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MATHEMATICAL MODELLING OF MARINE POWER PLANTS WITH THERMOCHEMICAL FUEL TREATMENT

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ABSTRACT

The article considers the methodological aspects of the theoretical investigation of marine power plants with thermochemical fuel treatment. The results of the study of the complex influence of temperature, pressure, and the ratio of steam / base fuel on the thermochemical treatment efficiency are presented. The adequacy of the obtained regression dependences was confirmed by the physical modelling of thermochemical fuel treatment processes. For a gas turbine power complex with a thermochemical fuel treatment system, the characteristics of the power equipment were determined separately with further merging of the obtained results and a combination of material and energy flow models. Algorithms, which provide settings for the mathematical models of structural and functional blocks, the optimisation of thermochemical energy transformations, and verification of developed models according to the indicators of existing gas turbine engines, were created. The influence of mechanical energy consumption during the organisation of thermochemical processing of fuel on the efficiency of thermochemical recuperation is analysed.

Keywords: marine power plants, thermochemical fuel treatment system, gas turbine engine, mathematical modeling

INTRODUCTION

Global trends in the energy efficiency of fuel resources, minimising emissions of CO_2, NO_x, and other harmful substances, require the adaptation of promising energy-saving technologies to marine energetics [1, 2].

The known technology of thermochemical treatment of fuels by the regeneration of secondary energy resources of heat engines is a set of processes resulting in an increase in the enthalpy of energy boosters (a mixture of hydrocarbon fuels and oxidants), due to the endothermic conversion process of base fuel using secondary heat engine energy resources [3-6].

The use of thermochemical recuperation in the gas turbine engines (GTE) of a simple and steam-injected gas turbine (STIG) cycle, as well as combined diesel-gas turbine power generating units, is very promising [7]. Such installations provide for thermochemical recuperation of the GTE exhaust gases by steam conversion of hydrocarbon fuels. In this case, conversion products are used as fuel [8, 9].

The variety of scheme solutions for the composition of a marine power plant, and a wide range of power equipment parameters, requires the identification of the relationships of components using mathematical modelling.

Functional decomposition allows the presentation of an energy module with thermochemical systems of recuperation (TCSR) of secondary energy resources in the form of a set of subsystems. In turn, each subsystem is formed as a set of units (superchargers, reactors, etc.) and groups of units united

Symbols and abbreviations

G	mass flow rate, kg/s
H_U	lower heat of combustion, kJ/kg
I	electric current, A
L	length, m
M	mass, kg
N	power, MW
p	pressure, MPa
s/bf	steam/fuel ratio, kg/kg
T	time, s
T, Θ	temperature, K
ε	comparative error
Δ	absolute error
η	efficiency
C	base fuel compressor
CC	combustion chamber
DP	desalination plant
GTE	gas turbine engines
HPC	high-pressure compressor
HPT	high-pressure turbine
HRSG	heat-recovery steam generator
LPC	low-pressure compressor
LPT	low-pressure turbine
PT	power turbine
R	reactor
STIG	steam-injected gas turbine
TCSR	thermochemical systems of recuperation

Indexes

air	air
B	base hydrocarbon fuel
C	conversion products
calc	calculations
exp	experimental data
fix	fixed parameters
fuel	fuel
G	exhaust gas
max	maximum allowable parameters
min	minimum allowable parameters
R	rational parameters
THR	parameters of the thermochemical fuel treatment

by a certain functional feature (gas turbine engine, internal combustion engine, etc.) [10].

Mathematical models of blocks, and groups of blocks, that form the mathematical model of the subsystem are usually a system of nonlinear algebraic equations.

In the mathematical modelling of new technologies, it is expedient to use the modular approach (Sequential Modular, SM) [11]. Equations for each unit (such as a thermochemical reactor) are solved using individual algorithms. In this case, for all calculation modules, a predetermined logical sequence of calculations is followed. The advantages of this approach to finding rational solutions are:

- the ability to test computational algorithms with subsequent verification of the results separately for some blocks or groups of blocks;
- a modular structure allows new blocks to be added easily and existing ones to be upgraded;
- relative simplicity and solution transparency allow easy verification of the original data for compliance and completeness.

An example of the use of this approach is the software for physicochemical processes modelling, which is implemented in the software package Aspen Plus [12, 13].

Mathematical modelling provides an opportunity to identify the range of effective use of promising fuels and their thermochemical treatment by the recuperation of secondary energy resources of marine power plants. Verification of the basic mathematical model provisions requires the physical modelling of individual processes of thermochemical fuel treatment.

IDENTIFICATION OF THE INVESTIGATION OBJECT

An energy module with thermochemical systems for the recuperation of secondary energy resources can be presented as a set of subsystems:

- an energy subsystem in which the chemical energy of the fuel is converted into mechanical, electrical, and thermal energy;
- subsystems of thermochemical recuperation and energy conversion.

The subsystem of thermochemical recuperation and energy conversion consists of two parts:

- a heat recovery circuit, which is designed to supply heat to the secondary energy engine resources to consumers of the thermochemical energy conversion circuit; and
- the circuit of thermochemical energy conversion, which can be performed in the form of a unit of thermochemical fuel treatment.

The modelling of physicochemical processes in blocks, groups of blocks, and the subsystems themselves is based on the fundamental laws of conservation of energy and mass. For the mathematical description of the processes of physical and chemical transformations, the equations of material and energy balances are used, which are closed by additional relations that take into consideration the features of a particular process.

The approaches formed in [14] propose to determine the minimum value of the calculated error in the mathematical modelling of processes in the selected class of phenomena, to confirm the acceptability of the selected model. It is proposed to use comparative error as a universal indicator [15, 16]:

$$\varepsilon = \Delta u_{pmm}/S \leq [(z^{|} - \beta^{|})/N_{SI} + [(z^{||} - \beta^{||})/(z^{|} - \beta^{|})], \quad (1)$$

where Δu_{pmm} is the dimensionless model error during the determination of the dimensionless variable u; S is the range of values of the dimensionless studied variable u; $z^{|}$ is the total number of dimensionless physical variables in the chosen class of phenomena; $\beta^{|}$ is the number of primary physical variables; $z^{||}$ is the given number of selected physical dimensional variables; $\beta^{||}$ is the number of the primary physical dimensional variables; and N_{SI} is the largest number of dimensionless complexes.

In the study of energy conversion processes in power plants, of the seven main variables of the SI system (L – length, M – mass, T – time, I – electric current, Θ – temperature, J – light intensity, F – the amount of substance) only three main ones are used (L, M, and Θ) and the fourth T is used for non-stationary processes. The processes of thermochemical transformations require additional consideration of F.

Achievable minimum comparative error in modelling energy conversion processes in power plants lies in a wide range of values (Table 1): from 0.004756, for stationary heat and mass transfer processes, to 0.13307, for modelling non-stationary heat transfer processes taking into consideration thermochemical transformations.

Thus, it is expedient to consider stationary conditions in the mathematical modelling of processes in the energy module with thermochemical systems, for the recuperation of secondary energy resources. On the one hand, this narrows the value of the results obtained, on the other hand, it allows obtaining the correct characteristics of power equipment.

Tab. 1. Achievable minimum comparative error according to different classes of phenomena

Class of phenomena	Description of the phenomena	Minimum comparative error ε_{min}
LMΘ	Stationary heat and mass transfer process	0.00476
LMΘF	Stationary process of heat and mass transfer taking into consideration thermochemical transformations	0.01458
LMTΘ	Non-stationary process of heat and mass transfer	0.04457
LMTΘF	Non-stationary process of heat and mass transfer taking into consideration thermochemical transformations	0.13307

Procedures for the verification and optimisation of processes in the energy module equipment with thermochemical energy conversion require adjustment of the heat engine model. Thus, when studying the efficiency of thermochemical fuel treatment by recuperating the gas turbine engine waste heat, the following characteristics are most often considered: effective power, specific fuel consumption, inlet turbine temperature, gas temperature at the engine outlet, and the rate of recuperation (regeneration).

In the case of modelling the internal combustion engine, the main parameters are: effective power, specific fuel consumption, average effective pressure, maximum combustion pressure, and maximum combustion temperature.

A variety of fuels can be used as a base energy source, which requires the development of algorithms for the preliminary assessment of the effectiveness of thermochemical technologies for fuel of a specific composition and verification. Further adjustment of heat engine models need to take into consideration the existing limitations and requirements for modern or future models.

DETERMINATION OF RATIONAL PARAMETERS OF THERMOCHEMICAL FUEL TREATMENT

Thermochemical fuel treatment can be carried out using a wide range of technologies [6, 17, 18]:

- recuperation by decomposition (thermal dissociation);
- steam reforming;
- partial recuperation by autothermal reforming (where part of the feed undergoes catalytic combustion in the presence of oxygen);
- dry reforming (where the exhaust gas is used to reform the feed);
- plasma reforming (where reforming processes are carried out using low-temperature plasma).

In preliminary studies, the authors analysed the possibility of using the presented technologies. Steam conversion of hydrocarbons using exhaust gas utilisation in heat engines was selected for further research. The selection was made according to several criteria, primarily based on the assessment of the temperature level of the reaction, the increase in calorific value and the value of the utilised heat flow, as well as the amount of obtained hydrogen, the heat of the reaction, and others.

The coefficient of increase of the heat of combustion for base fuel is chosen as the main criterion for an estimation of energy efficiency in thermochemical processing. The proposed criterion is defined as [7]:

$$\overline{H}_{U} = \frac{\Delta H_{U}}{H_{U}^{B}}, \quad (2)$$

where $\Delta H_{U} = H_{U}^{C} - H_{U}^{B}$ is the difference between the lower heat of combustion of the conversion products H_{U}^{C} (kJ/kg) and the base hydrocarbon fuel H_{U}^{B} (kJ/kg).

The calorific value of the components of the synthesis gas (obtained during the conversion) is converted to 1 kg of base fuel.

A further algorithm for determining the rational parameters of the thermochemical fuel treatment by recuperating secondary energy resources, provides the following. For fixed values of the pressure p_{THR} of the thermochemical treatment, the composition of thermochemical treatment products is calculated, followed by the estimation of the heat of combustion H_{U}. The coefficient of increase of the heat of combustion $\overline{H}_{U}$ is then determined, as a function of the temperature T_{THR} of the thermochemical treatment and steam / fuel ratio s/bf:

$$\begin{cases} \bar{H}^{1}_{U_{1\ldots l}} = f(T_{THR_{1\ldots m}},\ s/bf_{1\ldots n}),\ \ p_{THR_1} = const\ 1 \\ \bar{H}^{2}_{U_{1\ldots l}} = f(T_{THR_{1\ldots m}},\ s/bf_{1\ldots n}),\ \ p_{THR_1} = const\ 2 \\ \bar{H}^{3}_{U_{1\ldots l}} = f(T_{THR_{1\ldots m}},\ s/bf_{1\ldots n}),\ \ p_{THR_1} = const\ 3 \\ \bar{H}^{k}_{U_{1\ldots l}} = f(T_{THR_{1\ldots m}},\ s/bf_{1\ldots n}),\ \ p_{THR_1} = const\ k, \end{cases} \tag{3}$$

where k is the number of fixed pressure values; m is the number of fixed temperature values; n is the number of fixed values of the ratio s/bf; and $l = m \cdot n$ is the number of calculated values of $\bar{H}_U$.

Generalising the influence of the s/bf ratio on the increase in the heat of combustion, under conditions of variation of the parameter T_{THR} = var and a fixed value $p_{THR} = const$, allows us to parametrically represent the results in the form of graphical dependencies, an example of which is given in Fig. 1a.

For each fixed value of pressure at a fixed value of temperature and variable value of the steam / fuel ratio, the local maximum $\bar{H}^R_U$, which corresponds to a certain rational value of the parameter s/bf^R, was determined (Fig. 1b).

The mathematical description of parametric dependencies for thermochemical conversion processes is presented in the form of a system of equations:

$$\begin{cases} \bar{H}^{R623}{}_{U_1} = f(s/bf^{R623}),\ \ p_{THR_1} = const\ 1 \\ \ldots \\ \bar{H}^{R1123}{}_{U_1} = f(s/bf^{R1123}),\ \ p_{THR_1} = const\ 1 \\ \bar{H}^{R623}{}_{U_2} = f(s/bf^{R623}),\ \ p_{THR_2} = const\ 2 \\ \ldots \\ \bar{H}^{R1123}{}_{U_2} = f(s/bf^{R1123}),\ \ p_{THR_2} = const\ 2 \\ \bar{H}^{R623}{}_{U_3} = f(s/bf^{R623}),\ \ p_{THR_3} = const\ 3 \\ \ldots \\ \bar{H}^{R1123}{}_{U_3} = f(s/bf^{R1123}),\ \ p_{THR_3} = const\ 3 \\ \bar{H}^{R623}{}_{U_4} = f(s/bf^{R623}),\ \ p_{THR_4} = const\ 4 \\ \ldots \\ \bar{H}^{R1123}{}_{U_4} = f(s/bf^{R1123}),\ \ p_{THR_4} = const\ 4 \end{cases} \tag{4}$$

The obtained value $\bar{H}^R_U$, is the maximum achievable value of the coefficient of increase of the heat of combustion.

For each fixed value of pressure, the regression dependence of the maximum achievable value of the coefficient of increase of the heat of combustion on temperature as a polynomial function was determined:

$$\begin{cases} \bar{H}^R_{U_1} = c_{11} \cdot T^4_{THR} - c_{21} \cdot T^3_{THR} + c_{31} \cdot T^2_{THR} - c_{41} \cdot T_{THR} + d_1, \\ \qquad p_{THR_1} = const\ 1; \\ \bar{H}^R_{U_2} = c_{12} \cdot T^4_{THR} - c_{22} \cdot T^3_{THR} + c_{32} \cdot T^2_{THR} - c_{42} \cdot T_{THR} + d_2, \\ \qquad p_{THR_2} = const\ 2; \\ \qquad \ldots \\ \bar{H}^R_{U_n} = c_{1n} \cdot T^4_{THR} - c_{2n} \cdot T^3_{THR} + c_{3n} \cdot T^2_{THR} - c_{4n} \cdot T_{THR} + d_n, \\ \qquad p_{THR_n} = const\ n. \end{cases} \tag{5}$$

The dependence of the coefficients of the polynomial function $\bar{H}^R_U = f(T_{THR}, p_{THR})$ on the pressure was established by regression analysis methods:

$$\bar{H}^R_U = a_1 \cdot T^4_{THR} - a_2 \cdot T^3_{THR} + a_3 \cdot T^2_{THR} - a_4 \cdot T_{THR} + b, \tag{6}$$

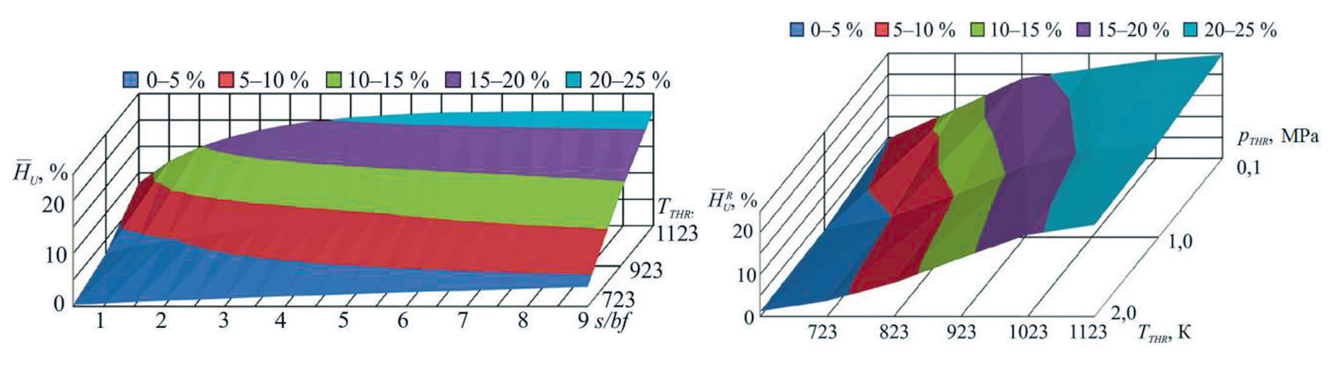
where:

$a_1 = -A_{11} \cdot p^2_{THR} - A_{22} \cdot p_{THR} + B_1$, $a_2 = -A_{11} \cdot p^2_{THR} - A_{22} \cdot p_{THR} + B_2$,

$a_3 = -A_{31} \cdot p^2_{THR} - A_{32} \cdot p_{THR} + B_3$, $a_4 = -A_{41} \cdot p^2_{THR} - A_{42} \cdot p_{THR} + B_4$,

$b = -A_b \cdot p^2_{THR} - A_b \cdot p_{THR} + B_b$.

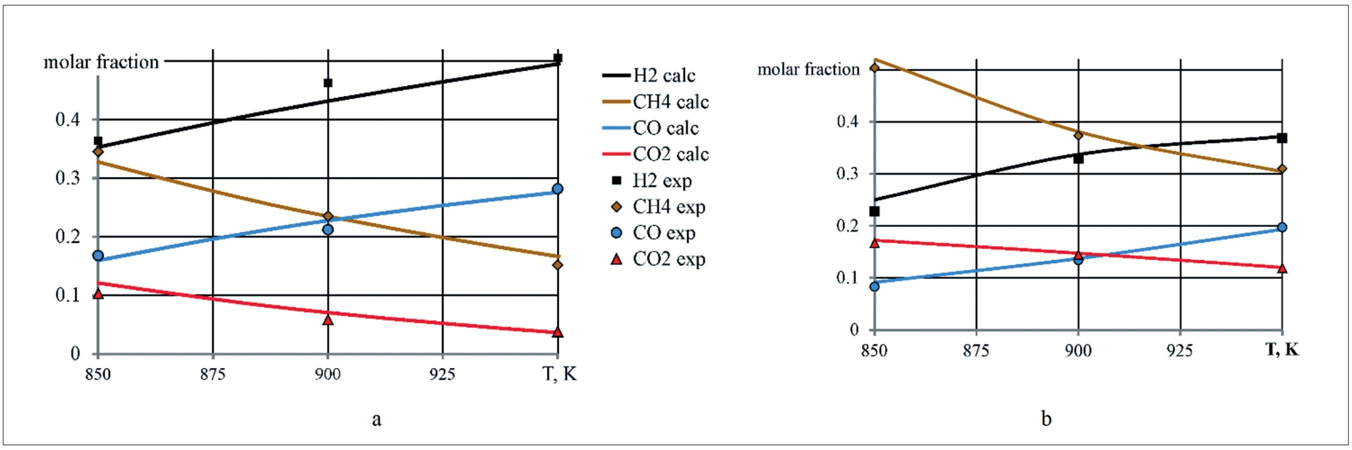
The given algorithm allows the determination of the maximum achievable value of the coefficient of increase of the heat of combustion under the following restrictions: available levels of temperatures of secondary energy sources, admissible conversion pressure under conditions of conformity to the rational value of parameter s/bf^R.



a

b

*Fig. 1. Parametric dependences for thermochemical conversion processes: **a** – dependence $\bar{H}_U = f(T_{THR}, s/bf)$ for thermochemical treatment of natural gas at p_{THR} = 2.0 MPa; **b** – dependence $\bar{H}^R_U = f(T_{THR}, p_{THR}, s/bf^R)$ for thermochemical treatment of natural gas in the ranges of parameterchanges: pressure 0.1–2.0 MPa; temperature 623–1123 K; steam / fuel ratio 0–9.*



a

b

Fig. 2. Comparison of the results of experimental studies of the synthesis gas composition and the results of theoretical calculations for s/bf =0.3: ***a*** *– p_{THR} = 0.1 MPa;* ***b*** *– p_{THR} = 0.45 MPa; H_2 calc, CH_4 calc, CO calc, CO_2 calc – theoretical calculations; H_2 exp, CH_4 exp, CO exp, CO_2 exp – experimental data*

In order to verify the results of mathematical modelling, an experimental study of the energy efficiency of thermochemical fuel treatment processes at a pressure corresponding to the conditions of fuel gas feeding to heat engines was carried out.

A comparison of the results of experimental studies on synthesis gas composition [19] with theoretical calculations gives a satisfactory convergence of the values, which is not less than 92% (Fig. 2), and confirms the adequacy of the regression dependences $\bar{H}_U = f(T_{THR}, p_{THR}, s/bf)$.

According to the approaches proposed by the authors [7], the maximum allowable temperature of the endothermic reaction of fuel conversion T^{max}_{THR} is determined as:

$$T^{max}_{THR} = T_4 - \frac{\bar{H}_U \cdot H^B_U \cdot G_{fuel}}{G_G \cdot c_p} \qquad (7)$$

where G_G is the exhaust gases flow rate; *cp* is the mean mass heat capacity of the exhaust gases at a constant pressure in the relevant temperature range, and G_{fuel} is the mass fuel consumption.

According to calculations for the range of average gas temperatures behind marine gas turbine engines, 700-820 K, the maximum increase in the heat of combustion for modified gaseous hydrocarbon fuels, due to the thermochemical treatment of natural gas, is 8-12%, depending on process pressure.

Further studies of the effectiveness of thermochemical fuel treatment technology in marine energetics require the development of a mathematical model of a gas turbine energy complex with TCSR.

MATHEMATICAL MODELLING OF GAS TURBINE ENERGY COMPLEX WITH THERMOCHEMICAL FUEL TREATMENT SYSTEM

Mathematical models of gas turbine engines or internal combustion engines, when working as part of an energy module with thermochemical fuel treatment, must be adjusted to the selected basic characteristics. Therefore, mathematical models of structural and functional blocks and groups of blocks contain calculation algorithms, including settings for specified characteristics.

Verification of the serial gas turbine engine model is based on the following characteristics:

- engine power N_{GT} is a fixed value N^{fix}_{GT};
- the maximum temperature behind the combustion chamber T_3 must not exceed the value T_3^{fix}.

When modelling processes in the energy module, the calculated values of the objective function $Y = f(x)$ must meet the conditions of the given tolerance for convergence ΔY^{tol}. In our case:

$$\Delta N_{GT} \le N^{tol}_{GT} \ldots \Delta T_3 \le \Delta T^{tol}_3 , \qquad (8)$$

where $\Delta N_{GT} = |N_{GT} - N^{fix}_{GT}|$ and $\Delta T_3 = |T_3 - T_3^{fix}|$ are the absolute errors of parameter values.

It has been found that, other things being equal, for the objective function N_{GT}= the main input variable is the amount of mass fuel consumption, i.e. $N_{GT} = f(G_{fuel})$. According to the objective function T_3, the main input variable is the mass air flow, i.e. $T_3 = f(G_{air})$.

The correct setting of the initial parameters of input variables significantly reduces the calculation time and provides the required convergence for less iteration.

Wegstein’s method [20] can be used as a method of convergence, according to which the results of the last two iterations were used to calculate the variable:

$$G_{fuel_k} = G_{fuel_{k-1}} - \frac{f(G_{fuel_{k-1}})(G_{fuel_{k-1}} - G_{fuel_{k-2}})}{f(G_{fuel_{k-1}}) - f(G_{fuel_{k-2}})} ;$$

$$G_{air_k} = G_{air_{k-1}} - \frac{f(G_{air_{k-1}})(G_{air_{k-1}} - G_{air_{k-2}})}{f(G_{air_{k-1}}) - f(G_{air_{k-2}})} . \qquad (9)$$

Mathematical models of the gas turbine engine, recycling circuit, and thermochemical fuel treatment unit were created using the Aspen Plus physicochemical process modelling system. In our calculations, we used the following assumptions: all gases are treated as ideal gases; there is a chemical equilibrium in the reformer (the equilibrium value is a function of temperature, pressure, composition of input gas, and steam to gas ratio). A Gibbs reactor in the Aspen® software is used to determine the composition of products in the reaction system. This reactor calculates the distribution of reaction products by minimising the Gibbs free energy of each of the existing elements in the reaction system. In [21], it is indicated that the results of computer modelling using this approach are confirmed by the data available from the industrial plant at the Puertollano petrochemical refinery.

The algorithm for calculating the parameters and characteristics of the gas turbine power complex with thermochemical fuel treatment contains three main stages (Fig. 3).

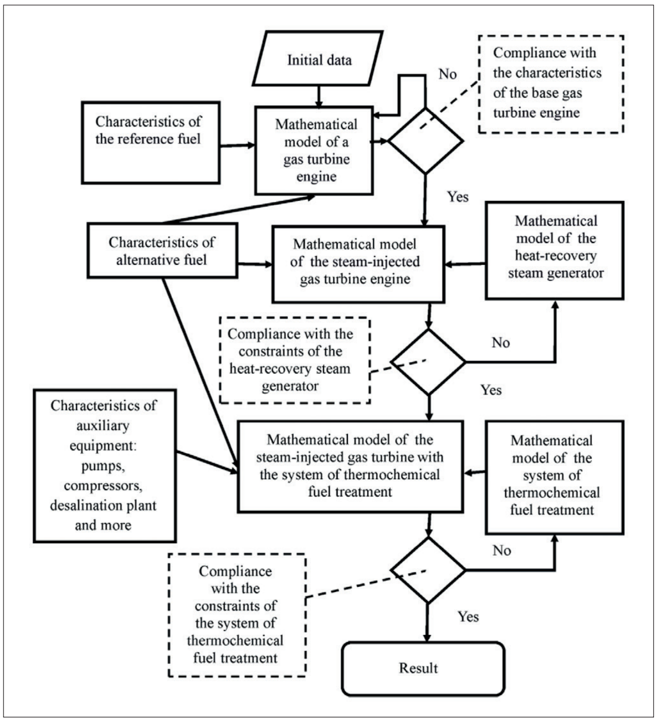


Fig. 3. Scheme of the algorithm for modelling processes in the energy module with thermochemical recuperation

The first stage involves adjusting the gas turbine engine model to the parameters of the serial engine at nominal operation mode: effective engine power, the gas temperature behind the combustion chamber, the rate of total pressure drop in the turbine or turbines, the rate of pressure increase in the compressor (compressors), mass air flow, and the mass consumption of reference fuel (e.g. methane). After verification of the model according to the parameters of the base engine, the model is adjusted to the operation of the gas turbine engine on alternative fuels.

In the second stage, the processes in the steam-injected gas turbine, created on the basis of the model of the first stage, are calculated.

The following parameters are defined:

- mass consumption of alternative fuels at a fixed value of power;
- steam productivity of the heat-recovery steam generator in the conditions of restrictions of the minimum temperature of the exhaust gases which is defined by the temperature of a dew point;
- change of mass air flow taking into consideration observance of the admissible temperature of gas behind the combustion chamber;
- the cost of mechanical energy to drive pressure change devices (pumps), which provide the necessary efficiency of the recycling system. At the third stage, the processes in the steam-injected gas turbine with the system of thermochemical fuel treatment are modelled.

The following parameters are defined:

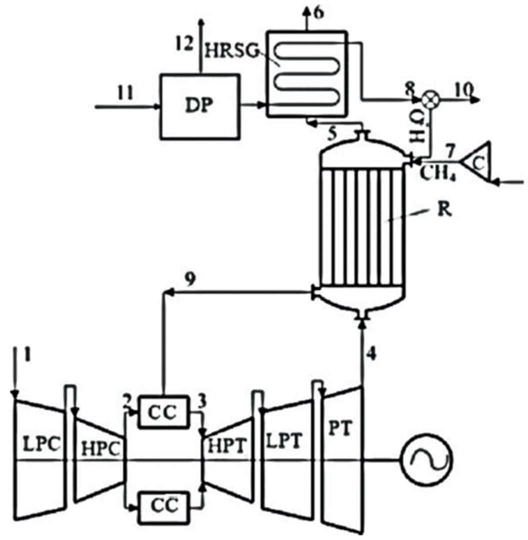
- mass consumption of alternative fuels;
- the maximum achievable temperature of the fuel treatment process in the thermochemical reactor;
- steam productivity of the heat-recovery steam generator in the conditions of restrictions of the minimum temperature of the exhaust gases;
- change of mass air flow, taking into consideration observance of the admissible temperature of gas behind the combustion chamber;
- energy consumption in the desalination plant;
- the cost of mechanical energy to drive pressure change devices (pumps and compressors), which provide the necessary efficiency of recuperation and thermochemical fuel treatment systems.

In order to verify the adequacy of the proposed algorithms, mathematical modelling of the energy complex, based on the UGT 25000 gas turbine engine with a thermochemical fuel treatment system, was performed (Fig. 4). The GTE is a simple cycle dual-rotor turbine engine with a free power turbine (Table 2). The UGT 25000 is produced by the enterprise "Zorya-Mashproekt" (Ukraine) and designed for electric power generation, natural gas transportation and marine propulsion.

Tab. 2. Parameters of the UGT 25000

Parameters	Value
Number of compressors	2
Number of turbines	3
Turbine inlet temperature, K	1518
Compressor pressure ratio	21.8
Exhaust gas flow, kg/s	90
Exhaust temperature, K	763
Power, MW	27.5
Efficiency, %	36.5

The modelling provided for the operation of the turbocompressor unit in the nominal mode. We proposed the installation of a thermochemical reactor behind the power turbine of a serial gas turbine engine. The principle of operation was as follows. Synthesis gas from the thermochemical reactor was fed to the combustion chamber of the engine. In the reactor, due to the heat of the exhaust gases, the methane-steam mixture was heated and then steam reforming took place. Behind the reactor, the exhaust gas temperature has sufficient potential to produce recovery of the boiler steam required for the 'steam reforming' of the base fuel in the reactor. In the power module,



Flow designation	Temperature, K	Mass flow rate, kg/s
1 (air)	288	86.910
2 (air)	690	86.910
3 (gas)	1450	90.000
4 (gas)	773	90.000
5 (gas)	738	90.000
6 (gas)	443	90.000
7 (methane)	415	1.454
8 (steam)	508	7.170
9 (synthesis gas)	700	3.100
10 (steam)	508	5.524
11 (sea water)	293	9.680
12 (brine)	303	2.51

Fig. 4. – Design scheme of energy module with thermochemical fuel treatment based on UGT 25000: LPC – low-pressure compressor; HPC – high-pressure compressor; CC – combustion chamber; HPT – high-pressure turbine; LPT – low-pressure turbine; PT– power turbine; R – reactor; HRSG – heat-recovery steam generator; C – base fuel compressor; DP – desalination plant

similar to STIG cycle turbine units [22-23], water was removed from the cycle [24]. A desalination plant was provided to compensate for water losses [25]. In more detail, the scheme of thermochemical utilisation of the waste heat of a gas turbine engine by steam reforming of hydrocarbon fuel, the composition of the base fuel, and the main components of the synthesis gas were presented in [8].

The efficiency of the power module is accepted as a criterion:

$$\eta = (N_{GT} - \Sigma N_{add})/(G^{B}_{fuel} \cdot H^{B}_{U}), \qquad \textbf{(10)}$$

where N_{GT} is the mechanical power on the output shaft of the engine, kW; ΣN_{add} is the power consumption for the driving of pumps and compressors, as well as for the needs of a desalination plant and other equipment of the thermochemical fuel treatment subsystem, kW; G^{B}_{fuel} is the base fuel consumption, kg/s; and H^{B}_{U} is the lower heat of combustion of base fuel, kJ/kg.

By mathematical modelling it was established that the use of thermochemical fuel treatment under steam reforming leads to the following changes in the basic cycle:

- increasing total pressure losses at the engine outlet due to total pressure losses in the reactor;
- increasing the amount of working fluid due to the injection of steam and synthesis gas into the combustion chamber;
- the recuperation of exhaust gas heat;
- power consumption for the driving of pumps and compressors, desalination plant and other auxiliary equipment of the thermochemical fuel treatment system.

An increase in the total pressure loss in the gas path, due to the thermochemical reactor, leads to a decrease in engine efficiency from 0.6-0.8% (absolute) and a decrease in specific power from 1.6-2.2% (higher values correspond to lower temperature value T_3).

Analysis of the results of the cycle calculation reveals an increase in efficiency (Fig. 5) compared to the steam-injected gas turbine cycle. It should be assumed that synthesis gas is better able to stabilise combustion than the steam-fuel mixture used in the STIG cycle. It can be seen that, compared with the STIG cycle, the increase in the unit's efficiency due to the use of thermochemical fuel treatment in the temperature T_3 range of 1300–1700 K, is 0.5–4.5% (absolute), and the increase is greater, the higher the maximum cycle temperature. If we take the baseline for comparing a gas turbine unit with a traditional waste heat recovery system, in which the steam obtained in the exhaust gas boiler at a single pressure is used in a steam turbine [26], then the efficiency gain will be about 3.0-8.9% for the same temperature range of 1300-1700 K.

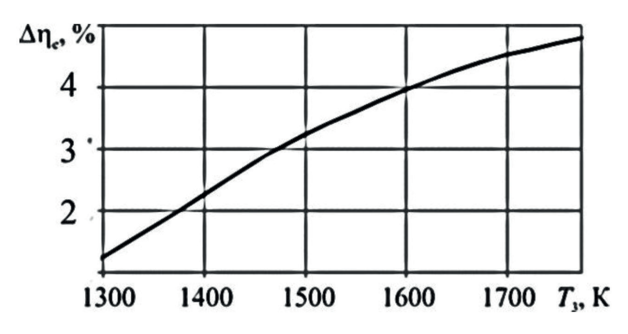


Fig. 5. Dependence of efficiency increase on the temperature behind the combustion chamber in comparison with the STIG cycle

As a result of endothermic reactions in the reactor, the amount of heat required for heating the methane-steam mixture and carrying out these reactions is removed from the exhaust gases. For the UGT 25000 engine at the given parameters, the part of the utilised heat makes 29% of the exhaust gases heat. In the total heat balance, this reduces the heat introduced into the cycle by the base fuel by 4.9%. Power consumption for the needs of the desalination plant is from 0.7-1.0% of the power of the energy module and depends on the steam/fuel ratio. Experimental studies to determine the efficiency of thermochemical fuel processes [17] confirm the results of mathematical modelling, according to which, the expense of mechanical energy for the organisation of thermochemical fuel processes and the supply of modified products to the engine reduces the efficiency of thermochemical utilisation by 6-12%.

The efficiency of the gas turbine power module with a thermochemical natural gas treatment system with a thermochemical reactor behind a power turbine obtained by mathematical modelling methods shows that, at the relatively low levels of gas temperatures behind the combustion chamber (<1523 K) and the exhaust gases (700–820 K), steam conversion of natural gas due to the heat of exhaust gases is not efficient enough and can be compared with the STIG cycle. This coincides with the results of other researchers [27].

Comparison with the results of previous studies shows that the considered scheme of the power module with thermochemical fuel treatment based on serial GTE of the simple cycle with reactor behind a power turbine may be promising when using fuels such as methanol, ethanol, and associated gas with heavy hydrocarbons. The proposed scheme seems appropriate when the gas temperatures behind the combustion chamber of a serial marine GTE will be at least 1673 K.

FINAL CONCLUSIONS

The results of a comprehensive study of the characteristics of a gas turbine power module with a thermochemical treatment system are presented. The following results were obtained:

- to calculate the coefficient of increase of the heat of combustion within the given ranges of temperatures and pressures, regression dependences are proposed, which take into consideration the complex influences of temperature, pressure, and steam/base fuel ratio. The adequacy of the obtained regression dependences $\bar{H}_U = f(T_{THR}, p_{THR}, s/bf)$ was confirmed by physical modelling of thermochemical fuel treatment processes;
- according to the results of experimental studies, the expense of mechanical energy during thermochemical fuel treatment and injection of modified products into the engine, reduces the efficiency of thermochemical recuperation by 6-12%, which requires a rational selection of marine power plant scheme solutions;
- the proposed algorithms provide adjustments for the mathematical models of structural and functional blocks, optimisation of processes of thermochemical transformations, and verification of the developed models;
- for the range of average gas temperatures behind serial marine gas turbine engines 700-820 K, the maximum increase in the heat of combustion for modified gaseous hydrocarbon fuels is 8-12%;
- the mathematical modelling shows that, at the current level of serial marine gas turbine engines characteristics, the efficiency of the proposed power module increase is 2-3%, compared to the STIG cycle;
- the considered scheme of a thermochemical fuel treatment system with a reactor behind a power turbine is quite effective when temperatures behind the combustion chamber are not lower than 1673 K;
- further work should study the effectiveness of the use of thermochemical technologies for the utilisation of secondary energy resources at partial operating modes of the installation.

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