Development of a control system for a gas turbine power unit with a thermal energy storage

Cite as: AIP Conference Proceedings **2467**, 030027 (2022); https://doi.org/10.1063/5.0092449

Eugene Pitukhin, Maxim Kukolev, Petr Pitukhin, et al.

AIP Conference Proceedings **2467**, 030027 (2022); https://doi.org/10.1063/5.0092449 **2467**, 030027

Development of a Control System for a Gas Turbine Power Unit with a Thermal Energy Storage

Eugene Pitukhin[1,a)], Maxim Kukolev[2,b)], Petr Pitukhin[3,c)] and Mileta Gubaeva[3,d)]

[1]*Petrozavodsk State University, Lenin Ave. 33, 185910, Petrozavodsk, Russia*
[2]*Peter the Great St. Petersburg Polytechnic University, Polytechnicheskaya st. 29, 195251, St. Petersburg, Russia*
[3] *Filial "Protvino" of the State University "Dubna", Severny Proezd 9, 142281, Protvino, Moscow region, Russia*

[a)]Corresponding author: eugene@petrsu.ru
[b)]m_kukolev@mail.ru
[c)]p.pitukhin@mail.ru
[d)]mileta.gubaeva@mail.ru

Abstract. The article deals with the problem of synthesis of the control system of the power unit of a solar space gas turbine power unit. To ensure the uninterrupted operation of the turbine in the shadow region of the orbit, a thermal storage unit is used as an energy source, which prudently stores solar energy in the light region of the orbit. Operation of the turbine is provided by the system "receiver of solar radiation – thermal storage", which forms a single power unit. The problem of structural and parametric identification of its mathematical model is solved. Thermal storage efficiency is justified by maximum possible temperature of working fluid at turbine inlet. The criterion of optimality of choice of operating parameters of power plant is to ensure constancy of thermal storage characteristics at maximum thermodynamic efficiency of the system, which is equivalent to maximization of exergy efficiency of the system. The results of calculations have shown the possibility of using the proposed structural solutions to control the capacity of the power unit.

INTRODUCTION

The creation of new orbital systems in near-Earth space and the expansion of the range of tasks solved by the existing spacecraft causes an increase in the available power and stability of onboard power plants.

Solar gas-turbine power units (SGTU) [1] are among the promising systems proposed for use and investigated over the past few decades. Their design provides for the use of various energy storage devices, in particular, thermal ones [2]. Thermal storage accumulates part of the solar energy in the light part of the orbit and gives it away in the shadow part, when solar energy is not available. Thus, the continuous operation of the power plant is ensured.

The problems of optimal design and control of a solar power unit for space station are discussed in [3–8].

Such power plants can be successfully used not only in space, but also in any remote region of the Earth where autonomy is required. The solar dish-micro gas turbine system together with the heat accumulator are promising power sources and can be used for small-scale power generation (<100 kW) in rural off-grid areas [9]. Also, distributed solar gas turbine systems with thermal energy storage will overcome the intermittency and instability of solar radiation and produce reliable and flexible electricity for remote areas and islands [10].

In encyclopedia [11] summarizes developments, key techniques and trends, analyses problems and difficulties in design and application of solar thermal power systems and discusses the methods for solving these problems.

At the same time, despite the existence of a lot of work on research of a solar power unit with thermal energy storage [11–19], the issue of space solar power unit performance and stability remains relevant. To resolve this issue, you need information about the dynamic characteristics and modes of system "receiver of solar radiation – thermal storage".

When creating SGTU control systems, there are problems associated with unequal energy inputs and outputs in different parts of the orbit. The first problem is to ensure a given level of power generated by the turbo-generator unit.

Proceedings of the II International Conference on Advances in Materials, Systems and Technologies
AIP Conf. Proc. 2467, 030027-1–030027-8; https://doi.org/10.1063/5.0092449
Published by AIP Publishing. 978-0-7354-4349-5/$30.00

The second, more complicated one, is to regulate the power of the power unit according to the control law set by the onboard consumer.

The article deals with the solution of the first problem by means of structural synthesis – introduction of shunt elements in the design of the power unit, which consists of a receiver of solar radiation and a thermal storage device. Supporting the specified power is ensured by optimal control of redistribution of working fluid flow inside the power unit from the position of maximum exergic efficiency.

The purpose of the work is to ensure the specified power of the turbo-generator unit of the power plant in all parts of the orbit.

Objectives of the work:

- Structural synthesis of the power unit.
- Identification of the mathematical model of the power unit.
- Optimization of control system parameters by the criterion of thermodynamic efficiency of the thermal storage unit.

METHOD

Structural Synthesis of the Power Unit

The main subsystems of SGTU are (see Fig. 1): mirror-concentrator of solar radiation (1); receiver of solar radiation (2) and heat accumulator (3), constituting a single power unit; turbo-generator unit (4); regenerator (5); heat exchanger (6); refrigerator-emitter (7).

Let's briefly describe the scheme of power unit operation. Concentrated by the mirror 1 solar radiation enters the receiver of solar radiation (RSR) 2. The working fluid (WF) of the SGTU circuit is heated and enters the thermal storage unit (TS) 3, giving part of the energy to the operation of the unit in the shadow section of the orbit. Then WF goes to the turbine of the turbo-generator unit 4, where the energy of the flow is converted into the rotational energy of the shaft with the electric generator and compressor. The unused energy is partially returned to the cycle by the regenerator 5, and the remainder goes to the cooler-emitter 7. The cooled WF enters the compressor, is heated in the regenerator 5, and is sent to the receiver 2.

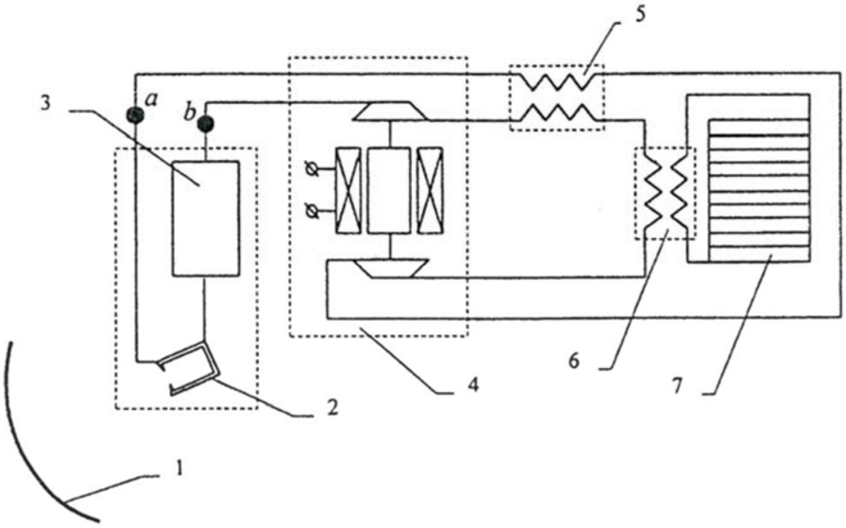

FIGURE 1. Schematic diagram of a solar gas-turbine power unit (SGTU).

Consider the power unit as an object of "black box"' type, bounded by points (a) and (b), which should be subjected to regulation.

The input and output parameters of the object, respectively represented by the characteristics of the WF at points (a) and (b) and, by the condition of the task, must be constant at all parts of the orbit.

Figure 2 shows a functional diagram of the power unit with the proposed structural changes.

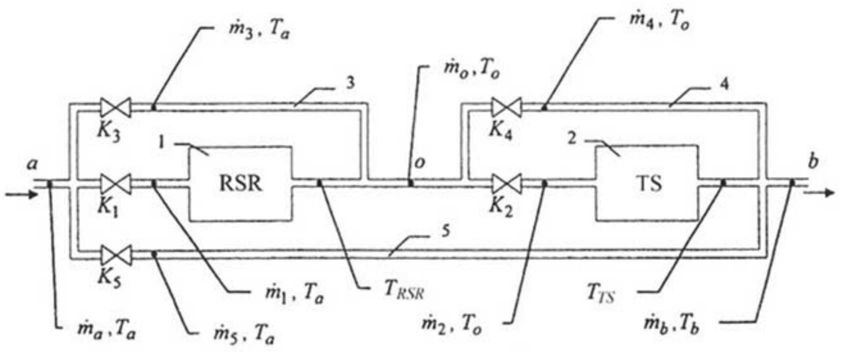

FIGURE 2. Energy block: receiver of solar radiation (RSR) – thermal storage (TS).

Hereinafter, the following designations of elements of the power unit and their parameters are used:

a — entry point of the WF into the power unit;
b — point of the WF exit from the power unit;
o — middle point;
1 — solar radiation receiver pipeline;
2 — thermal storage pipeline;
3,4,5 — bypass (control) pipelines;
K_i — regulator of the WF flow through the i -th pipeline;
$\dot{m}_i = f(K_i)$ — specific mass flow rates of the WF through the corresponding pipelines i;
$\dot{m}_a, \dot{m}_o, \dot{m}_b$ — specific mass flow rates of WF through points (a), (o) and (b), respectively;
T_a, T_o, T_b — WF temperatures at points (a), (o) and (b), respectively;
T_{RSR} — temperature of the WF at the outlet of the solar radiation receiver;
T_{TS} — temperature of the WF at the outlet of the thermal storage.

The proposed structural synthesis of the SGTU control system is an addition of the power unit bypassing links in the form of additional pipelines 3, 4, 5 in the RSR–TS bundle and flow regulators K_i.

These pipelines are designed for redistribution of WF flows of the SGTU circuit. By determining the optimal flow rate control law in all lines, it is supposed to achieve constancy of the unit output power under condition of maximum use of its useful work.

The task of structural synthesis can be considered solved. It remains to make a mathematical model adequate to the control system and solve the problem of parametric synthesis, in which the laws of variation of the WF flow rate in the mains will be found. From the position of optimal control and thermodynamics, this should be achieved by maximizing the exergy efficiency of the thermal storage [20].

Identification of the Mathematical Model of the Power Unit

Let's assume that the working fluid of the power unit circuit has the properties of an ideal gas. Then the change in the energy state of the WF will be determined by the temperature difference at the input (a) and output (b) of the power unit. Let us also assume that the power unit is sufficiently protected from heat leakage, and dissipation losses at the receiver of solar radiation are minimized. Then the product of heat capacity of the working fluid by the specific mass flow rate will be the same at points (a) and (b), provided that there is no leakage and the SGTU circuit operation is constant, i.e.

$$\dot{m}_a c_p = \dot{m}_b c_p = \ const \tag{1}$$

in all parts of the orbit.

Consequently, a constant power of the power unit will be provided by maintaining a constant temperature difference of the working body at the outlet and inlet at each moment of time.

Below the indices I and II will indicate the values of the variables in the light and shadow sections of the orbit, respectively. Let's set the condition that the operation of the power unit will take place uniformly in all sections of the orbit, so that it will give out equal power per unit time:

$$\dot{m}_a c_p \frac{d(T_b^I - T_a^I)}{dt} = \dot{m}_a c_p \frac{d(T_b^{II} - T_a^{II})}{dt} \ . \tag{2}$$

This condition is necessary to introduce and maintain operation of the turbine generator in nominal mode.

From (1) it follows that the condition of stabilization of operation of the whole circuit SGTU around a certain operating point will be compliance with the following equations

$$\begin{aligned} T_b^I &= T_b^{II} = T_b = \ const \ , \\ T_a^I &= T_a^{II} = T_a = \ const \ . \end{aligned} \tag{3}$$

Then the power P emitted by the installation in all parts of the orbit will be equal:

$$P = \dot{m}_a c_p (T_b - T_a) = \ const \ . \tag{4}$$

The value ranges of the parameters $\dot{m}_\alpha$, c_p, T_a and T_b for the SGTU of the specified type without TS are known [21].

One of the problems when calculating a power unit with a TS is the power loss associated with a decrease in the output temperature of the working fluid T_b at the stage of discharge. It is obvious that the introduction of TS reduces the total power of the power unit – part of the energy from the RSR goes to the TS charge. On the other hand, the constancy of the SGTU power in all parts of the orbit is ensured. Therefore, one of the goals in stabilizing the operating modes of the power unit is to achieve the maximum possible value of constant power (4):

$$P \to \max \ , \tag{5}$$

and, consequently, the working fluid output temperature at known values of $\dot{m}_a$, c_p и T_a:

$$T_b \to \max \ . \tag{6}$$

Let's write down the mass transfer equations of the mathematical model of the power unit (Fig. 2) for the flows of the working fluid in the light and shadow sections of the orbit:

$$\dot{m}_a^I = \dot{m}_3^I + \dot{m}_1^I + \dot{m}_5^I \ ; \tag{7}$$

$$\dot{m}_b^I = \dot{m}_4^I + \dot{m}_2^I + \dot{m}_5^I \ ; \tag{8}$$

$$\dot{m}_a^{II} = \dot{m}_3^{II} + \dot{m}_1^{II} + \dot{m}_5^{II} \ ; \tag{9}$$

$$\dot{m}_b^{II} = \dot{m}_4^{II} + \dot{m}_2^{II} + \dot{m}_5^{II} \ . \tag{10}$$

The heat transfer equations take into account working fluid temperatures and specific mass flow rates:

$$T_o^I = \frac{\dot{m}_3^I}{\dot{m}_3^I + \dot{m}_1^I} T_a^I + \frac{\dot{m}_1^I}{\dot{m}_3^I + \dot{m}_1^I} T_{RSR}^I \ ; \tag{11}$$

$$T_b^I = \frac{\dot{m}_5^I}{\dot{m}_a^I} T_a^I + \frac{\dot{m}_2^I}{\dot{m}_a^I} T_{TS}^I + \frac{\dot{m}_4^I}{\dot{m}_a^I} T_o^I \ ; \tag{12}$$

$$T_o^{II} = \frac{\dot{m}_3^{II}}{\dot{m}_3^{II} + \dot{m}_1^{II}} T_a^{II} + \frac{\dot{m}_1^{II}}{\dot{m}_3^{II} + \dot{m}_1^{II}} T_{RSR}^{II} \ ; \tag{13}$$

$$T_b^{II} = \frac{\dot{m}_5^{II}}{\dot{m}_a^{II}} T_a^{II} + \frac{\dot{m}_2^{II}}{\dot{m}_a^{II}} T^{II}_{TS} + \frac{\dot{m}_4^{II}}{\dot{m}_a^{II}} T_o^{II} \ . \tag{14}$$

Let us transform equations (7-10) and (11-14), taking into account (1), (3) and (4):

$$\dot{m}_3^I + \dot{m}_1^I + \dot{m}_5^I - \dot{m}_a = 0 \ ; \tag{15}$$

$$\dot{m}_3^{II} + \dot{m}_1^{II} + \dot{m}_5^{II} - \dot{m}_a = 0 \ ; \tag{16}$$

$$\dot{m}_4^I + \dot{m}_2^I + \dot{m}_5^I - \dot{m}_a = 0 \ ; \tag{17}$$

$$\dot{m}_4^{II} + \dot{m}_2^{II} + \dot{m}_5^{II} - \dot{m}_a = 0 \ ; \tag{18}$$

$$\frac{\dot{m}_5^I}{\dot{m}_a} T_a + \frac{\dot{m}_2^I}{\dot{m}_a} T^I_{TS} + \frac{\dot{m}_4^I}{\dot{m}_a}\left[\frac{\dot{m}_3^I}{\dot{m}_3^I+\dot{m}_1^I} T_a + \frac{\dot{m}_1^I}{\dot{m}_3^I+\dot{m}_1^I} T^I_{RSR}\right] - T_b^I = 0 \ ; \tag{19}$$

$$\frac{\dot{m}_5^{II}}{\dot{m}_a} T_a + \frac{\dot{m}_2^{II}}{\dot{m}_a} T^{II}_{TS} + \frac{\dot{m}_4^{II}}{\dot{m}_a}\left[\frac{\dot{m}_3^{II}}{\dot{m}_3^{II}+\dot{m}_1^{II}} T_a + \frac{\dot{m}_1^{II}}{\dot{m}_3^{II}+\dot{m}_1^{II}} T^{II}_{RSR}\right] - T_b^{II} = 0 \ ; \tag{20}$$

$$T_b^I - T_b^{II} = 0 \ . \tag{21}$$

The ranges of values of the working fluid temperature parameters at the exit from the solar receiver in the light T^I_{RSR} and shadow T^{II}_{RSR} sections of the orbit are known.

The method of determining the dependence of the coolant (working fluid) temperature on a number of design parameters of the heat storage device is of the greatest interest. A model that allows obtaining such analytical dependence is based on the approach that uses the concept of dimensionless rate of movement of the phase transition boundary [20, 22]. In these works, for the first time, the dependences characterizing the process of charge and discharge of TS cells of different forms are offered: for absorbed and separated TS energy, the rate of movement of the phase transition boundary, thermodynamic efficiency and other parameters.

According to the conditions of the problem, the TS operates in two modes - charge and discharge. The charge mode corresponds to the light part of the orbit (I), the discharge mode to the shadow part (II). The energy storage stage is absent. In particular, when considering a one-dimensional mathematical model of TS with a plate-like cell, nonlinear dependences for T^I_{TS} and T^{II}_{TS} were obtained:

$$T^I_{\text{TH}} = f_1(\dot{m}_2^I, t^I, c_p, TI_o, T_m, K^I, F_p, \eta^I, \lambda^I, \rho^I, L_m) \ , \tag{22}$$

$$T^{II}_{\text{TH}} = f_2(\dot{m}_2^{II}, t^{II}, c_p, TII_o, T_m, K^{II}, F_p, \eta^{II}, \lambda^{II}, \rho^{II}, L_m) \ , \tag{23}$$

where

$\dot{m}_2^{I,II}$ — specific mass flow rate of the working fluid passing through the TS, kg/s;
$t^{I,II}$ — charge or discharge time of VT, s;
c_p — specific mass heat capacity of DH, $J(kgK)$;
$T_o^{I,II}$ — working fluid temperature at the inlet to the TS, K;
T_m — melting temperature of thermal storage material (WF), K;
$K^{I,II}$ — heat transfer coefficient, $W/(m^2K)$;
F_p — total area of the phase transition boundary, m^2
$\eta^{I,II}$ — energy efficiency at charge and discharge;
$\lambda^{I,II}$ — thermal conductivity of thermal storage material (WF) , $W/(mK)$;
$\rho^{I,II}$ — thermal storage material (WF) density in solid and liquid phases, kg/m^3;
L_m — latent specific heat of melting of thermal storage material (WF), J/kg.

The mathematical model of the SGTU is a system of equations (15-21), taking into account the dependencies (22-23), which must be solved with respect to the following variables:

$$\dot{m}_1^I,\ \dot{m}_2^I,\ \dot{m}_3^I,\ \dot{m}_4^I,\ \dot{m}_5^I,\ \dot{m}_1^{II},\ \dot{m}_2^{II},\ \dot{m}_3^{II},\ \dot{m}_4^{II},\ \dot{m}_5^{II},\ T_b^I,\ T_b^{II} \ . \tag{24}$$

Optimization of Control System Parameters by the Criterion of Thermodynamic Efficiency of the Thermal Storage Unit

The mathematical model of the power unit with the synthesized control system was obtained above (15-21). Let's proceed to the parametric synthesis, i.e. the search for the optimal values of the control variables. In accordance with (6), as the initial target function, we take the sum of

$$|T_b^I| + |T_b^{II}| \rightarrow \max \ . \tag{25}$$

The power unit model consists of 7 equations (15-21) and 12 unknowns (14). It is necessary to set constraints on the parameters of the mathematical model in order to obtain a real solution.

The above-described model of the power unit was implemented in MathCAD environment. In the process of modeling it was found that the highest efficiency at energy release in the shadow section (II) is achieved when the coolant (WF) flows through the heat accumulator in full, excluding bypasses 4 and 5. This is due to the need for complete extraction of stored energy from the TS. Consequently, a limitation is added to the system

$$\dot{m}_2^{II} \geq \dot{m}_a \ . \tag{26}$$

Hence, the satisfaction of condition (25) is equivalent to the restriction (26). Therefore, it is necessary to introduce a new target function for the model.

Let us also introduce restrictions on the range of values of specific mass flow rates of coolant (WF), which cannot be negative:

$$\begin{gathered} \dot{m}_1^I \geq 0,\ \dot{m}_2^I \geq 0,\ \dot{m}_3^I \geq 0,\ \dot{m}_4^I \geq 0,\ \dot{m}_5^I \geq 0, \\ \dot{m}_1^{II} = 0,\ \dot{m}_3^{II} \geq 0,\ \dot{m}_4^{II} \geq 0,\ \dot{m}_5^{II} \geq 0. \end{gathered} \tag{27}$$

The variable $\dot{m}_1^{II}$ must take a zero value due to the need to close pipeline 1 of the RSR at the discharge stage (in the Earth's shadow zone) to avoid heat leakage in the form of radiation from the RSR into the surrounding space.

By entering different initial values of variables (24), Math-CAD simulations showed that a number of solutions (24) are in the vicinity of maximum (25). Thus, using one criterion of maximum (25) of working fluid temperature at point (b) is not enough.

The objective to be achieved by the designed control system of the power unit must also carry another optimality criterion: ensuring the consistency of the coolant (WF) parameters of the circuit at the turbine outlet (at point b) at maximum thermodynamic efficiency.

The maximum thermodynamic efficiency is understood as the maximization of the exergic efficiency of the RSR–TS system.

The RSR efficiency is a predetermined value and its change is not considered in this work. Then, by analogy with (25), the total exergic efficiency of the TS at the charging (I) and discharging (II) stages can be taken as a new target function:

$$\begin{aligned} &\psi^I = f_3(\dot{m}_1^{*I}, \dot{m}_2^{*I}, \dot{m}_3^{*I}) = \max_{\dot{m}_{1-5}^{I,II}} f_3(\dot{m}_1^I, \dot{m}_2^I, \dot{m}_3^I), \\ &\psi^{II} = f_4(m_2^{*II}) = \max_{\dot{m}_{1-5}^{I,II}} f_4(\dot{m}_2^{II}), \\ &\psi^I \psi^{II} \rightarrow \max \ , \end{aligned} \tag{28}$$

where $\dot{m}_1^{*I}$, $\dot{m}_2^{*I}$, $\dot{m}_3^{*I}$, $\dot{m}_2^{*II}$ are the optimal values of the coolant mass flow rates from the whole set of their allowed values $\dot{m}_{1-5}^{I,II}$ from (24), ensuring the maximum of the target function $\psi^I \psi^{II}$.

RESULTS AND DISCUSSION

The final model of the power unit, the numerical results of the solution of which will be given below, includes:

- Equations (15-23);

- Restrictions (26-27);
- Target function (28).

The left column of Table 1 shows the numerical values of the input parameters that were used in the numerical experiment with the model {(15-23), (26-28)}. As a result of model calculations and optimization, numerical values of control parameters were obtained, which are presented in the right column of table 1.

TABLE 1. Results of numerical calculations of power unit parameters.

Input parameters	Optimization results
$\dot{m}_a = 1.2\ \ kg/s$	$\dot{m}_1^I = 0.609\ \ kg/s$
$c_p = 519.0\ \ J(kgK)$	$\dot{m}_2^I = 0.03\ \ kg/s$
$T_{RSR}^I\ = 1200.0\ \ K$	$\dot{m}_3^I = 0.0\ \ kg/s$
$T_{RSR}^{II}\ = 900.0\ \ K$	$\dot{m}_4^I = 0.579\ \ kg/s$
$T_m = 1040.0\ \ K$	$\dot{m}_5^I = 0.591\ \ kg/s$
$K^{I,II} = 100.0\ \ W/(m^2K)$	$\dot{m}_1^{II} = 0.0\ \ kg/s$
$F_p = 33.0\ \ m^2$	$\dot{m}_2^{II} = 1.2\ \ kg/s$
$\eta^{I,II} = 0.95$	$\dot{m}_3^{II} = 1.2\ \ kg/s$
$t^I = 5400.0\ \ s$	$\dot{m}_4^{II} = 0.0\ \ kg/s$
$t^{II} = 1800.0\ \ s$	$\dot{m}_5^{II} = 0.0\ \ kg/s$
$\lambda^I = 1.7\ \ W/(mK)$	$T_b^I = 999.095\ \ K$
$\lambda^{II} = 3.8\ \ W/(mK)$	$T_b^{II} = 999.095\ \ K$
$\rho^I = 2190\ \ kg/m^3$	
$\rho^{II} = 2590\ \ kg/m^3$	

As a result of numerical optimization, the values of the multipliers of the target function (28) $\psi^I = 0.22$ and $\psi^{II} = 0.89$ are obtained. At the same time, the total exergy efficiency was at the level of 19%. The heat capacity of the power unit in the continuous mode was P=124 kW. The temperature $T_b^{I,II}$ at the turbine inlet is supported at the level of 999 K.

CONCLUSION

The article considers the case of SGTU power regulation, set by a constant law. Further development of the work will be to investigate the possibility of controlling SGTU by more complex control laws using probabilistic-statistical methods of calculation.

The results obtained in the simulation allow us to conclude that it is possible to control the power unit capacity according to the specified laws with the help of the proposed structural changes of the power unit.

In order to use the obtained optimal values of control parameters of SGTU, it is necessary to introduce software control of K_i regulators of flow rates through the i-th pipeline. It is reasonable to do this by means of an automation complex, which will allow reconfiguring the operation mode of the SGTU power unit depending on changes in the power consumption cyclogram [23].

REFERENCES

1. I. Kurkin, D. Sevruk, D. Sidorov, M. Kukolev and A. Kotelnikov, *Development of the Infrastructure and Simulation of the Energy Series Assemblies for Solar Space Electric Power Stations. Solar Power Satellites: the Emerging Energy Option*, edited by P. Glaser, F. Davidson, K. Csigi *et al.* (Ellis Harwood, New York, 1993), pp. 152-161.
2. M. Conti and Ch. Charach, "Thermal Storage for Solar Dynamic Power Generation: Second Law Analysis in Space Application Perspective", *Proc. of Fourth European Space Power Conference* (Poitiers, 1995) pp. 145-150.

3. C. Cougnet, B. Gerber, F. Steinsiek, R. Laine and M. Perren, *The 10 KW Satellite: a First Operational Step for Space Based Solar Power* (ASTRIUM, All the Space You Need, 2010), p. 10.
4. J. S. Mankins, *Space Solar Power, the First International Assessment of Space Solar Power: Opportunities, Issues and Potential Pathways Forward* (International Academy of Astronautics, Yater, 2011), p. 272.
5. V. A. Vanke, Problems and Methods of Science **4**, 3 (2008).
6. V. K. Sysoev, K. M. Pichkhadze, L. I. Feldman, E. A. Arapov and A. S. Luzyanin, Vestnik, FSUE NPO im.S.A.Lavochkina **2**, 12–19 (2011).
7. G. G. Raikunov, A. A. Verlan, V. M. Melnikov, K. M. Pichkhadze, V. K. Sysoev and B. N. Harlov, Acad. Sci. Energy **4**, 10 (2012).
8. G. T. Yermoldina, B. T. Suimenbayev, V. K. Sysoev and Zh. B. Suimenbayeva, Acta Astronautica **158**, 111-120, (2019).
9. M. A. Bashir, A. M. Daabo, K. P. Amber, M. S. Khan, A. Arshad and H. Elahi, Applied Thermal Engineering **195**, (2021).
10. J. Yang, G. Xiao, M. Ghavami, J. Al-Zaili, T. Yang, A. Sayma and D. Ni, Journal of Cleaner Production **304**, (2021).
11. K. Lovegrove and A. Luzzi, *Solar Thermal Power Systems*, *Encyclopedia of Physical Science and Technology (Third Edition)*, edited by Robert A. Meyers (Academic Press, 2003), pp. 223-235.
12. I. Ortega-Fernández, A. B. Hernández, Y. Wang and D. Bielsa, Energy **217**, 119378 (2021).
13. H. Zuo, Y. Zhou, M. Wu, K. Zeng, Z. Chang, S. Chen, W. Lu and G. Flamant, Renewable Energy **175**, 29-43 (2021).
14. B. Climent, O. Torroba, R. González-Cinca, N. Ramachandran and M. D. Griffin, Acta Astronautica **93**, 352-358 (2014).
15. E. F. Camacho and M. Berenguel, IFAC Proceedings Volumes **45(15)**, 848-855 (2012).
16. J. D. Álvarez, J. L. Guzmán, L. J. Yebra and M. Berenguel, Simulation Modelling Practice and Theory **17(4)**, 664-679 (2009).
17. I. L. García, J. L. Álvarez and D. Blanco, Solar Energy **85(10)**, 2443-2460 (2011).
18. A. Mawire, M. McPherson, and R.R.J. van den Heetkamp, Solar Energy Materials and Solar Cells **92(12)**, 1668-1676 (2008).
19. U. Herrmann, B. Kelly and H. Price, Energy **29(5–6)**, 883-893 (2004).
20. M. Kukolev, Yu. Kukelev and L. Lutsenko, "Calculation of Thermodynamic Efficiency of a Designed Thermal Accumulator Cell Using the Dimensionless Rate of Movement of Phase Transition Boundary", *Proceedings of the Second Russian National Conference on Heat Transfer*, vol. 3 (Moscow Power Engineering Institute Publishing House, Moscow, 1998), pp. 206-209.
21. T. W. Kerlslake and M. B. Ibrahim, Journal of Solar Energy Engineering **115**, 22-31 (1993).
22. M. Kukolev, Yu. Kukelev and L. Lutsenko, "Analytical Equations for the Design of Heat Storage Systems", *Proceedings of CSME Forum*, vol.1 (Toronto, 1998), pp. 584-588.
23. E. Pitukhin and J. Yanuk, "The Design of an Optimal Control Algorithm for the DAMATIC-XD System for Decreasing the use of Energy in Afterflotational Drying of Wood Chips", Abstracts of International Conference: *New Information Technology in Pulp and Paper Industry and Energetics* (Petrozavodsk, 1998), pp. 37-38.