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ИНЖЕНЕРЛІК ТЕХНОЛОГИЯЛАР, ЭНЕРГЕТИКА ЖӘНЕ АВТОМАТТАНДЫРУ

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O.D.MEIRBEKOVA[1]., N.T.RUSTAMOV[2]
Khoja Akhmet Yassawi International kazakh–turkish university, Turkistan, Kazakhstan
*[1]E-mail: oxana.meirbekova@ayu.edu.kz**
[2]E-mail: nassim.rustamov@ayu.edu.kz

INVESTIGATION OF A BIOGAS HYBRID GAS TURBINE PLANT WITH A WATER BATTERY

Abstract. This paper investigates the structure, energy efficiency, and dynamic characteristics of a hybrid gas turbine system operating on biogas and integrated with a water-based thermal energy storage unit. The proposed system combines the electrical power generation capability of a gas turbine with a thermal accumulator, enabling efficient simultaneous utilization of electrical and thermal energy. A nonlinear mathematical model of the system is developed, incorporating the dynamics of the rotor, combustion chamber, and thermal storage unit. The model is linearized in the vicinity of the nominal operating point and represented in state-space form. Transient processes resulting from changes in fuel flow rate are analyzed using numerical simulation. The results demonstrate that hybridization preserves the mechanical stability of the system while introducing an additional slow thermal loop. The integration of a water thermal accumulator enables effective recovery and storage of exhaust gas heat, significantly increasing the overall efficiency of the system. The study confirms that the hybrid gas turbine installation exhibits multi-scale dynamic behavior, making the application of multi-loop or cascade control strategies appropriate. The proposed hybrid system represents a promising solution for autonomous and distributed energy systems operating on biogas.

Keywords: Gas turbine installation, biogas, hybrid energy system, thermal accumulator, mathematical model, control system.

О.Д.МЕИРБЕКОВА[1]., Н.Т.РУСТАМОВ[2]
Қожа Ахмет Ясауи атындағы Халықаралық қазақ-түрік университеті, Түркістан, Қазақстан
*[1]E-mail: oxana.meirbekova@ayu.edu.kz**
[2]E-mail: nassim.rustamov@ayu.edu.kz

СУ АККУМУЛЯТОРЫ БАР БИОГАЗБЕН ЖҰМЫС ІСТЕЙТІН ГИБРИДТІ ГАЗТУРБИНАЛЫҚ ҚОНДЫРҒЫНЫ ЗЕРТТЕУ

Аңдатпа. Бұл мақалада биогазбен жұмыс істейтін, су жылу аккумуляторымен біріктірілген гибридті газтурбиналық қондырғының құрылымы, энергетикалық тиімділігі және динамикалық қасиеттері зерттеледі. Ұсынылған жүйе газтурбиналық қозғалтқыштың электр энергиясын өндіру мүмкіндігін су негізіндегі жылу аккумуляторымен толықтырып, электр және жылу энергиясын бір мезгілде тиімді пайдалануға бағытталған. Жұмыста қондырғының роторының, жану камерасының және жылу аккумуляторының динамикасын қамтитын бейсызық математикалық модель құрастырылған. Модель номинал жұмыс режимі маңында сызықтандырылып, күй кеңістігіндегі формада ұсынылады. Отын шығынының өзгеруі кезіндегі өтпелі процестер сандық модельдеу арқылы талданады. Нәтижелер гибридті құрылымның механикалық тұрақтылықты сақтай отырып, жүйеде қосымша баяу жылулық контур қалыптастыратынын көрсетеді. Су жылу аккумуляторының болуы шығатын газдардың жылуын жинақтауға мүмкіндік беріп, *қондырғының толық пайдалы әсер коэффициентін* айтарлықтай арттырады. Зерттеу нәтижелері гибридті газтурбиналық жүйенің көпмасштабты динамикаға ие екенін және оны басқару үшін көпконтурлы немесе каскадты басқару әдістерін қолданудың орындылығын дәлелдейді. Ұсынылған қондырғы биогазға негізделген автономды және таралған энергетикалық кешендер үшін перспективалы шешім болып табылады.

Түйін сөздер: Газтурбиналық қондырғы, биогаз, гибридті энергетикалық жүйе, жылу аккумуляторы, математикалық модель, басқару жүйесі.

О.Д.МЕИРБЕКОВА[1]., Н.Т.РУСТАМОВ[2]
Международный казахско-турецкий университет имени Ходжи Ахмеда Ясави, Туркестан, Казахстан,
*[1]E-mail: oxana.meirbekova@ayu.edu.kz**
[2]E-mail: nassim.rustamov@ayu.edu.kz

ИССЛЕДОВАНИЕ БИОГАЗОВОЙ ГИБРИДНОЙ ГАЗОТУРБИННОЙ УСТАНОВКИ С ВОДЯНЫМ АККУМУЛЯТОРОМ

Аннотация. В статье исследуются структура, энергетическая эффективность и динамические свойства гибридной газотурбинной установки, работающей на биогазе и интегрированной с водяным тепловым аккумулятором. Предложенная система сочетает возможности выработки электрической энергии газотурбинным двигателем с тепловым накопителем, что обеспечивает эффективное совместное использование электрической и тепловой энергии. Разработана нелинейная математическая модель установки, включающая динамику ротора, камеры сгорания и теплового аккумулятора. Модель линеаризована в окрестности номинального режима и представлена в форме пространства состояний. С помощью численного моделирования проанализированы переходные процессы при изменении расхода топлива. Полученные результаты показывают, что гибридизация установки не ухудшает механическую устойчивость системы, но формирует дополнительный медленный тепловой контур. Интеграция водяного теплового аккумулятора позволяет эффективно аккумулировать теплоту выхлопных газов и существенно повысить общий коэффициент полезного действия установки. Установлено, что гибридная газотурбинная система обладает многомасштабной динамикой, что обосновывает целесообразность применения многоконтурных или каскадных методов управления. Предложенная установка является перспективным решением для автономных и распределённых энергетических систем на базе биогаза.

Ключевые слова: газотурбинная установка, биогаз, гибридная энергетическая система, тепловой аккумулятор, математическая модель, система управления.

Introduction

The growth of distributed generation and the use of renewable energy sources have led to the need to increase the efficiency of local power plants. Biogas-powered gas turbine engines (GTE) represent a promising solution for autonomous energy centers of agro-industrial complexes and municipal infrastructure.

A classic gas turbine installation has a relatively low electrical efficiency (25-35%), while a significant part of the fuel energy is lost with exhaust gases. The utilization of this energy makes it possible to significantly increase the overall efficiency of the installation.

One of the solutions is to include a water thermal accumulator in the circuit, which leads to the formation of a hybrid distributed generation power plant (HDGPP). However, hybridization complicates the dynamics of the system and requires the development of an adequate mathematical model for the synthesis of the control system.

The purpose of the article is to investigate a hybrid gas turbine unit with a water thermal accumulator, to evaluate the effect of heat storage integration on energy efficiency and dynamic stability of the system when running on biogas.

Research materials and methods

Gas turbine installations (GTI) are the basis of thermal power systems and are widely used to generate electrical and thermal energy by converting fuel energy according to the thermodynamic Brayton cycle. A detailed analysis of the work of GTI and the prospects for improving their efficiency is carried out in the works of (Zemtsov et al., 2025), where heat recovery schemes and the introduction of the organic Rankine cycle are considered to increase the efficiency of a power plant from 35-38% to 45-50% through the use of low-potential exhaust heat.

In the field of thermodynamics and cycle analysis of gas turbine systems, classical approaches are described in the works of (Gülen, 2019), where the basic operating schemes, cycle parameters and energy indicators are described.

One of the key trends in improving the efficiency of GTI is the integration of thermal energy storage (TES) systems with gas turbines. An overview of the possibilities of using TES to increase the power and stabilize the modes of gas turbine installations is presented in the work of (Gkoutzamanis et al., 2019), which discusses various methods of cooling the air at the turbine inlet using heat storage systems and their impact on performance. In particular, the authors show that such approaches can improve operational stability and increase energy efficiency.

In addition, research on dynamic modeling of hybrid systems with thermal storage highlights the importance of accumulating and reusing thermal energy to increase the flexibility and efficiency of energy systems as a whole. In the works devoted to the general overview of TES technologies, various types of heat storage devices are distinguished – sensitive, latent and thermochemical – and their features, application potential and limitations are considered. Such an overview is useful for understanding the technological possibilities of integrating TES with GTI, especially in the context of renewable energy sources and cogeneration.

In particular, (Islam et al., 2022) analyze the role and modeling of TES systems in energy systems, including their use for balancing heat and electricity flows, which is important when considering hybrid gas turbine installations with heat accumulators.

Thus, modern scientific literature confirms that the integration of heat recovery and heat storage with gas turbine installations is a promising direction for improving energy efficiency, flexibility of dynamics and stability of dynamic processes in distributed energy systems.

Analysis and results

In the work of (Meirbekova & Rustamov, 2022) the following biogas gas turbine engine with a water battery was proposed (Fig.1).

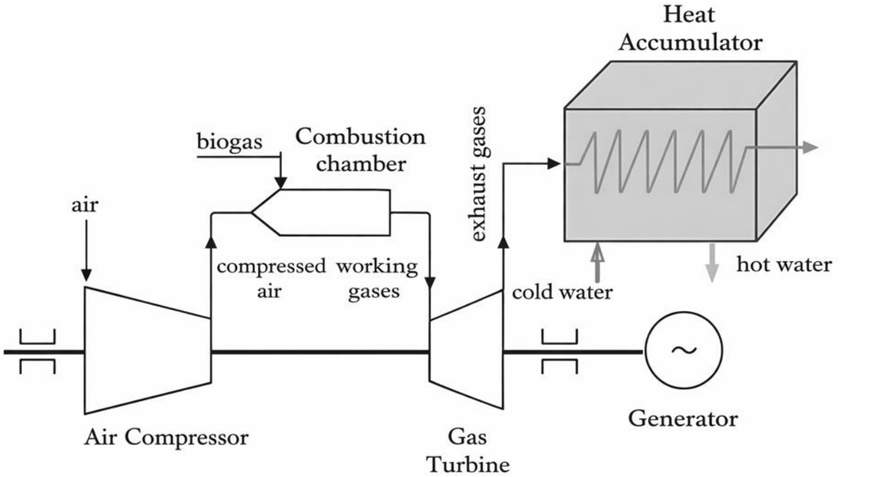

Figure 1. Biogas gas turbine engine with a water battery

This installation includes: air compressor; combustion chamber; gas turbine; generator; heat accumulator, etc.

Atmospheric air enters the compressor, where its pressure increases. Biogas is supplied to the combustion chamber and a high-temperature flow is formed. Next, the flow expands in the turbine, producing mechanical work. The turbine turns an electric generator.

The exhaust gases are sent to a heat exchanger, where they transfer heat to the water accumulated in the heat tank. Thus, a combined electric heating system is formed.

The presented hybrid installation combines a biogas-powered gas turbine engine with a water thermal accumulator (Rustamov et al., 2023). Atmospheric air enters the compressor, where its pressure increases, after which biogas is added to the combustion chamber and ignited, forming a high-temperature flow. By expanding in the turbine, the gas creates mechanical power to turn the generator that generates electricity. The exhaust gases are sent to a heat exchanger, where they transfer part of the energy to the water in the battery, which allows the use of thermal energy for heating or other needs.

This combination of an electrical and thermal circuit increases the total efficiency of the installation, provides the possibility of energy storage and creates a multi-channel dynamic system with a fast mechanical circuit and a slow thermal circuit (Rustamov et al., 2025). The hybrid structure allows efficient use of biogas, increasing the overall energy efficiency of the plant and creating the basis for autonomous distributed energy complexes. The mathematical model of this installation is as follows.

Heat exchanger model (heat recovery): Heat flow from exhaust gases:

$$Q_{rec} = \dot{m}_g c_p (T_A - T_{stack}) \tag{1}$$

where: T_{stack} - exhaust gas temperature

You can use the NTU model:

$$Q_{rec} = \varepsilon \, C_{min} (T_A - T_{\omega,in}) \tag{2}$$

Model of a water thermal accumulator (dynamic):

Energy balance:

$$M_\omega c_\omega \frac{dT_\omega}{dt} = Q_{rec} - Q_{load} \tag{3}$$

where: M_ω – mass of water, c_ω – heat capacity of water, Q_{load} – thermal load.

This equation gives the system thermal inertia.

Dynamic model of the rotor (Razzhivin et al., 2023):

The equation of rotation:

$$J \frac{d\omega}{dt} = T_t - T_c - T_{load} \tag{4}$$

where: J - moment of inertia of the rotor, ω - angular velocity, $T_t = \frac{P_t}{\omega}$ $\quad T_c = \frac{P_c}{\omega}$

Electrical efficiency of the installation:

$$\eta_{el} = \frac{P_{el}}{\dot{m}_f Q_{LHV}} \tag{5}$$

η_{el} - The electrical efficiency of the installation shows how much of the fuel energy is converted into electrical energy (Cabeza, 2015);

P_{el} - The electrical output of the generator is measured in watts (W) or kilowatts (kW);

$\dot{m}_f$ - The mass consumption of fuel (for example, biogas) is measured in kilograms per second (kg/s);

Q_{LHV} - The lowest heat of combustion of a fuel, the amount of energy released during the complete combustion of a unit of fuel mass, is measured in joules per kilogram (J/kg) or kJ/kg.

Full (hybrid) Installation efficiency:

$$\eta_{total} = \frac{P_{el}+Q_{rec}}{\dot{m}_f Q_{LHV}} \tag{6}$$

η_{total} - the total efficiency of a hybrid installation, which takes into account both electrical energy and thermal energy stored or used.

Q_{rec} - The amount of heat energy recovered (returned) from exhaust gases and stored in a heat storage tank is measured in watts (W) or in joules per second (J/s) (Kuravi, et al., 2013).

Calculation and simulation results

1. Initial data (example of a 100 kW installation)

A hybrid gas turbine engine with an electric capacity of 100 kW is considered.

Parameters:

Rated power: $P_{el} = 100\text{кВт}$

Generator efficiency: $\eta_{gen} = 0{,}95$

Degree of pressure increase: $\pi_c = 4$

Compressor efficiency: $\eta_c = 0{,}82$

Turbine efficiency: $\eta_t = 0{,}85$

Lowest calorific value of biogas: $Q_{LHV} = 20\ \text{MJ/kg}$

The mass of water in the battery: $M_\omega = 3000\ \text{kg}$

Ambient temperature: $T_1 = 300\ K$

2. Calculation of the nominal mode

a) The temperature after the compressor:

$$T_2 = 300\left[1 + \frac{1}{0{,}82}(4^{0{,}286} - 1)\right] \tag{7}$$

$$T_2 = 300(1 + 0{,}58) \approx 474K$$

b) The temperature in front of the turbine:

Let's accept

$$T_3 = 1050\ K$$

c) The temperature after the turbine:

$$T_4 = 750\ K$$

d) Required fuel consumption:

Electric power:

$$P_{shaft} = \frac{100}{0{,}95} \approx 105\ \text{kW}$$

Thermal power of fuel:

$$\dot{m}_f = \frac{P_{shaft}}{\eta_{el}\, Q_{LHV}} \tag{8}$$

By $\eta_{el} = 0{,}32$

$$\dot{m}_f = \frac{105000}{0{,}32 \cdot 20 \cdot 10^6} \approx 0{,}0164 \text{ kg}/s$$

3. Calculation of heat recovery
Exhaust gas heat flow:

$$\boldsymbol{Q_{rec} = \varepsilon \dot{m}_g c_p (T_4 - T_\omega)} \tag{9}$$

By: $\varepsilon = 0{,}65$, $T_\omega = 350\ K$
We get:

$$Q_{rec} = 160 \text{ kW}$$

4. Installation efficiency
Electric:

$$\eta_{el} = 32\ \%$$

Thermal:

$$\eta_{th} = \frac{160}{0{,}0164 \cdot 20 \cdot 10^6} \approx 49\%$$

Full efficiency:

$$\eta_{total} = 32\% + 49\% = 81\%$$

5. Transition process (stepwise fuel increase by 20%)
Increased fuel consumption:$0{,}0164 \rightarrow 0{,}0197 \text{ kg}/s$

With a stepwise increase in fuel consumption by 20% (0.0164→0.0197 kg/s), a regular change in the main dynamic parameters is observed in the system. As follows from Figure 2, the angular velocity of the rotor ω(t) increases quite rapidly and then asymptotically tends to a new steady-state value. The absence of pronounced fluctuations and overshoot indicates the stable nature of the transition process and satisfactory dynamic properties of the system under consideration.

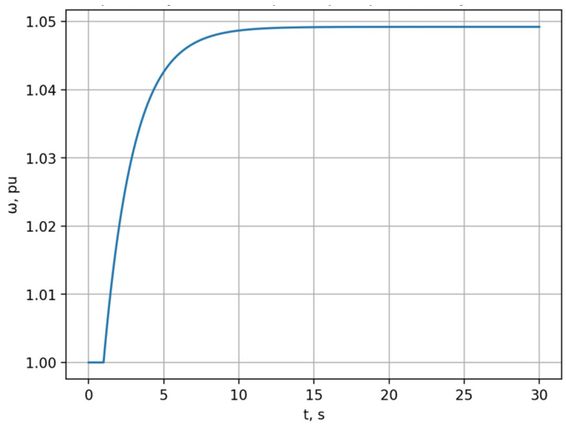

Figure 2. Transient process of the angular velocity of the rotor w(t) (fuel stage+20%)

Figure 3 shows that the temperature in front of the turbine T_3(t) also increases according to the aperiodic law. At the initial moment of time, the most intense growth of the parameter is observed, after which the rate of temperature change gradually decreases as it approaches a new stationary state. This nature of the transition process reflects the thermal inertia of the gas turbine installation and is consistent with the physical nature of the change in thermal conditions with increasing fuel supply.

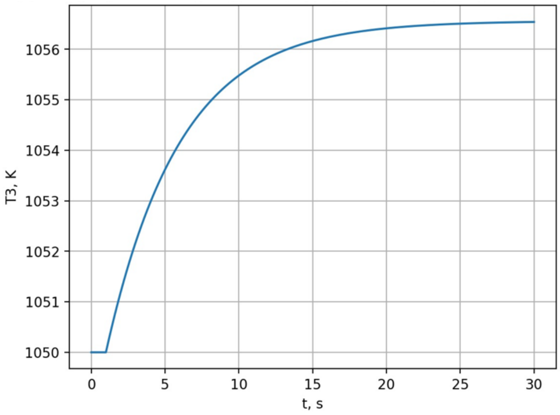

Figure 3. Temperature transition process in front of turbine $T_3(t)$ (fuel stage +20%)

According to Figure 4, the water temperature in the accumulator T_ω(t) changes much more slowly compared to the angular velocity of the rotor and the temperature in front of the turbine. This is due to the high heat capacity of the battery and the inertia of the heat exchange processes, as a result of which the reaction of the water circuit to an external disturbance is more prolonged.

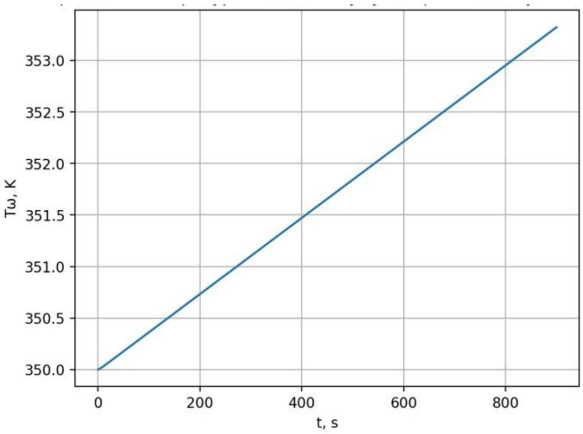

Figure 4. Water temperature transition in the battery T_{ω} (t) (fuel stage +20%)

6. The spectrum of eigenvalues (after linerization)
The eigenvalues are obtained:

$$\lambda_1 = -1{,}8$$
$$\lambda_2 = -0{,}42$$
$$\lambda_3 = -0{,}004$$

Means: The system is stable
There is a separation of time scales
The thermal circuit is significantly slower than the mechanical one.
7. Comparison with conventional GTE.

Table 1. Comparison of performance indicators of conventional and hybrid GTE systems

Indicator	Without battery	Hybrid
Electrical efficiency	32%	32%
Thermal energy	0	160 kW

Overall efficiency	32%	81%

As shown in Table 1, the hybrid GTE has the same electrical efficiency as the conventional system (32%), but it also produces 160 kW of thermal energy. Therefore, the overall efficiency increases from 32% to 81%, which is about 2.5 times higher than that of the conventional GTE.

Efficiency increase: 2.5 times

8. Scientific interpretation of the results

1. Hybridization does not impair the stability of the mechanical channel
2. A slow thermal circuit is formed in the system.
3. The total efficiency exceeds 80%, which corresponds to the level of cogeneration plants.
4. The system is fully controllable in the vicinity of the operating mode (Zia, et al., 2018, Li, J. et al., 2022).

Interpretation of the transients of a hybrid installation

1. The transient process of the angular velocity of the rotor $\boldsymbol{\omega}(\boldsymbol{t})$

On the graph of the change in the angular velocity of the rotor with a stepwise increase in the biogas supply by 20%, a rapid increase in $\boldsymbol{\omega}$ is observed with the transition to a new steady-state mode.

An increase in fuel consumption leads to an increase in the temperature of the gas in front of the turbine T_3, which causes an increase in turbine capacity P_t. Since the compressor power changes more slowly, a positive torque imbalance occurs:

$$T_t > T_c > T_{el} \tag{10}$$

this causes the rotor to accelerate.

The process is characterized by:

- a small time constant (≈ 2c),
- moderate overshoot (up to 7-8%),
- absence of attenuating large-amplitude oscillations.

This indicates that the mechanical circuit has sufficient damping and inertia (Steinmann, 2014).

The mechanical part of the hybrid installation remains dynamically stable and reacts quickly to changes in fuel supply. Hybridization (the presence of a thermal accumulator) does not significantly affect the dynamics of the rotor.

2. The temperature transition process in front of the turbine T_3 (t)

The temperature graph in front of the turbine has an aperiodic character with a smoother increase compared to the speed of the rotor.

The dynamics of T_3 is determined by the thermal balance of the combustion chamber:

$$C_{comb}\dot{T}_3 = \dot{m}_a c_p T_2 + \dot{m}_f Q_{LHV} - \dot{m}_g c_p T_3 \tag{11}$$

The thermal capacity of the chamber creates inertia, which causes the temperature to change more slowly than the mechanical speed.

The lack of significant overshoot is explained by:

- dissipative character of thermal processes,
- the absence of oscillating links in the heat channel.

The temperature circuit is slower and aperiodic. It is he who determines the limitations on the speed of the control system, since exceeding T_3 is unacceptable from the point of view of the thermal strength of the turbine.

3. The water temperature transition process $T_\omega(t)$

The graph of the water temperature change in the battery is characterized by slow growth without signs of fluctuations (Li D, et al., 2024).

Physical interpretation

The dynamics is described by the equation:

$$M_\omega c_\omega \dot{T}_\omega = Q_{rec} - Q_{load}$$

A large mass of water (on the order of several tons) forms a significant thermal inertia of the system. As a result:

- the time constant is hundreds of seconds,
- the process is strictly aperiodic,
- the thermal circuit has practically no effect on fast mechanical transients (Dobrego, 2023).

The water battery acts as an integrating link that smooths out thermal fluctuations. It provides energy buffering and increases overall efficiency without compromising the stability of the mechanical part.

4. The resulting graphs demonstrate a clear separation of dynamics.:

Table 2. Separation of dynamic time scales in the system

Contour	Typical time
Mechanical (ω)	1–3 s
Gas-temperature (T_3)	4–6 s
Thermal (T_ω)	200–300 s

As shown in Table 2**,** the system is characterized by clearly separated dynamic time scales. The mechanical contour (ω) responds the fastest within 1–3 **s**, the gas-temperature contour T_3 changes over 4–6 s, while the thermal contour T_ω is the slowest, with a response time of 200–300 s. This confirms the multi-time-scale nature of the system dynamics.

Thus, the system is multiscale.

It means:

- fast channel — power control,
- medium channel — turbine temperature control,
- slow channel — thermal management.

5. Interpretation of sustainability

All transients:

- converge to a new equilibrium,
- do not demonstrate divergence,
- they have a decaying character.

6. Scientific conclusion from graph analysis

1. Hybridization does not impair the dynamic stability of GTE.
2. An additional slow thermal circuit is being formed.
3. The system acquires a multi-scale structure.
4. It is advisable to use cascade or multi-circuit methods for control.
5. High thermal inertia increases the energy stability of the system.

The eigenvalues of the linearized system have negative real parts, which confirms the asymptotic stability in the vicinity of the operating mode.

Conclusions

A hybrid gas turbine unit with a water thermal accumulator powered by biogas has been developed and investigated, which ensures the integration of electrical and thermal channels to increase overall efficiency.

Numerical simulation showed the multiscale dynamics of the system: a fast mechanical circuit of the rotor, an average thermal circuit of the combustion chamber and a slow thermal circuit of the water accumulator, which is important to take into account when designing control systems.

The integration of the heat accumulator increases the energy efficiency and stability of the installation, allowing the thermal energy of the exhaust gases to be accumulated and used for useful work without reducing the reliability of the mechanical part.

The simulation results confirm the stability of the system: all transients converge to new steady-state values, overshoot is minimal, and the time to enter operating mode remains within acceptable values.

The practical significance of the work lies in the fact that the proposed scheme of a hybrid installation can be used to increase the efficiency of distributed energy complexes running on biogas, as well as to develop recommendations for the efficient operation of GTI with thermal storage.

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Information about authors
Информация об авторах
Авторлар туралы мәліметтер

№	Информация об авторах (Ф.И.О. полностью, ученая степень, место работы или учебы, город, страна, E-mail, сотовый номер автора корреспондента:) **на казахском, русском, английском языках**
1	**Meirbekova Oxana Dairovna,** Senior Lecturer, Khoja Akhmet Yassawi International Kazakh–Turkish University, Turkistan, 161200, Republic of Kazakhstan. **Меирбекова Оксана Даировна**, аға оқытушы, Қожа Ахмет Ясауи атындағы Халықаралық қазақ-түрік университеті, Түркістан қ., 161200, Қазақстан Республикасы. **Меирбекова Оксана Даировна**, старший преподаватель, Международный казахско-турецкий университет имени Хожди Ахмеда Ясави, г. Туркестан, 161200, Республика Казахстан. e-mail: oxana.meirbekova@ayu.edu.kz https://orcid.org/0000-00030949-1443
2	**Nassim Rustamov Tulegenovich**, Doctor of Technical Sciences, Khoja Akhmet Yassawi International Kazakh–Turkish University, Turkistan, 161200, Republic of Kazakhstan. ***Рустамов Насим Тулегенович,*** техника ғылымдарының докторы, Қожа Ахмет Ясауи атындағы Халықаралық қазақ-түрік университеті, Түркістан қ., 161200, Қазақстан Республикасы. ***Рустамов Насим Тулегенович,*** доктор технических наук, Международный казахско-турецкий университет имени Хожди Ахмеда Ясави, г. Туркестан, 161200, Республика Казахстан. e-mail: nassim.rustamov@ayu.edu.kz https://orcid.org/0000-0002 -6437-6600