OPEN-CYCLE MULTI-MEGAWATT MHD SPACE NUCLEAR POWER FACILITY

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The results of calculations of the characteristics and development of a scheme and technical make-up of an open-cycle space power facility based on a high-temperature nuclear reactor for a nuclear rocket motor and a 20 MW Faraday MHD generator are presented. A heterogeneous channel-vessel IVG-1 reactor, which heated hydrogen to 3100 K, with the pressure at the exit from the reactor core up to 5 MPa, burn rate 5 kg/sec, and thermal power up to 220 MW is examined. The main parameters of the MHD generator are determined: Cs seed fraction 20%, stopping pressure at the entrance 2 MPa, electric conductivity ≈30 S/m, Mach number ≈0.7, magnetic induction 6 T, electric power 20 MW, specific energy extraction ~4 MJ/kg. The construction of the scheme of a MHD facility with zero-moment exhaust of the working body and its main characteristics are presented.

The growth of the required electric power of space power systems up to 20–100 MW is due to the prospects of using in space vehicles the propulsion power motor modules based on electric rocket (magnetoplasma) motors and (or) users with forced short-time operating regimes [1–6]. The optimal choice of the primary energy and the type of energy system is determined by its purpose (target function) as part of the space vehicle. The efficiency may not even be one of the determining parameters. The multi-megawatt level of the electric powers of the space power facility can be achieved by using machine (gas- or steam turbine systems) as well as machine-free (fuel cells, thermionic converters, MHD generators) energy converters [1–3, 6–10].

It is known that MHD energy and momentum converters can be used as part of the power propulsion systems as on-board systems for multiple-regime multi-megawatt electricity supply and MHD accelerators [6–8, 11]. The development of up to 1000 MW(e) MHD generators based on chemical fuel with pulsed (up to 10 sec) and short-time (100–1000 sec) action does not present any great difficulties [12–14]. Ground-based prototypes of such MHD generators already reach power levels up to 500 MW(e) with specific “dry” mass up to 0.1 ton/MW, energy conversion coefficient up to 15%, and power density up to 600 MW/m³. However, the specific energy extraction in them does not exceed 1 MJ/kg, which requires a substantial working-body mass in order to obtain a large amount of electric energy on-board.

Energy facilities based on nuclear reactors, including with different types of MHD generators, are promising for solving space problems [2, 4–7, 15–17].

For powerful space nuclear energy facilities operating for a long time (≥1 yr), it is desirable to consider the possibility of using a closed cycle based on heterogeneous gas-cooled reactors and MHD generators based on nonequilibrium plasma [10, 18]. In this case, it is sufficient to have a working-body (inert gas) temperature at the level 2000 K, which will make possible a gas-dynamic channel with a long service life. Stationary MHD generators based on nonequilibrium plasma are at the experimental-research stage. This experimental work might make it possible reach energy conversion efficiency up to 20% (30–40% in the future) [19]. The development of stationary high-temperature nuclear reactors with coolant temperature 2000 K and service life ≥1 yr will require a large volume of research work, large amounts of materials, and a long time.
An open-cycle space power system based on high-temperature nuclear reactors, developed for nuclear rocket motors, and MHD generators based on equilibrium plasma may turn out to be, based on all their characteristics and functional possibilities taken as a whole, optimal for obtaining multi-megawatt electric power and energy with total operating times of several or tens of hours [1, 3–5, 9, 11]. The advantages and drawbacks of power systems of this type are well known.

The working body of the power facility is hydrogen, whose enthalpy is 10 times greater than that of the products of combustion. Estimates show that when hydrogen is used together with an easily ionizing seed (cesium, potassium) the specific energy extraction in the MHD channel can be increased to 5 MJ/kg. The hydrogen temperature reached in American reactors for nuclear rocket motors is 2500 K, which does not permit obtaining adequate equilibrium electric conduction of the flow of the medium $H_2 + Cs$ [1, 3, 5]. Consequently, the conceptual and design work on space MHD facilities with such reactors (NERVA type) is based on the possibility of creating molecular nonequilibrium hydrogen-cesium plasma, which is problematic [1, 5].

Domestic experimental and test samples of a high-temperature nuclear reactor for nuclear rocket motors give hydrogen temperatures up to 3100 K [3, 15, 18]. Such a temperature makes it possible to obtain equilibrium electric conduction of the flow of the mixture $H_2 + Cs$ or $H_2 + KNa$ which is adequate for efficient MHD-conversion of energy. The level of MHD technologies will enable successful technical realization of an open-cycle MHD facility with a high-temperature nuclear reactor and a MHD generator.

The purpose of the present work is to propose a structural scheme, the technical make-up, and the integral and specific characteristics of a 10–30 MW(e) power facility based on nuclear and MHD technologies. The schematic diagram of an open-cycle MHD system based on a high-temperature nuclear reactor and a MHD generator is well known and is extremely simple (Fig. 1) [9, 10]. The basic scheme consists of a nuclear reactor for the nuclear rocket motor and a linear Faraday MHD generator using equilibrium hydrogen plasma seeded with cesium. It is proposed that a reactor for the nuclear rocket motor with characteristics close to the experimentally completed IVG-1 reactor with thermal power reaching 220 MW(t) be used as the high-temperature nuclear reactor for the MHD system [3, 15, 20]. A prototype of a cooled Faraday MHD generator is a short-time action MHD generator using products of combustion of hydrogen in oxygen seeded with cesium or a sodium-potassium eutectic [16]. Since the efficiency of MHD generators using equilibrium plasma and a linear channel is now ≥10%, the electric power of the system will be ≥20 MW(e) [12, 13].

The basic initial data for the development of a MHD facility are as follows:

- Thermal power of the reactor, MW(t): ≤200 (refined by calculations)
- Main working body: $H_2$
- Seed: Cs or K
- Gas temperature at the exit of the reactor, K: ≤3100
- Gas pressure at the exit of the reactor, MPa: <5
- Electric power of MHD generator, MW: ≥20
- Operating regime: Repetitive–short-time, (quasi)stationary

![Fig. 1. Schematic diagram of an open-cycle nuclear power facility with a MHD generator: 1, 3] reservoir (tank) with liquid hydrogen and cesium, respectively; 2) reactor; 4) nozzle; 5) MHD channel; 6) magnetic system; 7) exit cone or nozzle in a propulsion power system.