UDC 621.438(045)
DOI: 10.18372/2306-1472.82.14609

Mykola Kulyk[1]
Larysa Volianska[2]
Fedor Kirchu[3]

ENERGY SUPPORT FOR THE PERMANENT MISSION TO MARS

National Aviation University, 1, Lubomyr Husar ave., Kyiv, 03058, Ukraine
E-mails: [1]kulykms@nau.edu.ua, [2]lvolia@nau.edu.ua, [3]fkirchu@gmail.com

Abstract

The concept of using a closed-cycle gas turbine plantfor a planetary energy supply system is considered in the article. The analysis of the currently relevant projects in the field of creating closed-cycle gas turbine plants for energy supply of spacecraft and autonomous objects is given. General information on the main subsystems of power plants operating according Brayton closed cycle is presented. It is shown that the closed-cycle gas turbine having a compact and simple construction demonstrates to be an optimum approach for space nuclear power. The constituent components of the plant performing the cycle processes are a compressor, a turbine, a heat source, a cold source and a regenerator. Therefore, the working fluid performs a heat cycle in which thermal energy is converted into electrical energy, able to use in space and planetary devices.Particular attention is paid to the justification of the choice of the working fluid, the physicochemical properties of which significantly affect the working process of the plant and determine its main characteristics. The thermodynamic calculation of one of such plant is presented.

Keywords: Brayton cycle; closed-cyclegas turbine; carbon dioxide; nuclear reactor; heat recuperation

1. Formulation of the problem

As it is known, Elon Musk and SpaceX plan to carry out the Martian mission in the second half of the 20s of this century. The Starship (two-stage rocket) is designed to deliver 150 tons of cargo and up to 100 passengers to Mars. For the return flight from the Red Planet, Musk considers methane as fuel. For this purpose, methane-fueled rocket engine Raptor is already designed and tested. In this, the authors of the project consider nine locations on Mars for landing and building the base. There is ice under a thin layer of surface and it can be easily reached. All these locations are at a low height in the middle latitudes of the northern hemisphere. In Musk opinion, here huge glaciers being in their original form lie near the surface. The choice of relatively low height is not arbitrary. In such places, the atmosphere is slightly denser which facilitates the production of carbon dioxide.

Using solar or nuclear energy it is possible turn water and carbon dioxide into methane with the Sabatier reaction. The Sabatier reaction was proposed as a key factor in reducing the cost of exploring Mars by using local resources [1, 2].

After the production of methane and water by compound hydrogen and carbon dioxide taken from the atmosphere in Mars, oxygen can be extractedfrom water by electrolysis and it can be used with methane as a rocket fuel component. This fuel together with oxygen extracted from water can be used to refuel Starships before they return to the Earth. Some components of the autonomous system implementing this process have already been tested by NASA on the Earth.

For similar reasons the slope of Shackleton crater located near the *Moon's south pole* is suggested for location of the Lunar base [3, 4].

Of course, such grandiose projects can be carried out with an appropriate source of energy on the surface of the planet. The closed-cycle gas turbines (closed-cycle GT) with external heat source (nuclear reactors, solar concentrators) are considered as promisingenergy converter formanned spacecraft, planetary (Lunar and Martian) bases, orbital solar power plants. They have undoubted advantages over other types of energy converters due to the large power, small dimensions and weight. In addition, it is necessary to pay attention to:

- high efficiency of closed-cycle GT at moderate temperatures at the turbine entrance;
- high specific power;
- high reliability due to the use of neutral gases or mixtures of these gases, chemically compatible with materials of structural elements;

- long life time of continuous operation;
- compatibility with different sources of heat: solar radiation, nuclear and chemical;
- possibility of using heat accumulator instead of electric ones;
- significantly lower cost and dimensions as compared with solar cell panels.

2. Purpose and research's objectives

The creation of closed-cycle gas turbine plants for power supply of spacecraft and autonomous objects is a difficult scientific and technical problem, especially for simultaneous power supply and cold supply. Part of the heat removed from the installation can be used for room heating or heating (cooling) cryogenic rocket fuel that can improve the efficiency of closed-cycle gas turbine power plant as a whole.

The choice of optimal cycle parameters is limited both by the need to achieve a high efficiency of electric power generation and the minimum possible expansion ratio in a turboexpander, which provides heat removal from the conditioned object.

The closed-cycle gas turbine plant designed to provide base structure with electricity, heat and cold at the required temperature level is the core of the energy conversion system. In general the scheme of the energy supply system includes a heat source system that provides heating of the working fluid to the required level, an energy converter - the closed-cycle GT, which drives an electric generator; consumers of cold at two temperature levels; a heat utilizer and a heat removal system from the contour.

Consider a closed-cycle gas turbine plant with energy and refrigeration parts connected in parallel for energy supply of a constant planetary base and simultaneous generation of electricity and cold (heat). A scheme of such plant is shown in Fig.1. This scheme, in contrast to a sequential one, allows adjusting the volume of the working fluid involved in energy supply and air conditioning systems in a wide operating range.

The working fluid iscompressed in the compressor 4, after which it is divided into two streams: energy and refrigerative. The energy part of the working fluid enters the regenerator 2 where it is heated by the gas exiting the turbine 3 and then enters the gas-heater 1 where its temperature rises to the maximum value. The heated gas expands in the turbine then passing through the regenerator and the gas cooler 7 is returned to the inlet of compressor 4.

The cooling part of the working fluid enters the gas cooler 11, and then into the heat exchanger 10, where it is cooled, then expands in the turboexpander 8 and with a minimum cycle temperature enters the heat exchanger of the object for conditioning 9. Then it enters the refrigeration regenerator 10, is heated to the initial temperature, and mixes with the working fluid of energy contour at the inlet to the compressor.

The use of small turbomachines can significantly reduce the weight of the plant and its dimensions and at the same time ensure a high internal efficiency of plants. The cantilever arrangement of a high-speed centripetal turbine and a high-pressure centrifugal compressor with gas-lubricated bearings makes it possible to obtain a highly reliable unit.

The same fluid is supplied to the bearing lubrication. This design has several advantages: the purity of the gas flow is guaranteed, operation is simplified and the reliability of the unit is increased.

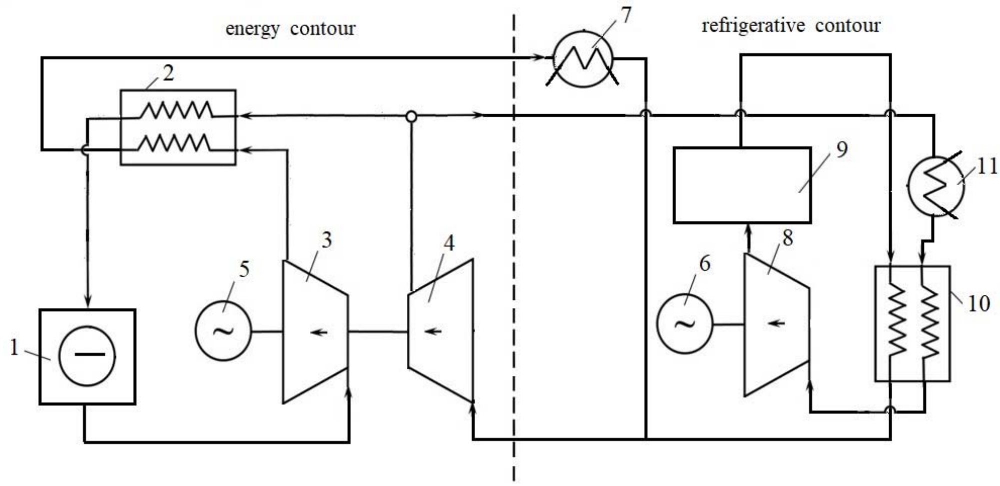
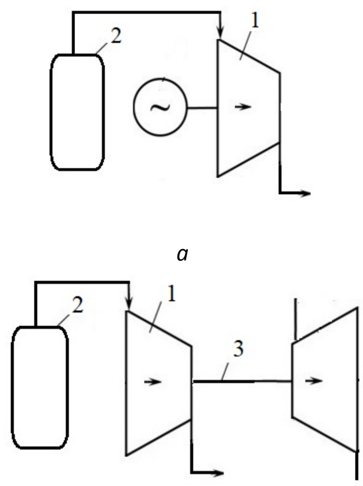


Fig. 1. Scheme of closed cycle gas turbine plant with parallel connected energy and refrigerative parts:
1 – gas heater; 2–regenerator; 3– turbine; 4–compressor; 5,6– generator; 7,11– gas cooler;
8– turbo-expander; 9– object for conditioning; 10– heat exchanger



b

Fig. 2. Working fluid leakage compensation system: 1- booster compressor; 2- feed vessel

Possible (natural) leakages of the working fluid from the circulation system are compensated by the installation of a short-term operating booster compressor 1 (Fig. 2) (autonomous with power of the conditioning system generator - variant *a*, or drive by the shaft 3 of the main unit - variant *b*) and additional feed vessel 2 (in an open cycle - from the atmosphere).

3. Justification of the working fluid choice

To optimize the operation of the plant, first of all, it is necessary to know precisely enough the thermophysical and transport properties of the working fluid. These properties should be known in the operating range of pressures and temperatures. One of the promising ways is the use of inert gases or mixtures of inert gases as a working fluid.

Argon is the cheapest of inert gases. However, the choice of the working fluid is determined not only by its price, but by the whole complex of thermophysical properties of the working fluid and the specific power of closed-cycle gas turbine.

For closed-cycle gas turbine plant with an electric power of 1 to 20 kW, it is necessary to use a working fluid with a molar mass of about 80 kg/kmol, and it is krypton one of the most expensive inert gases.

Currently, most of closed-cycle gas turbine plants is designed for the working fluid what is mixture of gases similar krypton, they are helium and xenon [5].

The best choice of inert gases as the working fluid is inexpensive helium He, which has the highest thermal conductivity and the lowest dynamic viscosity coefficient. Of all inert gases, He has the smallest molecular weight, which leads to a maximum aerodynamic load on the blades of turbomachines and requires a significant increase in the number of stages or diameter of turbomachines with the same cycle parameters [6]. There is no mass restriction for terrestrial plants, so helium is an ideal working fluid. A closed-cycle gas turbine plant space application has very strict restriction on the specific gravity per unit of generated power.

Therefore, to minimize the size of turbomachines, one should choose a working fluid with transport and thermophysical properties like He, but with a much larger molar mass. It was established [7, 8] that the using of binary mixtures of He with the other heavier component (Kr, Xe, N_2) allows considerably to decrease the aerodynamic load on the blades of turbomachines by increasing the molar mass of gas.

Studies [9] showed that the most promising way to increase the efficiency of power plants is to use working fluids with low values of the Prandtl number Pr = 0.2 ... 0.6, what allows to increase the heat transfer coefficient at Reynolds numbers Re≤1200 and significantly reduce the size of heat exchangers.

Particularly promising is the using binary mixtures of inert gases as working fluids in power turbines operating on the closed Brayton cycle, the heat source of which is a gas-cooled nuclear reactor. However, transportation, storage and especially the production of such mixtures in large volumes under Martian conditions seems to be a rather difficult problem. In addition, operation for a long time is difficult without leakage from the system or the Martian atmosphere entering the system. The easiest way to prevent this problem is to design a system to work in the Martian atmosphere.

It is known that the atmosphere of Mars is 95% carbon dioxide. The results of the study [10] and the operating experience of terrestrial plants in which CO_2 was used as a working fluid showed both the possibility of its use and a slight effect on the physicochemical state of structural materials during long-term operation. Therefore, carbon dioxide CO_2 was chosen as the working fluid.

4. Thermodynamic calculation method

Thermodynamic calculation of closed-cycle gas turbine plantfor space and planetary applications providing the consumer with electricity, heat and cold is determination the parameters of the cycle:

work and power of turbomachines; the amount of heat supplied, removed or transferred in heat exchangers; temperatures at characteristic points of the cycle; the mass flow of the working fluid through the compressor; thermodynamic and *electric* power plant *efficiency*.

When you choose the initial parameters, especially the rotor speed, the pressure ratio in the compressor and the temperature of the gases in front of turbine, the determining factor is the provision of acceptable mass, size and service life characteristics of closed-cycle gas turbine plant.

For the calculation, a scheme was chosen with the energy part and part of the conditioning of the living area (life support module excluding the production module) sequentially connected, which allows us to simplify the calculation scheme. The design scheme of a closed-cycle gas turbine plant is shown in Fig. 3.

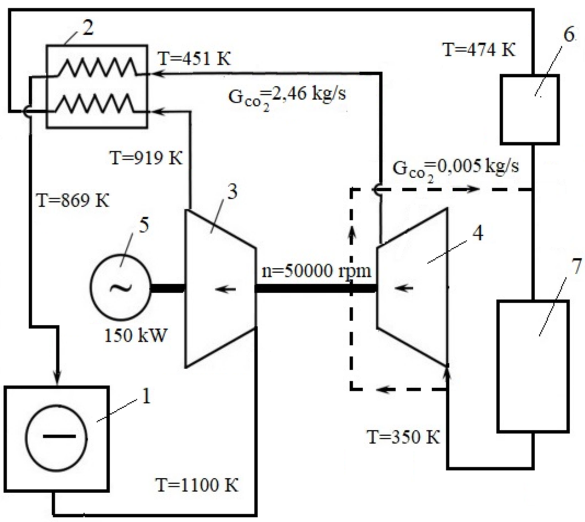


Fig. 3. The scheme of a closed-cycle gas turbine plant: 1-compressor; 2- turbine; 3- electric generator; 4-regenerator; 5-gas heater; 6 - gas cooler; 7- object for conditioning

The maximum gas temperature in front of the turbine isselected from the weight and size limitations and the capabilities of the gas heater (heat source). A closed-cycle gas turbine plants on radioisotope heat sources operate at temperatures of 1250 ° C and promising nuclear reactors make it possible to maintain the gas temperature at the turbine inlet in the range of 1100-1200K.

Decrease the temperature at the inlet to the compressor leads to increasing the efficiency and at the same time leads to an increase in the surface area of the gas cooler (size and total weight of the power plant). For operating and developing space power plants with a nuclear reactor of similar plant power the temperature T_1 is set in the range of 350-500 K.

The pressure ratio is selected not only from the power characteristics (the lower the unit power the lower the pressure ratio and vice versa), but also taking into account the thermophysical characteristics (thermal conductivity, molar mass, gas constant, specific heat) of the selected working fluid. In order to use the unique property of carbon dioxide (high heat transfer coefficient), it is necessary to choose the pressure ratio in the range 2.0-2.5, slightly higher compared to the helium cycle.

The initial data for the calculation are presented in Table 1.

Table 1

Initial data for the calculation

Parameter	Value
Power, *N*, kW	150
Shaft rotational speed n, prm	50000
Compressor pressure ratio, $\pi_к$	2,3
Temperature at the compressor inletT_1^*, К	350
Temperature at front of turbineT_3^*, К	1100
Gas constant of carbon dioxide,R_g,J/kgK	189
Adiabatic exponent of carbon dioxide, *k*	1,33
Compressor efficiency,η_c^*	0,80
Turbine efficiency,η_t^*	0,88
Mechanicalefficiency, η_m	0,98
Degree of regeneration, ε	0,95
Head coefficient, ψ	0,70

The operating temperature of the bearing is one of the most important factors determining the reliability and durability of its operation. Therefore, to maintain the required operating thermal state of the bearings, it is necessary to cool the working area. The gas lubricant temperature in the gap is kept constant [11].

Losses due to friction in hydrodynamic bearings, in the gaps between the rotor disks and housings, as well as ventilation during cooling of the stator by the working fluid are taken into account by the introduction of mechanical efficiency η_m.

Thermodynamic calculation of the main components (compressor, turbine, gas cooler, regenerator, air conditioning zone):

- compressor discharge temperature:

$$T_2^* = T_1^* \left\| 1 + \left(\pi^{\frac{k-1}{k}} - 1 \right) \frac{1}{\eta_c^*} \right\|;$$

- work done by the compressor:

$$L_c = c_p T_1^* \left(\pi^{\frac{k-1}{k}} - 1 \right) \frac{1}{\eta_c^*};$$

- turbinedischarge temperature:

$$T_4^* = T_3^* \left\| 1 - \left(1 - \pi^{\frac{k_g - 1}{k_g}} \right) \eta_t^* \right\|;$$

- expansion work of the fluid in turbine

$$L_t = c_p T_3^* \left(1 - \pi^{\frac{1-k_g}{k_g}} \right) \eta_t^*;$$

- the gas temperature at the outlet of the regenerator is determined by way of the degree of regeneration

$$T_2^* = T_4^* + \varepsilon \left(T_4^* - T_2^* \right);$$

- temperature at the inlet of the heat exchanger of a conditioned object

$$T_5^* = T_4^* - \Delta T;$$

- heat output of a heat exchanger of a conditioned object

$$q_{cob} = c_p (T_5^* - T_1^*);$$

- mass flow rate of carbon dioxide:

$$G = \frac{N}{L_t - L_c};$$

- the amount of heat supplied to the working fluid in the gas heater:

$$q_1 = c_p \left(T_3^* - T_2^* \right);$$

- thermal efficient of a closed-cycle gas turbine plant:

$$\eta_{th} = \frac{L_t - L_c}{q_1}.$$

Main compressor parameters:
- head coefficient:

$$\psi = \frac{L_c}{u_2^2};$$

- impeller tip velocity:

$$u_2 = \sqrt{\frac{L_c}{\psi}};$$

- the impeller diameter:

$$D_2 = \frac{u_2}{\pi n}.$$

Results of a closed-cycle gas turbine plant calculation are shown in Table 2

Table 2

Results of a closed-cycle gas turbine plant calculation

Parameter	Value
Compressor discharge temperature, K	451
Turbine discharge temperature, K	919
Gas temperature at the turbine inlet, K	1100
Gas temperature at the inlet to the object for conditioning, K	474
Heat supplied in regenerator, J/kg	338645
Mass flow rate of carbon dioxide, kg/c	2,46
Impeller tip velocity, m/s	331
Compressorimpellerdiameter, m	0,126
Cycle thermal efficiently	0,39

Thus, the performed studies have shown the fundamental possibility of creating gas turbine units with high values of thermal and electrical efficiency of closed-cycle units operating according to the Brayton cycle, in which carbon dioxide is used as a working fluid. High efficiency can be achieved due to the high degree of heat regeneration.

5. Conclusions

The data obtained as a result of the calculation are estimates, but despite that, they make it possible to justify the prospects of the chosen way to solve the problem of energy supply of a large colony with minimal costs for transportation, installation and long-term operation of the system.

In this regard, it should be noted that heat removal by radiation in a strongly reared atmosphere of Mars remains a rather difficult problem. Here the determining factors are the mass and size of the, radiating surfaces structure and their reliability (micrometeorites, dust, sudden temperature changes). Therefore, it is advisable to devote a separate study to this problem.

References

[1] Michael J. Swickrath, Molly Anderson. (2012). The Development of Models for Carbon Dioxide Reduction Technologies for Spacecraft Air Revitalization. Papers # AIAA 2012-3482, 19 p.

[2] Kogan I. L. (2015). Raschetno-eksperimental'nyy analiz raboty reaktora gidrirovaniya dioksida ugleroda [Kogan I. L. Precalculated and Experimental analysis of hydrogenation reactor operation]. Trudy MAI. №82, 23 p. (in Russian)

[3] Electric Power System Technology Options for Lunar Surface Missions / Thomas W. Kerslake // NASA/TM–2005–213629, 19 p.

[4] Power System Concepts for the Lunar Outpost: A Review of the Power Generation, Energy Storage, Power Management and Distribution (PMAD) System Requirements and Potential Technologies for Development of the Lunar Outpost / Z. Khan [et al.] // Proc. STAIF-2006. American Institute of Physics. Albuquerque, New Mexico. 2006, pp. 1083 – 1092.

[5] Arbekov A.N., Novitskiy B.B. (2014). Razrabotka maketnogo obraztsa kosmicheskoy zamknutoy gazoturbinnoy ustanovki [Development of a prototype of a multi-loop closedbrayton cycle gas turbine power system]. Vestnik of Samara universityaerospace and mechanical engineering, №5(47). (in Russian)

[6] Tournier J-M.P., El-Genk M.S. (2008). Alternative working fluids to reduce size of turbomachinery for VHTR plants // Intern. Congress on Advances in Nuclear Power Plants. ICAPP'08 (Anaheim, CA, USA, June 8-12, 2008): Proceedings. RedHook, Vol. 1, pp. 351–360.

[7] El-Genk M.S., Tournier J-M.P. (2007).Noble-Gas Binary Mixtures for Closed-Brayton-Cycle Space Reactor Power Systems // Journal of Propulsion and Power. Vol. 23. No. 4, pp. 863-873.

[8] Tournier J-M.P., El-Genk M.S. (2008). Transport properties of He-N2 binary gas mixtures for CBC space applications // Space Technology and Applications International Forum - STAIF 2008. Melville: AIP, pp. 637 – 647.

[9] Kochurov D.S., Schegolev N.L. (2016). Analiz vliyaniya sostava smesey na osnove geliya na koeffitsiyent vosstanovleniya temperatury i chislo Prandtlya [Investigating the Influence of Helium Based Mixtures Composition on the Temperature Recovery Factor and Prandtl Number Values]. *Aerospace Scientific Journal*; 2(6), pp. 26-48. (in Russian)

[10] Dostal V., Driscoll M. J., Hejzlar P., Todreas N. E. (2002). CO_2 Brayton Cycle Design and Optimization. Massachusetts Institute of Technology, MIT-ANP-TR-090.

[11] Adam Martowicz, Jakub Roemer, Michał Lubieniecki, Grzegorz Żywica, Paweł Bagiński (2020). Experimental and numerical study on the thermal controlstrategy for a gas foil bearing enhanced with thermoelectricmodules// Mechanical Systems and Signal Processing. Volume 138, p. 106581.

М.С. Кулик[1], Л.Г. Волянська[2], Ф.І. Кірчу[3]

Енергозабезпечення постійної марсіанської місії

Національний авіаційний університет, просп. Любомира Гузара, 1, Київ, Україна, 03058
E-mails: [1]kulykms@nau.edu.ua, [2]lvolia@nau.edu.ua, [3]fkirchu@gmail.com

В роботі розглянута концепція застосування установки замкнутого циклу для планетарної системи енергозабезпечення. Наведено аналіз актуальних наданий час проектів, що ведуться в області створення газотурбінних установок замкнутого циклу для енергозабезпечення космічних апаратів і автономних об'єктів, представлена загальна інформація про основні підсистеми енергетичних установок, що працюють по замкнутому циклу Брайтона. Показано, що газотурбінні установки із замкнутим циклом, маючи компактну і просту конструкцію, мають потенціал для підвищення ефективності вироблення електроенергії. Підсистеми установки, які забезпечують процеси теплового циклу: компресор, турбіна, джерело тепла, джерело холоду і рекуператор. Отже, потік робочого тіла виконує тепловий цикл, який перетворює теплову енергію в електричну енергію, яку можна використовувати в приміщеннях і різноманітних пристроях. Особливу увагу приділено обгрунтуванню вибору робочого тіла, фізико-хімічні характеристики якого істотно впливають на перебіг робочог опроцесу установки і визначають її основні характеристики. Наведено термодинамічний розрахунок одного з варіантів такої установки.

Ключові слова: цикл Брайтона; замкнута газотурбінна установка; діоксидвуглецю; ядерний реактор; рекуператор

Н.С. Кулик[1], Л.Г. Волянская[2], Ф.И. Кирчу[3]

Энергообеспечение постоянной марсианской миссии

Национальный авиационный университет, просп. Любомира Гузара, 1, Киев, Украина, 03058
E-mails: [1]kulykms@nau.edu.ua, [2]lvolia@nau.edu.ua, [3]fkirchu@gmail.com

В работе рассмотрена концепция применения установки замкнутого цикла для планетарной системы энергообеспечения. Приведен анализ актуальных в настоящее время проектах, ведущихся в области создания газотурбинных установок замкнутого цикла для энергообеспечения космических аппаратов и автономных объектов, представлена общая информация об основных подсистемах энергетических установок, работающих по замкнутому циклу Брайтона. Показано, что GT с замкнутым циклом имея компактную и простую конструкцию обладают потенциалом для повышения эффективности выработки электроэнергии. Подсистемы установки, выполняющие процессы цикла, это компрессор, турбина, источник тепла, источник холода и рекуператор. Следовательно, поток рабочего тела выполняет тепловой цикл, который преобразует тепловую энергию в электрическую энергию, которую можно использовать в помещениях и наземных устройствах. Особое внимание уделено обоснованию выбора рабочего тела, физико-химические характеристики которого существенно влияют на протекание рабочего процесса установки и определяют ее основные характеристики. Приведен термодинамический расчет одного из вариантов такой установки.

Ключевые слова: цикл Брайтона; замкнутая газотурбинная установка; диоксид углерода; ядерный реактор; рекуператор

Mykola Kulyk (1952). Dr. Sci. (Engineering)
Professor ofAviation Engines Department, National Aviation University
Education: Kiev, Institute of Civil Aviation Engineers (1978)
Research area: assessmentofthetechnicalconditionofaviationenginesandpowerplants
Publication: 260.
E-mail: kulykms@nau.edu.ua

Larysa Volianska (1950). Candidate of Technical Sciences,
Associate professorof Aviation Engines Department, National Aviation University
Education: Tula, Politekhnicheskiy Institut Tulgu (1972)
Research area: heat engines
Publication: 100.
E-mail: lvolia@nau.edu.ua

Fedor Kirchu (1980). Candidate of Technical Sciences,
Associate professor of Aviation EnginesDepartment, National Aviation University
Education: Kiev, National Aviation University (2003)
Research area: improvement of gas-dynamic stability of turbine engine compressors
Publication: 103.
E-mail: fkirchu@gmail.com