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SEARCH FOR STATE PARAMETERS OF THERMODYNAMIC MODELS OF GAS TURBINE SYSTEMS WITH DIFFERENT THRUST AMOUNTS

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Abstract. *Individual values of working time and working conditions, thermal and technical condition of gas turbine systems may differ significantly from the indicators of the average statistical object. The work examines modern approaches to thermodynamic modeling of gas turbine system state parameters and methods of assessing the actual degradation of characteristics over time. The article presents the results of computational and experimental studies of the possible influence of changes in the state of characteristics of engine components on the thermal state of gas turbine components. An algorithm for finding the best combination of parameters of the state of the characteristics of nodes of the thermodynamic model of the gas turbine system using the quasi-Newtonian method and the finite-difference gradient is proposed. It was established that there are promising methods of forming individual assessments of the technical condition of heat engine units and working out measures to maintain a stable level of key characteristics in the process of resource depletion and recovery during repairs.*

Keywords: *compressor, combustion chamber, gas turbine, thermodynamic model, algorithm, identification, state parameters*

Introduction

The actual operating conditions of heat engines are accompanied by physicochemical processes of changing the mechanical properties of materials and material systems from which their components are made, processes of changing the characteristics of fuel-regulating equipment units and gas-air tracts. In the process of real work (characterized by the operating time from the beginning of operation τ and the number of load cycles N), there is a process of multifactorial influence on the technical condition of heat engines and scenarios of its change in the future. Karpinos, Korovin, Lobunko, Vedischeva (2014) performed a study of the operational damage of structural elements of more than 100 gas turbine engines of the same type with different working hours since the beginning of operation. It was established that with an increase in the operating time of heat engines from the beginning of operation, there is a degradation of the properties of materials and an increase in the number of rejected parts as a result of defects.

A set of operational damages $P(\tau > 0, N > 0)$ set of parts and components of the flow part of heat engines (according to different mechanisms) leads to a shift in the functional characteristics of its nodes, which may differ significantly from the characteristics of the corresponding node of the same engine at the beginning of its operation ($\tau = 0, N = 0$).

The deterioration of the characteristics of heat engines in operation, the search for technical and technological possibilities of maintaining their stable level as the resource is exhausted, diagnosis and the choice of rational methods of restoration during repair remain an urgent problem. The urgency of the problem is determined not only by economic considerations, but also by the loss of traction by the heat engine $\Delta R(\tau)$, increasing the amount of heat $\Delta Q(\tau)$ to ensure the specified parameters of the thermodynamic cycle.

The value of thermodynamic parameters of the same name $X_1, X_2 \ldots X_n$, reflecting the real working processes of a sample of n heat engines of the same type with different amounts of work since the beginning of operation ($\tau_x > 0$, $N_x > 0$) under identical external operating conditions (P_H, T_H) and the position of control bodies (α) can differ significantly. These discrepancies are determined by the individual characteristics of heat engine units and their units. One of the urgent problems of mechanical engineering is the search for opportunities to increase the reliability of modeling changes in thermodynamic parameters $\Delta X^P(\tau)$, which characterize the working process of the object depending on the working time.

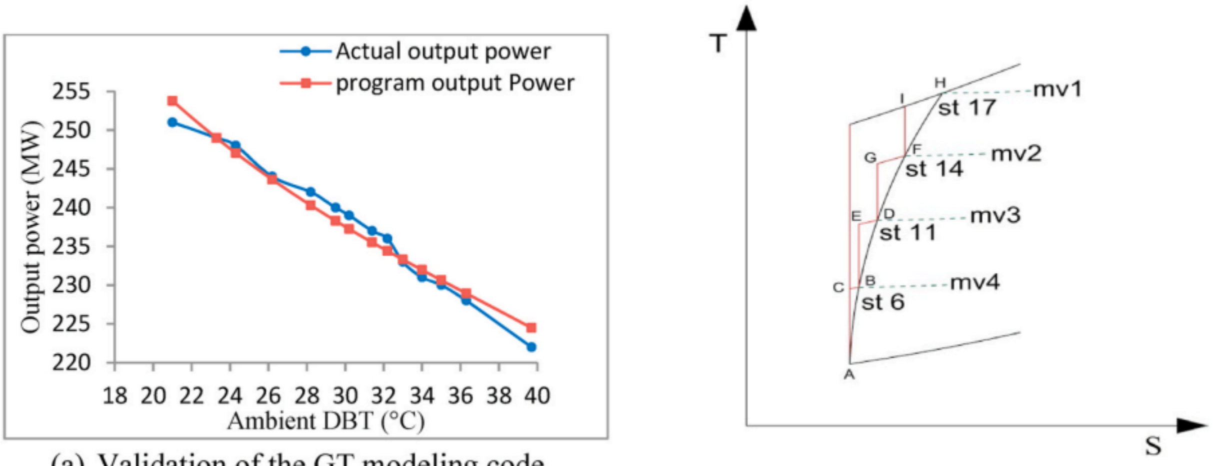
Main text. Literature review.

Fentai, Amare Desalegn, Baheta, Aklylu, Gilany, Syed Ihtsham Ul-Haq (2018) presented a quantitative method of heat engine diagnostics. Artificial neural networks are used to evaluate the progressive wear of one and several gas tract components from the point of view of mass flow and isentropic efficiency indices. The data necessary for training and testing this method are obtained from the thermodynamic model of the engine in stationary conditions. Gaussian noise values were considered to assess the tolerance of the method for measuring uncertainties. For complex problems of diagnosing engines based on the structure of one artificial neural network, it may not be enough to obtain reliable and accurate results. The authors used seven decentralized frameworks to evaluate seven different component failure scenarios, which significantly improves the accuracy of fault identification.

Khaled A. Naeim, Ahmed A. Hegazi, Mohamed M. Awad, Salah H. El-Emam (2022) used the enthalpy-entropy approach to model the actual gas turbine cycle (Figure 1). The developed program was used to study the influence of ambient temperature, relative humidity, and ambient pressure on the output parameters of the gas turbine. The gas turbine simulation results showed that as the temperature increased, the power of the gas turbine decreased, while the thermal efficiency of the gas turbine decreased, and the specific fuel consumption increased. Gas turbine power decreased with increasing relative humidity.

Jeffryes W. Chapman, Thomas M. Lavelle, Jonathan S. Litt (2016) noted the fact that the cost and risks associated with the design and operation of gas turbine engine systems have led to increased dependence on mathematical models. In paper (4), the main aspects of engine simulation, performance analysis and connections with the development of the engine control system are considered. The focus is on thermodynamic modeling using techniques common in the industry: Brayton cycle, component efficiency maps, scaling maps, and generation of design point criteria. The T-MATS scheme of the engine model is presented in the figure 2.

Alfredo Gimelli, Raniero Sannino (2017) applied a multifactorial multiobjective methodology aimed at validating the thermodynamic model of a microgas turbine. The methodology is based on a genetic optimization algorithm, where decision variables and objectives are set depending on available experimental data. The results of the studied case emphasize the ability of the method to indicate some inconsistencies in experimental data and the fact that it can lead to a consistent thermodynamic reconstruction of microturbine behavior.



(a) Validation of the GT modeling code with M701F3 actual readings during baseloads.

(b) GT compressor T–S diagram.

Figure 1 – Validation and compressor T–S diagram

Source: [3]

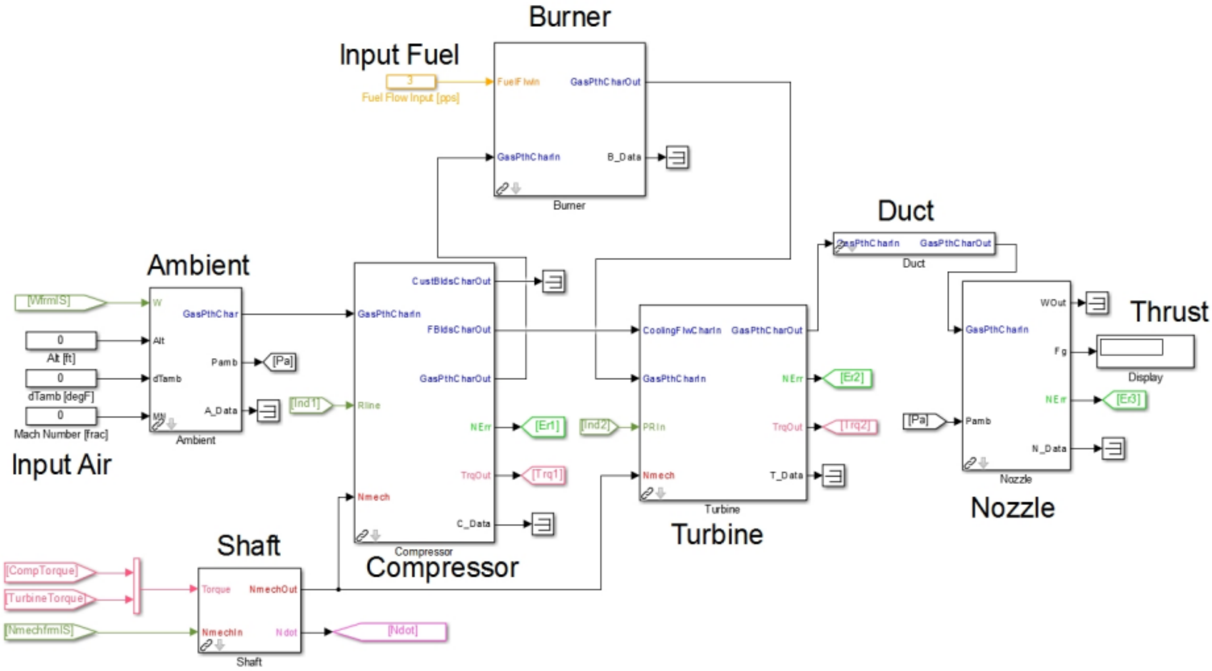


Figure 2 – T-MATS turbojet model

Source: [4]

Work R. Yadav, Yogesh Kapadi, Abhay Pashilkar (2005) is dedicated to the development and validation of an aerothermodynamic model of a turbofan engine based on the variable state and control volume approach. Using actual performance data, steady-state and transient engine simulations were performed using MATLAB-SIMULINK. A simulation model is systematically developed. Graphs of the engine states are constructed for various stable operating conditions. The model is equipped with capabilities that can be integrated with engine control design software. The results are verified by software Gas turbine Simulation Program.

Pawel Magryta, Konrad Pietrykowski, Michal Geca (2018) proposed a one-dimensional model of an aircraft engine. This model is developed in software AVL BOOST. The model is used to calculate the fuel and air flow parameters in the engine intake system, as well as to analyze the combustion process and the flow of exhaust gases into the external environment. The model is based on the equations describing the isentropic flow. The geometry of the channels and all parts of the model is displayed on the basis of an empirical study of engine elements.

Materials and methods.

Analysis of literary sources, applied thermogas dynamics, theory and practice of the use of heat engines, reliability, technical diagnostics, computer modeling of thermodynamic processes (Figure 3).

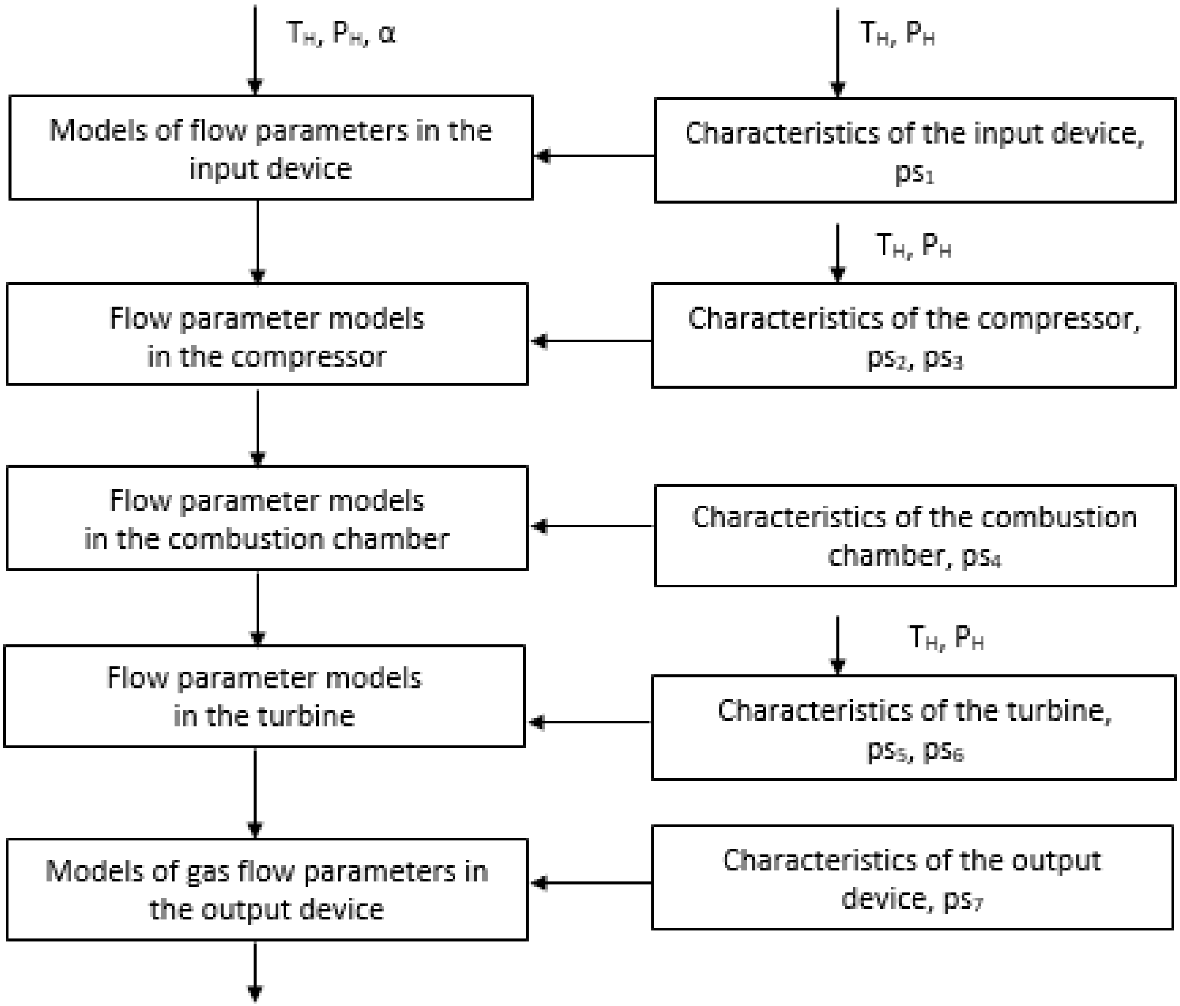


Figure 3 – Diagram of a thermodynamic model of a heat engine
Author's development

The thermodynamic model of a heat engine (Figure 3) is represented by a sequence of equations that describe the work processes of air flow compression in the compressor, heat supply in the combustion chamber, expansion in the gas turbine, and acceleration in the output device. The thermodynamic model allows you to simulate the values of the parameters in different parts of the engine when the input data changes (T_H, P_H, α).

In order to assess the effect of changes in compressor characteristics on the operating conditions of heat engine components, a calculation experiment was performed. The thermodynamic model of the engine and the model of the gas turbine blades were used in the experiment. In order to model the displacement (degradation) of the characteristics of the elements of the flow part relative to the characteristics of the engine at the beginning of operation, as well as to implement the procedure for refining the individual thermodynamic model of the engine, a vector of state parameters was introduced $\overline{ps}_x$.

To the composition of the components of the vector $\overline{ps}_x$ parameters of characteristic shifts are included (Figure 4, on the left) relative to the corresponding characteristics of an average engine.

Results and discussion.

Computer modeling of the degradation of the signs of the technical state of the unit is implemented by adjusting the values of the state parameter of the compressor efficiency: – $ps_{EK} = 1,0$ – the value is valid for the engine at the beginning of operation; – $ps_{EK} = 0,96$, $ps_{EK} = 0,92$ – the value of the correction coefficients, which correspond to the displacement of the characteristic branches of the compressor efficiency coefficient to smaller values by *4%* and *8%*.

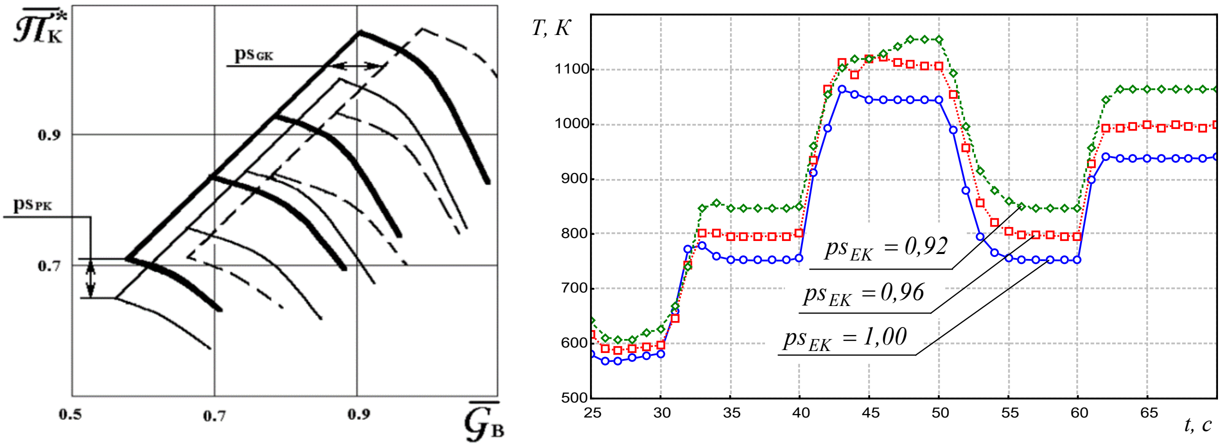


Figure 4 – Scheme of changes in state parameters (on the left), simulation results of changes in the material temperature of turbine parts due to degradation of compressor characteristics

Author's development

Analysis of the results of modeling the thermal state of the turbine parts (Figure 4) shows that a decrease in the efficiency of the compressor leads to a change in the operating conditions of the unit under study. The automatic control system (8) compensates for the deterioration of the characteristics by additional heat supply ΔQ in the thermodynamic cycle (fuel supply to the combustion chamber). At the same time, the values of the parameters of the work process increase (T_G).

It was established that the displacement of the branches of the characteristics of the coefficient of useful action of the compressor $\Delta\eta_K$ on *8%*, under other identical operating conditions (same external conditions and mode parameters (P_H, T_H, α) heat engine, leads to an increase in the temperature of the turbine blades $\Delta T \approx 100$ K. The total duration of operation of turbine parts at elevated temperature also increases. In transient regimes, fuel overdose can lead to its afterburning in the turbine path, which contributes to intensive thermal destruction of the material of gas turbine parts.

Based on many years of computational and analytical research, an algorithm for refining the thermodynamic model is proposed (Figure 5).

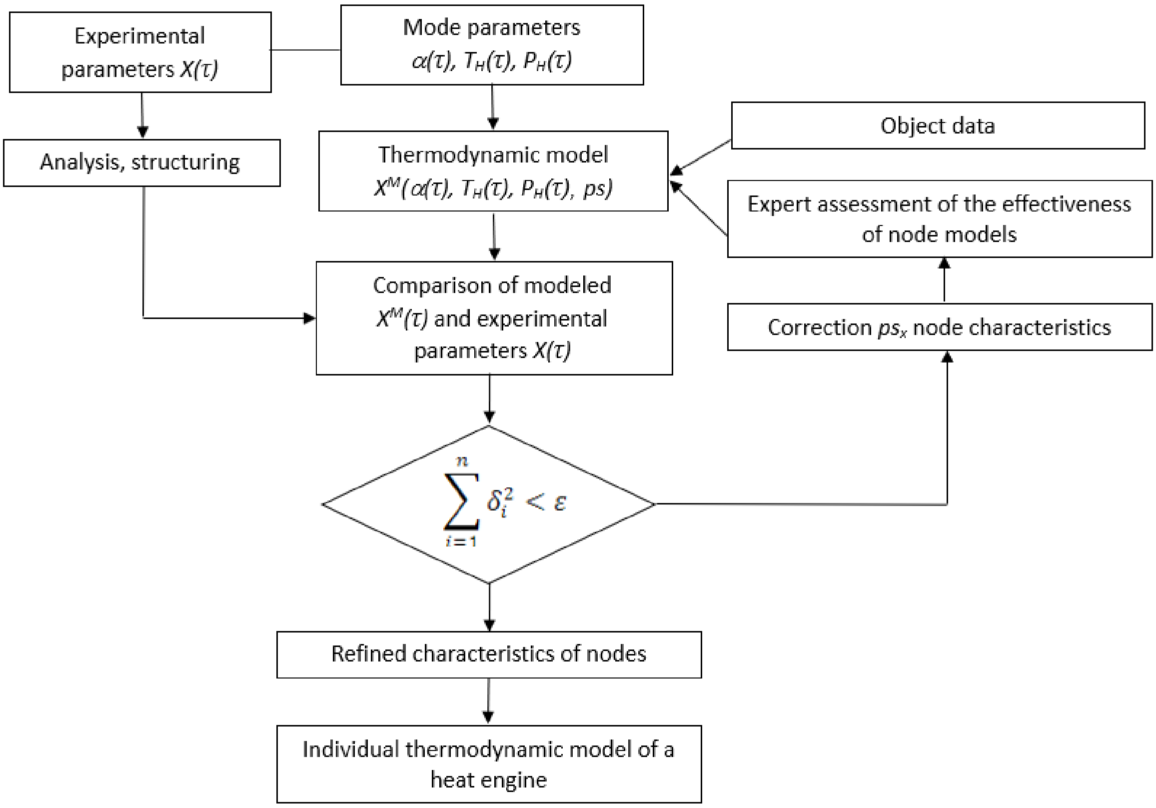


Figure 5 – Algorithm for identifying the thermodynamic model of the engine
Author's development

The task of refining the thermodynamic model is solved by finding (2) the optimal combination of state parameter values $\overline{ps}_x$, which ensure the minimum value of the root-mean-square discrepancy $E(\overline{ps}_x)$ between registered and calculated parameters of the same name - signs of the state of the object under study.

$$E(\overrightarrow{ps}) = {}^1/_m \sqrt{\sum_{j=1}^{m} (H(\overrightarrow{ps}))_j^2} \Rightarrow min, j = \overline{1,m}, \tag{1}$$

m – the number of experimental parameters used in the refinement of the thermodynamic model;

$\overline{ps}_x$ – vector of state parameters of the thermodynamic model of the node;

H_j – the relative incoherence between the j-th components of the vectors $\vec{X}^P$, $\vec{X}^M$ $(\overrightarrow{ps})$, which is defined using a dependency

$$H_j = \frac{X_j^P - X_j^M}{\delta X_j}, j = \overline{1,m}, \tag{2}$$

δH_j – jth parameter registration error.

The software implementation of the developed algorithm involves the use of a subroutine for finding the minimum of the objective function with m variables. The quasi-Newtonian method and the finite-difference gradient are used in the process of searching for the best version of such solutions.

The use of the developed methodology in the algorithms for diagnosing and monitoring thermogasdynamic parameters will contribute to increasing the accuracy of the assessment of the current technical condition of the heat engine in operation (9).

Conclusions. The results of the calculation of the possible degradation of the thermodynamic parameters of the main units of the heat engine are presented. Considered possible factors that affect the measured parameters of the same type of heat engines. The presented approaches can be taken into account when: forming individual assessments of the technical condition of components and systems of the heat engine; development of measures to maintain a stable level of characteristics in the process of resource depletion and restoration during repair.

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Abstract. *Індивідуальні значення часу напрацювання і умови роботи, тепловий і технічний стан газотурбінних систем можуть суттєво відрізнятись від показників середньостатистичного об'єкту. В роботі розглядається сучасні підходи термодинамічного моделювання параметрів стану газотурбінних систем і способи оцінки фактичної деградації характеристик у часі. У статті представлені результати розрахунково-експериментальних досліджень можливого впливу змін стану характеристик вузлів двигуна на тепловий стан компонентів газових турбін. Запропоновано алгоритм пошуку кращого поєднання параметрів стану характеристик вузлів термодинамічної моделі газотурбінної системи з використанням квазіньютонівського методу і кінцево-різничного градієнту. Встановлено, що перспективними є способи формування індивідуальних оцінок технічного стану вузлів теплового двигуна і відпрацювання заходів з підтримання стабільного рівня ключових характеристик в процесі вичерпання ресурсу та відновлення при виконанні ремонту.*

Key words: *компресор, камера згоряння, газова турбіна, термодинамічна модель, алгоритм, ідентифікація, параметри стану.*

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