure rotor rotational speed

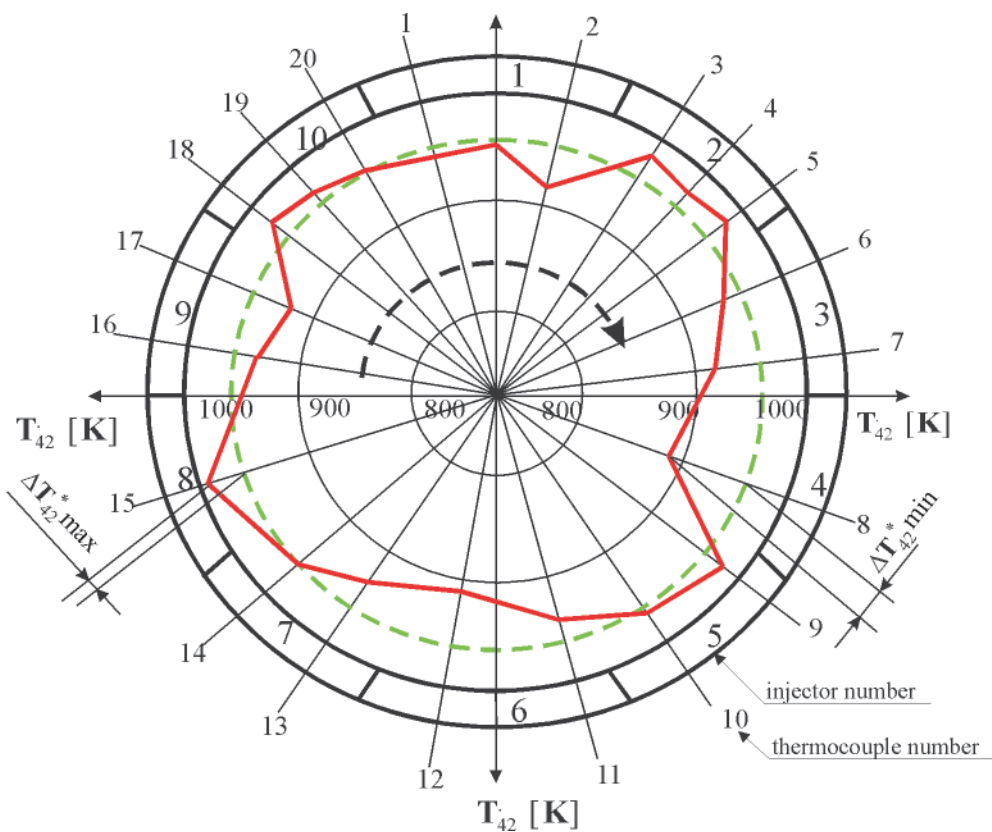


Fig. 10. Distribution of the exhaust gas temperatures behind the gas generator in the naval three-shaft internal combustion engine with a separate power turbine

for assessing the quality of functioning of the engine fuel installation, with particular attention being paid to the injectors, and is defined as the maximal deflection from the average exhaust gas temperature, which is received from readings of the individual thermocouples:

$$\Delta T_{42\min}^* = T_{42sr}^* - T_{42\min}^* \quad (9)$$

$$\Delta T_{42\max}^* = T_{42\max}^* - T_{42sr}^* \quad (10)$$

According to the requirements of the producer of UGT ZORYA naval engines, the permissible dispersions of the temperature values in this control section of the flow passage must not exceed $\Delta T_{42}^* < 60$ and $\Delta T_{42}^* < 100$ at nominal load. A practical method of engine diagnosing based on the nonuniformity of the exhaust gas temperature distribution behind the gas generator is shown in Fig. 10. The diagram was worked out for the three-shaft engine equipped with 20 chromel-alumel thermocouples TXA-1368 installed in the control section 4.2 (behind the low-pressure turbine). The series-and-parallel system of connections of the thermocouples, circumferentially distributed on the same radius of the flow passage cross-section, secures high accuracy of the average exhaust gas temperature measurement (measuring error below 1%), and high reliability of operation of the engine temperature protection system [15].

When assessing the operation of the injectors based on changes in the nonuniformity of temperature distribution, we should take into account a circumferential measuring shift between particular injectors and thermocouples, which is caused by the swirl of the exhaust gas flow. For instance, the indications of the thermocouples 1 and 2 give the diagnostic information for evaluating the state of the injector which supplies the flame tube 10.

Figure 10 shows the circle diagram of the exhaust gas distribution around the perimeter of the gas generator outlet section. This diagram can be used for verifying the applicability of the average exhaust gas temperature changes in this engine control section as:

- diagnostic parameter for evaluating the technical state of the gas generator flow section,
- diagnostic parameter for evaluating the technical state of the engine fuel installation (injectors).

It is calculated using the formula:

$$\Delta T_{42u}^* = \frac{T_{42\max}^* - T_{42\min}^*}{T_{42sr}^*} \leq 10\% \quad (11)$$

Based on the statistical analysis of the dispersion of this parameter for new engines revealing full technical capability (or those after repair done in a factory), the diagnostic tolerance of this parameter in operating conditions was assumed equal to 10% [7, 16].

CONCLUSIONS

- Systematic measurements of the exhaust gas temperature in characteristic control cross-sections of a naval turbine engine are the basis for the diagnostic inference process about the technical state of the flow section, and the air and fuel supply system (injectors, in particular).
- The presented results of operational diagnostic investigations of three-shaft engines with a separate power turbine confirm the importance of the selected and averaged exhaust gas temperatures measured behind the gas generator in steady-load states as high-value diagnostic information.

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