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Investigation of the high-voltage plasma thermionic diode electrical power dependence on the thermophysical parameters and the type of working fluid

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*The development of high-temperature current conversion systems based on plasma electric power devices, such as grid key elements and high-voltage plasma thermal emission diodes (*HVPTD*) is an urgent task in connection with the development of powerful nuclear power propulsion systems of spacecraft. The paper presents the results of studyingf the dependence of the specific electrical power of* HVPTD *on the thermophysical parameters of the filler of the interelectrode gap: its temperature and pressure, and also shows the dependence of the power of the* HVPTD *on the materials used for the manufacture of electrodes. The dependences of the specific electric power in the SDA as a function of temperature (anode and emitter) and vapor pressure of Caesium and binary mixture are obtained. Expediency of using binary filling in traffic regulations with a tungsten emitter to increase its specific electrical power is shown.*

Keywords: *thermionic diode, breakdown voltage, emission current, specific power, electrode materials, Caesium, Barium, binary mixture*

Introduction. Currently, special attention is paid to the development of high-power nuclear power plants (NPS) based on thermoemission converter reactors (TCR) [1, 2] and the improvement of the CCS [3] in order to harmonize the output electrical parameters of the TCR and the electric rocket propulsion system (ERPS).

The use of nuclear power plants is an alternative solution when designing spacecraft for long-range missions, coupled with the impact of negative factors of both outer space and nuclear power plants [4]. These, first of all, include ionizing radiation and high-temperature heat flows emanating from the TCR. Under these conditions, the mass and energy efficiency of the use of CCS based on semiconductor materials decreases [2, 4]. The use of a semiconductor base requires additional protection from ionizing radiation, which reduces the possible payload of the spacecraft. In order to ensure the required temperature mode of operation of a semiconductor electronics-based CCS, it is necessary to use refrigerating machines and the use of a refrigerator-radiator (RR) of considerable size [3, 4].

The use of plasma electric power devices eliminates additional protection from radiation and ionizing radiation, and the high operating temperature of thermal emission devices allows reducing the size of the RR and placing the conversion elements themselves in close proximity to the TCR [5]. All these advantages of high-temperature CSS indicate the relevance of the study of the features of their functioning.

The aim of the work is to theoretically determine the power of a high-voltage plasma thermionic diode at various thermophysical parameters of the system and to make a number of recommendations based on the results obtained.

Calculation method. To determine the dependence of the specific electrical power on the pressure of saturated Caesium vapor in the interelectrode gap (IEG) high-voltage plasma thermal emission diode by the formula:

$$P_{sp}(p_{\mathrm{Cs}}) = j_p U_b, \tag{1}$$

here j_{p} is thermal emission current density from the cathode, A/cm^2;

U_b is reverse arc breakdown voltage IEG, V.

The density of the thermal emission current can be calculated according to the Richardson — Deshman law [6, 7, 8]:

$$j_p(p_{\mathrm{Cs}}, T_E) = A \cdot T_E{}^2 \cdot \exp\left(-\frac{e \cdot \varphi_E(p_{\mathrm{Cs}}, T_E)}{k \cdot T_E}\right), \tag{2}$$

here T_E is emitter temperature, K;

$A = 120.4$ A/(cm^2·K^2) is Sommerfeld constant [8];

e = $1.6 \cdot 10^{-19}$ Kl is electron charge;

$\varphi_E(p_{\mathrm{Cs}}, T_E)$ is efficient operation of the emitter output in Caesium vapor, eV;

$k = 1.38 \cdot 10^{-23}$ Dg/K is Boltzmann constant.

The data of S-shaped Raiser curves are used in the work [1], which characterize the emissivity of the emitter surface from the degree of its coating with Caesium atoms. Figure 1 shows a typical *S*-shaped curve for low values of Caesium vapor pressure in IEG HVPTD.

The optimal value of the current density (Figure 1) corresponds to a low-temperature extremum on an *S*-shaped curve, and can also be selected on a high-temperature section of this curve. Based on these conditions, it is possible to choose two temperature modes of the emitter with the same current density. Note that HVPTDS with a current density of at least 1 A/cm^2 are technically feasible.

The operating voltage of HVPTD is usually 0.8…0.9U_b [9], therefore, to determine the specific electrical power, it is possible to use the value of the reverse arc breakdown voltage IEG, calculated by the formula presented below [9] or taken from experimental data:

$$U_b = \left[\frac{\chi_{ar}{}^2 m_{Cs}}{\varepsilon_0 k e} \cdot \frac{1}{n_a} \cdot (T^{cr}(d_K) - T_a(0))\right]^{1/3}, \tag{3}$$

here χ_{ar} is coefficient of thermal conductivity taking into account the reactive component, W/(m·K) [10];

$m_{\mathrm{Cs}} = 2.21\cdot10^{-21}$ kg is the mass of Caesium atoms [11];

$\varepsilon_0 = 8.85\cdot10^{-12}$ F/m is dielectric constant;

n_a is concentration of neutral atoms, 1/m^3;

$T^{cp}(d_K)$ is the critical temperature of atoms in the ion layer at the moment of ignition of an independent arc discharge, K;

$T_a(0)$ is temperature of Caesium vapor atoms in IEG, K.

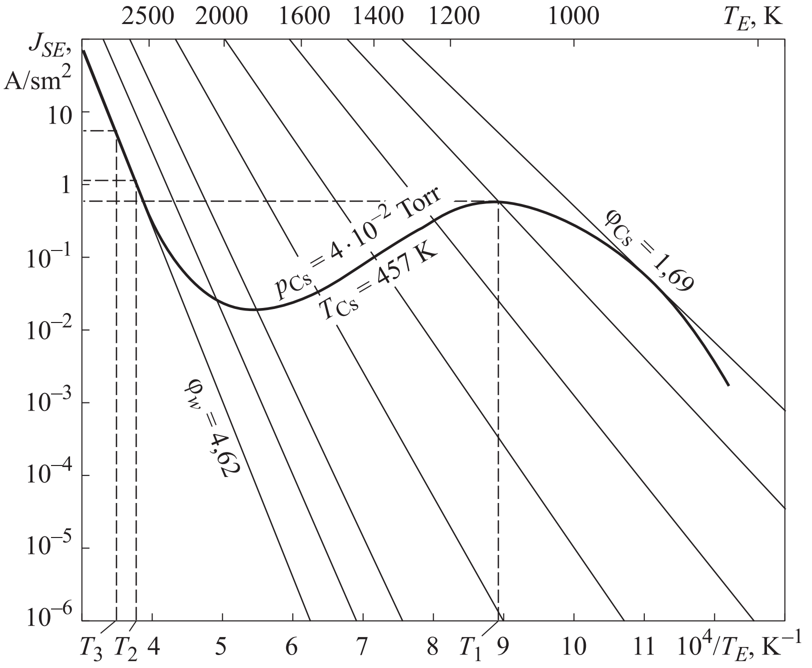

Figure 1. *S*-shaped curve for a tungsten cathode in cesium vapor at a temperature of 457K

The paper considers a method based on experimental data on the critical density of the reverse current HVPTD at the pre-breakdown moment and the dependence of the breakdown voltage on the pressure of saturated cesium vapors presented in [9]. The experimental data of [9] concerning the breakdown voltage are shown in Figure 2.

The Caesium vapor pressure can be determined by the formula [6, 7, 12]

$$\lg(p_{\mathrm{Cs}}) = 6.78 - \frac{3740}{T_{Cs}}. \tag{4}$$

The calculation of the thermal emission current density was carried out according to (2), taking into account the emitter material. Tantalum, molybdenum, tungsten and rhenium are considered as the emitter material. The effective operation of the output is determined by the dependence (5)

[7, 13] for the Reiser parameter $T_E/T_{\mathrm{Cs}} > 2.7$; which corresponds to the conditions of the problem under consideration (the corresponding coefficients in (5) are taken from [7] and are given in Table 1).

$$\phi_E(p_{Cs}, T_E) = \phi_1 + \phi_2 \cdot \frac{1}{1 + \exp\left[\dfrac{\beta \cdot T_{Cs}}{T_E} - \alpha\right]}, \tag{5}$$

here φ_1, φ_2, β, α is the dimensionless coefficients presented for the studied materials in table 1;

T_E is emitter temperature, K;

T_{Cs} is temperatures of the cesium tank, K.

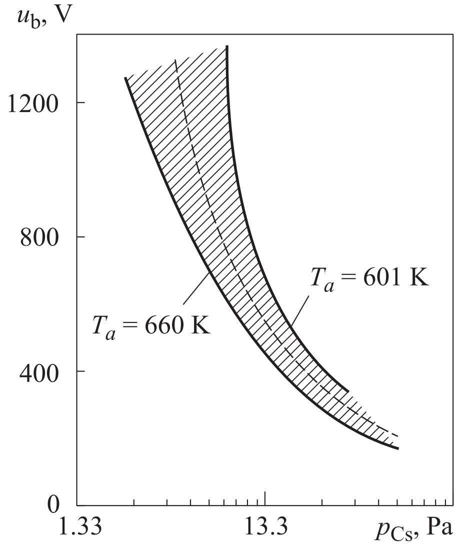

Figure 2. Experimental graph of voltage dependence $U_b(p_{\mathrm{Cs}})$ [9]

Table 1

Coefficients for determining the effective operation of the outputs of the studied materials

Ratio	Renius	Tungsten	Molybdenum	Tantalum
φ_1	1.57	2.08	2.15	1.86
φ_2	3.57	2.48	2.35	2.44
α	5.63	11.76	10.76	11.15
β	20.89	40.77	37.83	36.75

Calculation results and their analysis. The results of calculating the emission characteristics of HVPTD emitters are given in Tables 2 and 3.

Based on the calculated results of emission characteristics and breakdown voltage, the specific electrical power HVPTD is determined as a function of the pressure of Caesium vapor in the interelectrode gap (Figure 3).

Table 2

Efficient operation of the HVPTD emitter output at different temperatures of the cesium tank

Calculation conditions			φ_E, eV			
$p_{Cs}\cdot 10^{-2}$, torr	T_{Cs}, K	T_E, K	Renius	Tungsten	Molybdenum	Tantalum
4	$4.57\cdot 10^2$	2570	4.08	4.68	4.53	4.46
5	$4.63\cdot 10^2$	2600	4.07	4.68	4.53	4.46
8	$4.70\cdot 10^2$	2600	3.93	4.64	4.53	4.46
9	$4.78\cdot 10^2$	2630	3.96	4.65	4.53	4.46
10	$4.81\cdot 10^2$	2680	4.03	4.67	4.53	4.46

Table 3

The density of the thermal emission current from the emitter.

Calculation conditions			j_p, A/sm^2			
$p_{Cs}\cdot 10^{-2}$, torr	T_{Cs}, K	T_E, K	Renius	Tungsten	Molybdenum	Tantalum
4	$4.57\cdot 10^2$	2570	$5.37\cdot 10^{-1}$	1.05	1.46	3.33
5	$4.63\cdot 10^2$	2600	$7.02\cdot 10^{-1}$	1.36	1.89	4.26
8	$4.70\cdot 10^2$	2600	$8.39\cdot 10^{-1}$	1.39	1.95	4.35
9	$4.78\cdot 10^2$	2630	1.05	1.78	2.49	5.50
10	$4.81\cdot 10^2$	2680	1.46	2.65	3.66	8.04

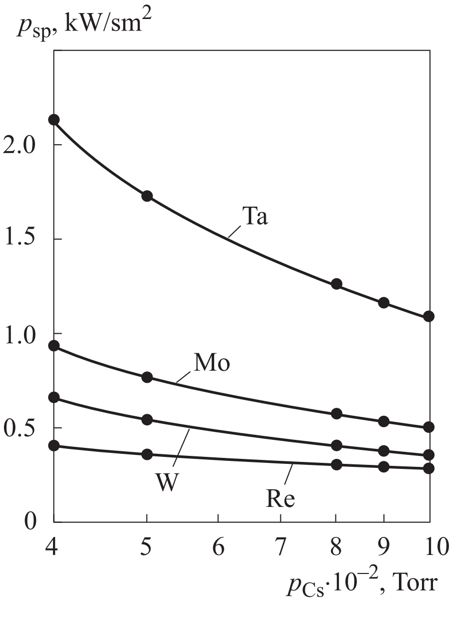

Figure 3. Dependence of the specific electrical power HVPTD on the pressure of saturated Caesium vapors for emitters made of different materials at their constant temperature $T_E = 2500$K

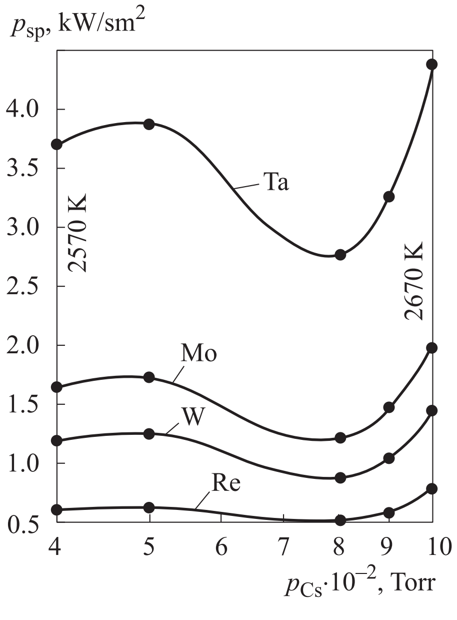

Figure 4. Dependence of the specific electrical power on the pressure of Caesium vapor for cathodes made of different materials at their optimized temperatures

Calculations have shown that at low Caesium pressures, the density of the thermal emission current of the HVPTD emitter is almost constant, the form of the resulting dependence is similar to the dependence of the $U_b(p_{Cs})$. This is due to the fact that at high emitter temperatures, the effective operation of the output is weakly dependent on the vapor pressure of Caesium in IEG and is close to the effective operation of the output of pure metal. And, as a consequence, the specific power of HVPTD varies similarly to the dependence of its breakdown voltage, see Figure 2.

Figure 4 shows a graph of the dependence of the specific electrical power on the saturated vapor pressure at a density-optimized HVPTD emitter temperature.

It can be seen from the graphs (see Figure 4) that tantalum is the best of the emitter materials under consideration, and for the most common tungsten emitter in thermal emission electronics, the specific electrical power of HVPTD is 1.5 kW/cm^2, which is three times lower than that of HVPTD with a tantalum emitter.

Binary mixture of gases. In order to increase the specific electrical power of HVPTD with a tungsten emitter, within the framework of this work, the emission characteristics in the case of binary (Caesium–Barium) IEG filling were studied. Using the data [9, 14], three characteristic values of the emitter output from Barium vapor pressure were selected, which can be seen in Table 4.

Table 4

The work of the output of tungsten in barium vapor [9, 14]

φ_1, eV	φ_2, eV	φ_3, eV
2.5	2.8	3.0

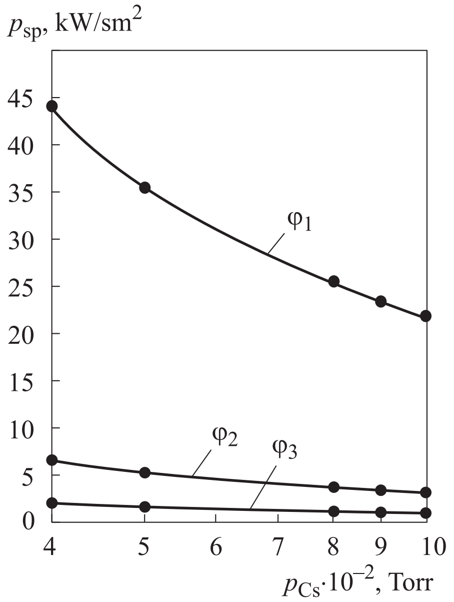

Figure 5. The dependences of the specific electrical power on the pressure of the binary mixture of gases for the three output works under consideration

The densities of the thermal emission current from the emitter were determined similarly to the first part of the work at the emitter temperature adopted according to the recommendation [7] 1800 K. Breakdown voltages of IEG HVPTD were taken according to Figure 1, as for HVPTD with Caesium filling.

The results of calculating the specific electrical power of HVPTD with binary filling are shown in Figure 5 (the mass fraction of barium is from 1% to 5% of the mass of the mixture).

Conclusion. The results of the computational study showed that there is a pronounced maximum of the dependence of $P_{sp.}(p_{Cs})$, which can be used to optimize the operation of the HVPTD. In addition, it was shown that with the cesium filling of the IEG, the use of a tantalum emitter allows for a significant gain in the power of the HVPTD, and the use of binary cesium-barium filling is the most effective solution when designing a HVPTD with a power of more than 10 kW with a tungsten emitter.

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