Study of Operation of Power and Propulsion System based on Closed Brayton Cycle Power Conversion Unit and Electric Propulsion

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Abstract: Expansion of near-Earth and deep space activity requires increasing spacecraft power and thrust level. For these missions the use of space vehicles based on high power nuclear system and electric propulsion is considered. One of the important tasks to be solved during nuclear powered space vehicles development is ground testing of whole system and its components. This paper presents a consistent approach both in logic and sequence to the power and propulsion system testing. System control features and system components joint operation and mutual influence on each other are also discussed.

Nomenclature

\[\begin{align*}
E &= \text{mismatch signal} \\
G &= \text{electrical conductivity} \\
j &= \text{number of current sampling increment} \\
J_z &= \text{axial moment of inertia} \\
K_d &= \text{differential PID-controller coefficient} \\
K_i &= \text{integral PID-controller coefficient} \\
K_p &= \text{proportional PID-controller coefficient} \\
n &= \text{rotational speed} \\
P &= \text{power} \\
R &= \text{electrical resistance} \\
r.u. &= \text{relative unit} \\
U &= \text{electrical voltage} \\
t &= \text{time}
\end{align*}\]

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I. Introduction

PROJECTS aimed at development and application of space vehicles based on nuclear power propulsion system (NPPS) of high power level have been conducted since the very beginning of space exploration Era. Interest to such projects arises as human activity in space grows. New NPPS projects continue to appear due to the development of new designs and technological solutions for the main parts and subsystems of NPPS with power level ranging from hundreds of kW up to tens of MW [1, 2, 3, 4]. One of the promising options is an NPPS consisting of a gas-cooled reactor, a closed Brayton cycle Power Conversion Unit (PCU) and an Electric Propulsion unit (EP) (see. Fig. 1) [2, 3, 5].

The main element of the closed Brayton cycle PCU is a turboalternator-compressor (TAC) – an assembly unit that combines:
- a turbine to convert the thermal energy of a heated in the nuclear reactor working fluid (inert gas or a mixture of inert gases) into the mechanical power of a rotating shaft;
- a compressor to provide working fluid circulation in the closed Brayton cycle with an appropriate pressure difference;
- an alternator to turn the excess mechanical power (the difference between the power generated by the turbine and the consumption power of the compressor) into AC electric power.

A heat exchanger-recuperator allows to increase the total efficiency of the conversion system by transferring the heat remaining in the working fluid at the turbine outlet to the working fluid at the inlet of the nuclear reactor. Heat exchanger-cooler passes the waste heat (which cannot be converted into electricity) to a heat radiation system that rejects the excess heat to the outer space.

Power Management and Distribution System (PMAD) distributes the electric power generated by the conversion system to a number of circuits with necessary voltage and current. Depending on the mission, the main power consumption system can be either the primary electric propulsion thrusters or the scientific payload.

![Figure 1. The scheme of the nuclear power and propulsion system based on closed Brayton cycle power conversion unit and electric propulsion](image-url)

AC electric power and PMAD parameters may be optimized for each particular mission. A detailed design development and the first experimental study of such NPPS had been done under “Prometheus” project on the base of a low power (2 kW) prototype [6]. An NPPS with a similar design scheme has been studied under DEMOCRITOS project performed in 2015-2017 under “Horizon 2020” Programme by the European Commission with the participation of Russian Space Agency (now State Corporation “ROSCOSMOS”). The DEMOCRITOS project was a continuation of a successful European-Russian project MEGAHIT [7, 8]. It was aimed at analysis of the experimental efforts necessary to demonstrate the NPPS MW-class technologies in the ground conditions [9].
II. Technical approach to experimental study of power and propulsion system based on closed Brayton cycle power conversion unit and electric propulsion

Development and application of high power level NPPS requires dedicated integration efforts aimed at studying of system components interaction, while each component itself is complicated enough. To identify the interaction specifics, each component or subsystem should be fully described via interface requirements.

In this case, EP thrusters as a load for PCU and PMAD can be characterized by a number of electric parameters: resistance, inductance and capacity. PMAD can be described as an electric power source with specified values of voltage, current and power. If the interface requirements are fully specified, then each subsystem may be tested separately and replaced by corresponding simulators for step-by-step integration tests. EP thrusters can be replaced by a set of resistors for PCU and PMAD tests, while for EP thrusters testing a set of commercially available electronic equipment may replace the PMAD.

An important feature of the PCU and PMAD system is a limited output power available for EP thrusters. Notably, the correlation between PMAD output current-voltage characteristic and EP operating parameters is an issue of critical importance because EP thrusters, as any plasma devices, could have abnormal regimes such as arcing, discharge instabilities or transient modes. Variation of EP thrusters regimes can influence PCU operation and may cause unstable performance of the entire power and propulsion system. For example, thruster switching off or significant drop of its power consumption results in difference of generated and utilized power in the TAC, and it leads to an uncontrolled increase in its shaft rotation speed. Increase of the rotation speed may cause a crash of the rotating parts or damage of the PMAD equipment due to a jump of alternator output voltage. Oppositely, an increase in thrusters’ power consumption may cause a decrease in TAC shaft rotation speed and a decrease in alternator and PMAD output voltage. A decreased PMAD output voltage may cause abnormal regimes of thrusters and result in unstable operation of the entire system.

The examples mentioned above show that the interaction of PCU, thrusters and PMAD system might cause abnormal operational regimes and even a failure of the system. In connection with the above, it seems best to conduct integration tests using a step-by-step approach, where only one part of the NPPS is tested simultaneously and the others are replaced with corresponding simulators. This approach allows to get experimental data to optimize logic and control algorithms during preliminary tests and minimize technical risks for following an entire system integration test. It is especially important for nuclear powered systems.

The considered approach to experimental study of the power and propulsion system [9] is described below (see the scheme in Fig. 2).

![Diagram](https://via.placeholder.com/150)

Figure 2. Approach and logic to experimental study of power and propulsion system based on closed Brayton power conversion cycle and electric thrusters
1) Autonomous tests of the closed Brayton cycle PCU, PMAD system and EP thrusters. These tests are conducted to check operation regimes of each component, control algorithms, simulate any abnormal and potential failure regimes.

For the autonomous tests of power conversion unit the following set of experimental equipment should be used:
- a thermal simulator of the nuclear reactor;
- a simulator of heat rejection system;
- an EP thruster simulator based on special controlled ballast resistors.

For the autonomous tests of PMAD the following simulators are necessary:
- a power conversion unit simulator providing electricity with required parameters of voltage and frequency;
- the EP thruster simulator mentioned above.

For autonomous tests of EP thrusters a number of DC power supplies simulating PMAD output parameters may be used.

2) Preliminary integration tests
The appropriate combinations of the tested system components with simulators of the other parts of the NPPS should be used, for example:
- a power conversion unit + PMAD + electric thrusters simulator;
- a PCU simulator (electronic or electro-mechanical type) + PMAD + EP thrusters.

The preliminary integration tests are meant to identify the mutual influence of the system components on each other, to specify time-resolution of the used control equipment, and imitate potential dangerous and abnormal regimes.

3) Integration tests of the entire power and propulsion system to verify the stability of the system in all operational regimes including thrusters switching on and switching off procedures, stationary and variable power regimes.

III. Features of the Control System for Power and Propulsion System based on Closed Brayton Cycle Power Conversion Unit and Electric Propulsion

To provide a stable EP operation it is necessary to maintain a proper value of voltage, generated by the PCU alternators and coming into PMAD equipment inputs.

The most considered type of TAC for closed Brayton cycle PCU assembly is a TAC including alternator with excitation by high-coercive permanent magnets located on the rotor [10, 11]. The advantages of the mentioned alternators are their high efficiency, high reliability and low weight due to a high magnetic power of the permanent magnets and absence of necessity in additional energy for excitation. The output voltage of this type of alternators is determined, first of all, by the rotor speed. As noted above, when EP thrusters or other electric power consumers switch on and off as well as when the mode of operation changes, the power balance in the TAC changes as well. This leads to a slowdown or an acceleration of its rotor and, as a consequence, to a decrease or increase in the electric voltage at the alternator output terminals. The voltage supplied by the PMAD equipment to the EP changes accordingly. An increased voltage can lead to a failure of the EP thrusters and PMAD equipment, and a low voltage can cause the thrusters to turn off.

Thus, maintaining the TAC shaft speed when changing the power mode of the connected electric load to provide the required voltage value is of main importance. Generally speaking, a stable TAC shaft speed can be achieved by the following two methods.

The first option is to regulate the PCU parameters, for example, to control the inlet turbine working fluid temperature by changing the power of the heat source, or bypassing a part of the working fluid between the turbine and the compressor, etc. The response time of this method of regulation is determined by the thermal inertia of the closed Brayton cycle power conversion unit and ranges from several seconds to several minutes. Therefore, this method can only be used with a smooth programmatic change in the operating modes of the EP or other electricity consumers.

The second method uses an adjustable parasitic load (PL) in the form of resistive elements connected to the electrical network in parallel with the EP thrusters (see Fig. 3). The response time of this method is determined by the response time of control equipment and PL switching devices and can reach fractions of seconds, which
allows to use it if it is necessary to change operating modes quickly, or for switching on and off the electric thrusters and other electricity consumers.

To execute the second method of the TAC shaft speed maintenance, the principle of changing the electric conductivity of add-on parasitic load according to the PID-controller law \[12\] can be used. According to the PID-controller law, the control signal of the parasitic load electrical conductivity at a given moment of time, \(G(t)\), is formed as a function of proportional, integral, and differential components of the mismatch signal \(E(t) = n_0 - n(t)\):

\[
G(t) = K_p (E(t) + K_i \int_0^t E(\tau)d\tau + K_d \frac{dE}{dt})
\] (1)

where \(n_0\) and \(n(t)\) represent the set and current values of TAC shaft speed; \(K_p, K_i, K_d\) are the proportional, integral and differential PID-controller coefficients respectively.

For use in algorithms of automatic control systems, the equation (1) can be represented in discrete form as follows:

\[
G(j) = G(j - 1) + K_p (E(j) - E(j - 1)) + K_i^{\text{discr}} E(j) + K_d^{\text{discr}} (E(j) - 2E(j - 1) + E(j - 2))
\] (2)

where \(j\) is the number of current sampling increment; 
\(K_i^{\text{discr}} = K_p K_i \Delta t\), 
\(K_d^{\text{discr}} = \frac{K_p K_d \Delta t}{2}\), here \(\Delta t\) is the time sampling increment.

The PID-controller coefficients can be determined from the results of mathematical simulation or from the experiments.

The parasitic load can be made in the form of \(z\) parallel-connected sections (see. Fig. 3), electric conductivities of which \(G=1/R\) are selected according to the law \(G_{i+1}/G_i=2\). This enables to create \(2^z\) stages of regulation with power step \(\Delta P=U^2G_1= U^2/R_1\).

The desired value of the control equipment and PL switching devices response time \(\Delta t\) (in seconds) can be calculated from the formula:

\[
\Delta t = 2\pi^2 J_z \frac{n_{\text{per}}^2 - n_0^2}{\Delta P}
\] (3)

where \(J_z\) is the axial moment of inertia of the TAC shaft, kg\(\cdot\)m\(^2\); 
\(n_{\text{per}}\) \& \(n_0\) are the maximum permissible and set values of the TAC shaft speed, s\(^{-1}\); 
\(\Delta P\) is the power step value, W.
IV. Experimental studies of the Joint Operation of Brayton Power Conversion Loop and Electric Propulsion

IV.A Test Bench for Experimental Studies

The experimental studies of the joint operation of the closed Brayton cycle power conversion loop and EP thrusters were conducted in the Keldysh Research Centre at the two test benches: the High-rpm Units Test Bench and the Electric Propulsion Test Bench. These two test benches are located in the adjacent rooms and connected by a high-voltage cable for electric power transmission.

The following assembly is located at the High-rpm Test Bench [13] (see, Fig. 4): the turboalternator-compressor established inside the chamber 1, the heat-exchanger recuperator 2, the heat-exchanger cooler 3 and the electric gas heater 4, which are joined into the closed Brayton power conversion loop by means of gas pipelines 5.

![Figure 4. High-rpm Units Test Bench](image)

Other technological equipment for preparing and carrying out the tests situated at the High-rpm Units Test Bench area includes:
- units of the vacuum system 6 for pumping the closed loop internal volume before filling it with the gaseous working fluid (argon);
- units 7 that remove the excess heat unused in the process of power conversion in the closed Brayton loop;
- equipment of the electric starting support system (SSS) providing the TAC rotor spin-up in the electric motor mode until its transition into power generation mode.

The turboalternator-compressor (see, Fig. 5) is the key element of the Brayton power conversion loop. It consists of a centrifugal compressor 1, a centripetal turbine 2 and a 3-phase synchronous permanent magnets alternator 3. The TAC shaft is rotated in radial and axial gasdynamic foil bearings. This type of bearings provides long-term (hundreds and thousands of hours) operation at high shaft speeds (tens of thousands rpm) without any additional lubrication system. During operation the TAC is located inside the chamber (see Fig. 4 pos. 1), in which, if necessary, the protective atmosphere (inert gas or vacuum) can be created to protect the structural materials from oxidization at high temperatures. Besides, the chamber walls act as a physical barrier for the high-speed flying elements in case of TAC shaft damage.

![Figure 5. Turboalternator-compressor](image)
The gaseous working fluid of the Brayton power conversion loop is heated by an electric gas heater of ohmic type (see Fig. 6) [14], simulating a reactor. Heating is carried out in the internal cavity while the working fluid flows through the tubes of refractory material, through which runs the electric current. The outer case of the heater is water-cooled. To minimize the heat leakages, metal screens and high-temperature insulation layers are installed between the outer case and the inner cavity.

Utilization of the generated electricity and maintenance of the required TAC shaft speed is carried out by using the controlled parasitic load of ohmic type. The PL sections switching on and switching off is performed according to the PID-controller law (see Chapter III above) formulated for the control system [15].

Monitoring and registration of the Brayton power conversion loop parameters (temperatures, pressures, working fluid flow rate, TAC shaft speed, vibrations etc.) as well as a remote control of tests modes is carried out with the help of the automated system, that is built on the basis of high-performance analog-to-digital converters and personal computers.

The PMAD equipment used in the investigation included:
- a 3-phase step-up transformer;
- a rectifier for conversion of the 3-phase AC voltage generated by the TAC alternator and stepped up into DC voltage of up to 4500 V by the transformer.

The DC voltage is supplied from the PMAD rectifier to the EP test bench by a high-voltage cable.

The main element of the Electric Propulsion Test Bench is the Cryogenic Vacuum Facility CVF-90 (see. Fig. 7). CVF-90 is equipped with the vacuum chamber with the diameter of 3.8 m and volume of 90 m³, the cryogenic pumps, control and power supply systems [16]. The CVF-90 vacuum pumping system parameters allow testing different types of EP thrusters with the power level of up to 35 kW.
The ion thrusters (IT) IT-200 with the power of up to 5 kW and IT-500 with the power of up to 35 kW (see Fig. 8) designed in Keldysh Research Centre [17, 18] were used during these studies.

The propellant (gaseous xenon) is fed from the bench systems to the ion thrusters via the flow-rate control unit.

A DC voltage is supplied from the PMAD rectifier to the ion thrusters via a switching unit, which also provided electrical circuit and equipment protection in case of long-term electrical breakdowns in the ion-optical system.

The IT parameters (xenon flow rate, currents and voltages) as well as the input and output electrical parameters of the PMAD equipment were monitored and automatically recorded in the course of studies.

**IV.B The studies sequence and obtained results**

Before conducting the studies of joint operation, autonomous tests of the Brayton power conversion loop, PMAD equipment and IT were carried out. During these tests the following tasks were completed:

- the parameters of the automatic PL controller were set up and its operation to maintain TAC shaft speed when connecting or disconnecting the parasitic load sections simulating the EP switching procedures was checked;
- the operation of the ion thrusters powered by the bench high-voltage DC supply was checked;
- the performance of the PMAD equipment and the high-voltage circuits switching unit was checked.

The experimental studies of the joint operation of the Brayton power conversion loop and electric propulsion were conducted in two stages (see. Fig. 9):

- **Stage 1** - integration tests of the PMAD equipment and the ion thrusters powered by the PCU simulator;
- **Stage 2** - tests with the generation of electricity in the closed Brayton power conversion loop with the PMAD equipment and ion thrusters connected.

In the course of Stage 1 the PCU simulator (see Fig. 10) based on Electric Motor – Alternator (EMA) was used as an electricity source for the PMAD equipment and ion thrusters. The EMA is an electric machine, in which an electric motor and an electric alternator are combined into a single structure with individual stator coils and a common rotor. The EMA rotor spins in gasdynamic foil bearings with a speed corresponding to the rotational speed of the TAC shaft of the closed Brayton power conversion loop. The stator coils of the EMA motor are connected through the converter to an industrial electrical network, and the mechanical energy of the rotor is converted into electricity in the EMA alternator. This type of electromechanical simulator unlike, for example, static converters made on the basis of width-pulse modulation, provides the AC electricity supply to the

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**Figure 8. Ion thruster IT-500**

**Figure 9. Study schematic**
PMAD equipment with parameters, which are identical to the parameters of the electricity generated by the TAC during the operation of the Brayton PCU. At the same time, unlike the TAC, the rotational speed of the EMA rotor is constant at loads switching on and off. This allows to study the joint operation of the PMAD equipment and electric thrusters without the influence of additional effects caused by AC frequency and voltage changes.

At the Stage 1 using the PCU simulator the following tasks were completed:
- the PMAD and the switching unit operation was tested with a resistive load simulator substituting for ion thrusters (see Fig.8); during the test periodically occurring breakdowns in the ion-optical system were simulated with IT high-voltage feed circuit artificial failures of various durations;
- the duration of the transition processes and AC and DC currents and voltages behavior (at the PMAD inlet and outlet respectively) were determined upon the ion thrusters switching procedures;
- the possibility of stable operation of the PMAD equipment with both a single thruster and a cluster of two ion thrusters (see. Fig. 11) was demonstrated.

At the Stage 2, power generation was carried out by the TAC of the closed Brayton power conversion loop. To exclude the processes that may occur during the operation of the cluster of several simultaneously operating thrusters [19, 20] causing an influence on the operation of the closed Brayton power conversion loop and the PMAD equipment, only one thruster ID-200 was used.

The transition to the electric power generation mode was carried out during the rotation of the TAC shaft from the SSS equipment, while gradually increasing the working fluid heating temperature at the turbine inlet. After the transition to the electric power generation mode, the SSS equipment was automatically switched off, and the PL sections were automatically switched on. The increase in electric power to the level necessary for the EP operation was carried out by increasing the working fluid heating temperature at the turbine inlet up to 1150 K.

A cyclogram of the joint operation of the Brayton power conversion loop and the ion thruster included the following modes typical for space PPS operation (see. Fig. 12): thruster switching on, steady-state operation, operation with thruster power change (then with a corresponding xenon mass flow rate change), thruster switching off. The thruster was also switched on and switched off again, followed by a thrust measurement.
Before the thruster switching on, the parasitic load utilizes all electric power, generated by TAC alternator. At the moment of the thruster switching on a stepwise increase in the power connected to the TAC alternator occurs. It causes the TAC shaft to slowdown (see. Fig. 13 a; hereinafter the time stamps correspond to the cyclogram in Fig. 12). The PL-controller based on the difference between the required and the current TAC shaft speed (see. Chapter III) decreases the electrical conductivity and the power of the connected parasitic load sections until the TAC shaft speed slowdown stops. With the beginning of the growth of the TAC rotor speed, the PL-controller gradually increases the electrical conductivity and the power of the connected parasitic load sections until the set TAC shaft speed is reached. Thereafter, the electrical conductivity of the connected parasitic load sections is maintained at the level where the total power of the thruster and connected PL are equal to the power generated by the TAC alternator.

Figure 12.  Ion thruster current and DC voltage changing (hereinafter the parameter values along ordinate axis are given in dimensionless relative units, r.u.)

Figure 13.  TAC shaft speed and parasitic load conductivity change at the thruster switching on and off
At the moment of thruster switching off, a stepwise decrease in the power connected to the TAC alternator occurs. It causes the TAC shaft to speed up (see, Fig. 13b). The PL-controller increases the electrical conductivity and the power of the connected parasitic load sections until the TAC shaft speed-up stops. With the beginning of the slowdown of the TAC rotor speed, the PL-controller gradually decreases the electrical conductivity and the power of the connected parasitic load sections until the set TAC shaft speed is reached. Thereafter, as in case of the thruster switching on, the electrical conductivity of the connected parasitic load sections is maintained at the level where the total power of the thruster and connected PL are equal to the power generated by the TAC alternator, thus providing the stability of TAC shaft speed. The charts in Figure 14 illustrate the operation of the parasitic load controller to maintain the TAC shaft speed when thruster’s power changes.

The data in Figures 13 and 14 show the acceptable efficiency of the implemented method of the TAC shaft speed maintenance using a controlled parasitic load. So, upon thruster’s switching on and off at the electric power level of around 50% of the generated by the Brayton power conversion loop, the initial deviation of the TAC shaft speed from the set value did not exceed ±10%, and the time needed to restore the set TAC shaft speed never exceeded two minutes limit. When thruster power changes, the deviation of the TAC shaft speed from the set value does not exceed ±3%, and at the steady-state conditions – ±0.5%. The DC voltage supplied by the PMAD equipment to the thruster also changes within these limits.

Analysis of the oscillograms in Figure 15 reveals the slight increase of the phase angle between voltage and current (current lags voltage) when IT power increases. This indicates the inductive nature of the load in the IT electrical feed circuit, that should be taken into account in PMAD system design.

Figure 14. Parasitic load power, TAC shaft speed and thruster power
Carried out studies demonstrated the possibility of stable joint operation of the closed Brayton cycle power conversion loop, PMAD equipment and Ion thruster (see. Fig. 16) both at steady and transient modes, including thruster switching on and off.

The proposed method of maintaining the rotational speed of the TAC shaft and the voltage of the generated alternating current by means of an adjustable parasitic load showed its effectiveness and did not make any additional features to the operation of the IT and PMAD equipment.

Figure 15. Oscillograms of currents and voltages in the electric circuit at the TAC alternator output

V. Conclusion

High power level NPPS development and application require mutual coordination of their main components (a closed Brayton cycle power conversion unit, an electric propulsion unit, power management and distribution equipment) operation. These components are represented by very complex technical systems, which could mutually influence each other during NPPS operation. Such an influence should be properly taken into account, otherwise it could lead to NPPS unstable operation.
In this regard, during experimental studies it is advisable to conduct a sufficient amount of preliminary integration tests using functional simulators of power conversion unit and electric propulsion thruster. Experimental data obtained during these tests, including possible mutual influence of components, allow to optimize control’s logic, procedure and sequence of the joint operation of the NPPS components, and to minimize technical risk of an incident or emergency appearing during tests. It is especially important when carrying out the experimental studies of high power level nuclear powered propulsion systems.

References


