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The Concept of the Combined Thermal Protection System for Leading Edges of Hypersonic Vehicles with Use of Thermionic Emission

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Abstract

This work represents a conceptual stage of the project on development of technology of the combined thermal protection system for hypersonic vehicles heat-stressed surfaces with use of technology of the thermionic power cell and thermal protection system with an external emission of electrons. The relevance of this work is to develop thermal protection system technology for aircraft, enabling prolonged controlled flight at hypersonic speeds, while providing low aerodynamic resistance and relative weight, the consistency of the geometric shape of the hypersonic vehicles leading edge. The various using types of thermal protection system are compared and the necessity to develop a new type of it using the effect of thermionic emission of electrons is proved. The scheme and the possible material composition of thermionic power cell with a reversed geometry of the electrodes are given. The problem of the choice of material for emission surface of the system with external electron emission and its manufacturing technology are discussed. Using cesium intercalated graphite as one of the possible coating materials is reviewed. A sequence of forthcoming studies is formulated at the stage of transition to the design basis for the operation of thermal protection of this type.

Keywords: thermionic emission, hypersonic vehicles, thermionic thermal protection system, thermionic power cell, thermionic energy converter, electron work function, heat-stressed surfaces, heat management problem, electron transpiration cooling.

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1. Introduction

The hypersonic vehicles (HSV) call the aircraft capable of performing an aerodynamic flight with a speed equal and higher than 5 M (M = M= $\frac{V_{vehicles}}{V_{sound}}$ where V-speed). Researches in this area involve a number of technical problems, which require innovative approaches and technologies.

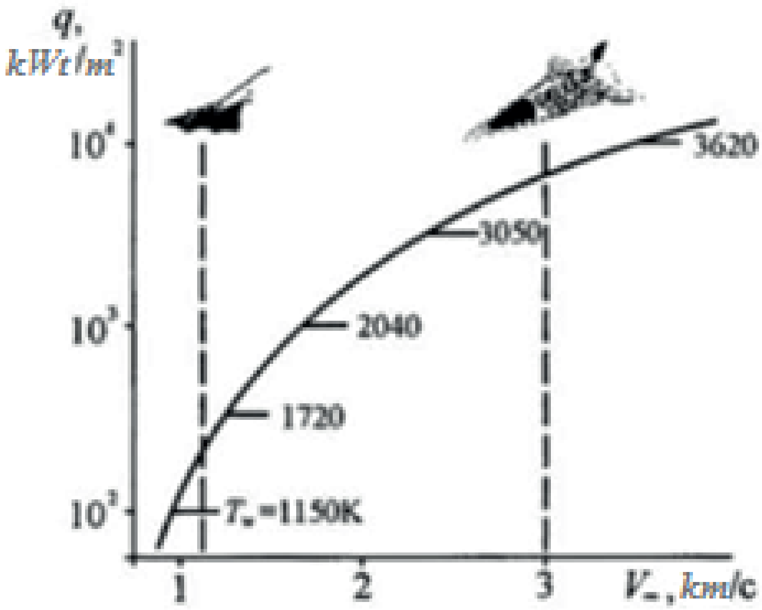

Figure 1: Dependence of density of a heat flux and surface temperature on the speed of flight of the aircraft.

Key problem of HSV design is aerodynamic heating and the related problem of heat management and heat rejecting from heat-stressed structural elements like leading edges. Therefore this problem leads to the need to equip the vehicles of the thermal protection systems (TPS).

Another important task is the need to provide the device with a compact, sufficiently powerful, autonomous power source that is resistant to temperature fluctuations and which allows the onboard systems to function. Existing thermal protection systems of aircrafts are unable to maintain the surface temperature of heat-stressed elements in the range meeting the requirements of strength and heat resistance (”hot circuit”, porous TPS, a convective circuit) or have unsuitable geometric and mass dimensions (ablation protection) [1,4], as shown in Figures 1-2.

2. Materials and methods

In this regard, considers the question of the design of thermal protection systems based on other physical principles and using innovative technologies.

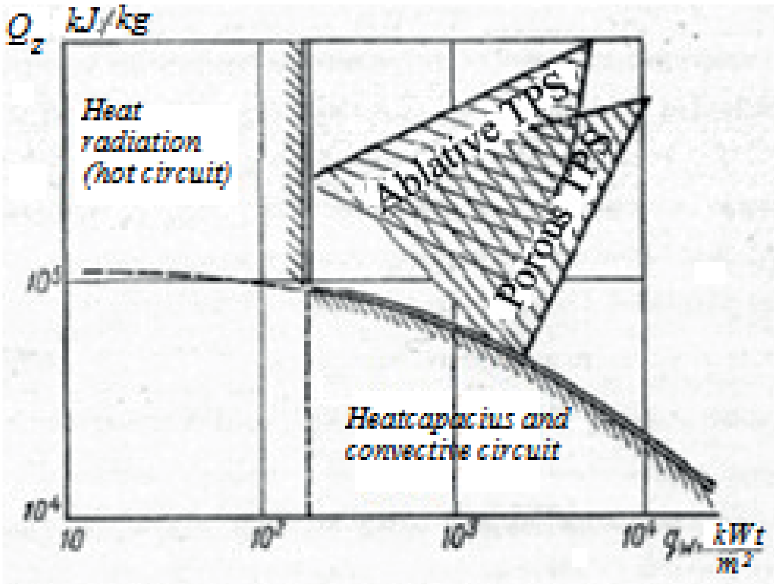

Figure 2: The region of applicability of the various systems of thermal protection depending on the specific and total heat fluxes.

One possible solution is the use of the phenomenon of electron transpiration cooling (ETC) of the emitter in thermionic workflow in the thermal protection system of hypersonic vehicle. In the basis of functioning of protection is the equation for the electron transpiration cooling phenomenon:

$$q = \frac{j}{e} \cdot (\Phi_E + 2kT_E). \tag{1}$$

The density of the emission current is described by the equation of Richardson

$$j = A_0 \cdot T_E^2 \exp\left(-\frac{\Phi_E}{kT_E}\right), \tag{2}$$

where Φ_E- a work function of the emitter, T_E – emitter temperature, A_0- Richardson's constant, k- a Boltzmann constant, e – elementary charge.

Consequently, the electron transpiration cooling effect increases exponentially with increasing temperature, i.e. positive feedback is observed. In this case, the values of the work function of the emitter and collector are extremely important for the magnitude of the ETC effect [2].

Thermionic thermal protection systems (TTPS) based on a thermionic converter in planar geometry were first proposed in [3]. In the same place, it was experimentally proved that it is possible to achieve the value of the temperature cooling effect ΔT up to 700 °. The main disadvantage of such a system is the small area of the emission surface, the complexity in the implementation and the need to verify the technology.

The effect of electronic cooling on the surface temperature is illustrated in Fig. 3.

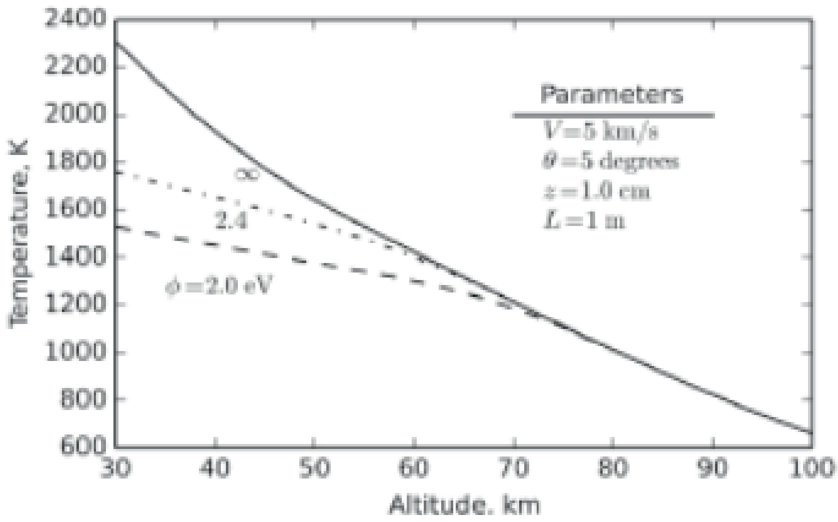

Figure 3: Steady-state surface temperatures for a flat plate in hypersonic flow with and without ETC, for two values of work function. An infinite work function is equivalent to being without ETC. [4].

In [4] systems of thermionic thermal protection with external emission of electrons were considered and their parameters were calculated. The temperature difference created by thermionic cooling is exceptionally large at low altitudes, and gradually decreases to zero as the altitude increases. This is explained by the fact that at high altitudes the aerothermal heat flux is too small to create the temperature necessary for thermionic emission. These points to an important feature of ETC: in the passive state at low temperatures the cooling system does not function, but as soon as the temperature increase exceeds the limits of the possibility of cooling by radiation, it naturally ”turns on”. Therefore, it can be expected that aircraft using ETC will be able to fly in modes with greater aerothermal heat load: the HSVs will be able to return to dense layers of the atmosphere without the use of ablative thermal protection, the air intakes of hypersonic ramjet engines can withstand interactions compression jumps of the fourth type, and high-speed flight on the final sections of the trajectory due to the use of ETC becomes to a much greater extent realized.

According to the calculations, using this technology, it is possible to reduce the surface temperature of heat-stressed elements by 1000 °. The most important factor is the critical dependence of the emission characteristics, and hence the capabilities of the heat sink in the TTPS from the work function of the material. In this case, the material must satisfy the requirements of strength and heat resistance. Another key feature of this technology is the significant influence of the bulk electron charge and the plasma shell on the emissivity of the coating at velocities of 5-10 M, which makes it necessary to apply an additional potential difference between the emitter and the collector. Consequently, an integral part of such a system should be a power source,

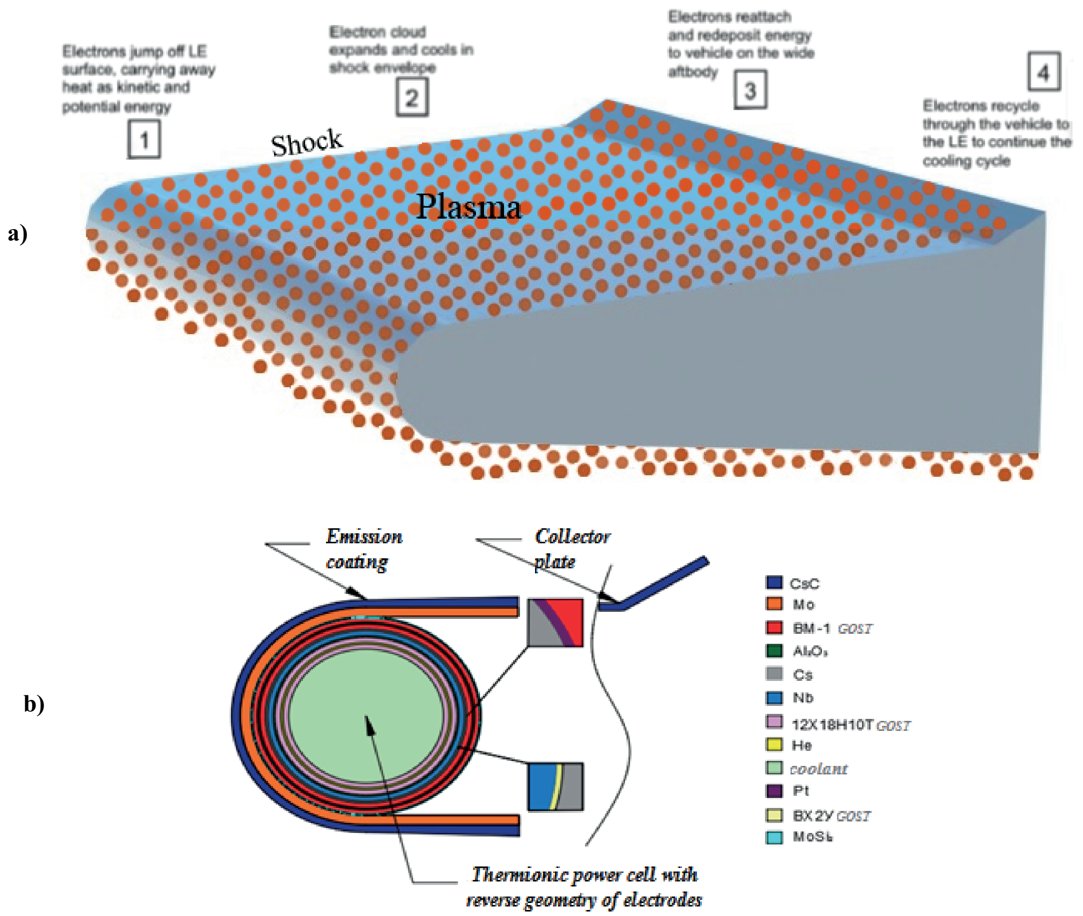

Figure 4: Diagram of combined thermionic thermal protection system: a - external cooling; b - internal cooling and power generation.

sufficiently powerful, resistant to external influences and temperature jumps.To solve the above problems, in my opinion, will allow the use of a combined thermionic thermal protection system. This system is based on a combination of coating technology with external electron emission [4] and internal cooling using the technology of thermionic power cell (TPC), successfully realized in thermionic reactor-converters of space nuclear power units "Topaz" and "Enisei" [2]. The external emission coating will create the main effect of temperature cooling. The TPC with the reversed geometry of the electrodes [2] being inside nose cone or in the leading edge will produce the electricity necessary to create an additional potential difference between the emitter and the external system collector, thus removing the residual thermal energy. The scheme of combined TTPS is shown in Figures 4 and 5.

The calculations of the electric and thermal physical characteristics of the TPC with the reversed geometry of the electrodes for a given isotropic heat flow and a fixed working fluid pressure allow us to estimate the effect of the temperature cooling achievable with the help of the TPC and conclude that the TPC can be used in the

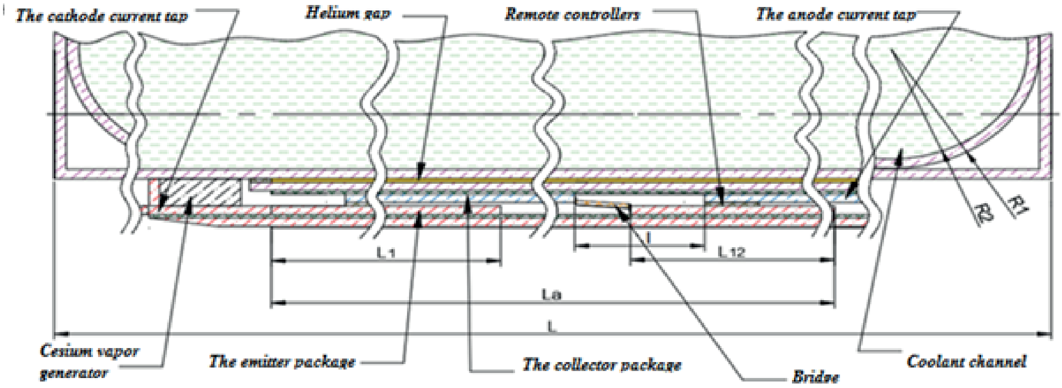

Figure 5: The scheme of the TPC with reverse geometry of the electrodes.

TTPS as internal source of electricity.Under these conditions, the effect of temperature cooling ΔT achievable with the use of TPCs is ΔT = 142... 593 K, and the use of TPC in the TTPS allows to generate an additional 4.2 kW of electric power.

3. Results

The development of a combined TTPS will reduce the temperature of heat-stressed HSV elements by 1000 °, utilizing up to 40% of the thermal energy, while ensuring the stability of operation at different aircraft speeds, especially in the range of 6-10 M, which is of interest to us. Electricity produced in the combined TTPS is used to provide its work by generating a bias potential and ensuring the circulation of the coolant. The remaining part of the electric power can be used to ensure the operation of on-board SFA systems. Thus, a thermal protection system with external electron emission will operate in the first generation square with an applied bias potential, while a TPC with an inverse geometry of the electrodes will operate in a mode close to the maximum efficiency for making the greatest possible generation of electricity. When creating a combined TPC, the decisive issue is the choice of emission material for the outer emission surface. Such promising materials include CsC and BaC compounds. [5, 6]. The laboratory-fixed effect of the formation of a graphene-like layered graphite structure intercalated by cesium on a nickel reservoir substrate under the conditions of dynamic cesium vapor supply in a thermal emission converter in which the work function of the collector changed from 1 eV in the presence of a cesium plasma to 2 eV without it.

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Table 1: Comparison of the functional of different types of thermal protection systems.

Type of heat protection system	Temperature of the leading edge, °C (evaluation)	Coolant	Reusability	Necessary of electricity source W	Relative mass (%)	Advantages/ Disadvantages
Passive («hot circuit»)	2200 and higher	-	no	no	-	For short flights
Heat pipe	1800 And lower	Na, Li, Ag i.e.	yes	no	80	Negative experience of use, heat inertia
Liquid metal circuit	1800 And lower	NaK, Li	yes	yes	120	Requires a pump power source I ~ 300A (MHD pump), heat inertia.
Convective circuit	1800 And lower	Aviation fuel	yes	yes	100	Low coolant resource, Requires a pump power source, heat inertia.
TTPS internal TTPS external TTPS combined	1800°C And lower 1600°C And lower 1500°C And lower	Aviation fuel Aviation fuel Aviation fuel	yes yes yes	no no no	70 70 70	It is both a source of energy for pumps and onboard consumers Positive temperature feedback, self-regulation Advantages/disadvantages will be determined at the next stage of work

4. Discussing

The results of comparison of different types of thermal protection systems are given in Table 1

5. Conclusion

Thus, it is possible to single out the main stages of forthcoming research and development of the combined system of TTPS.- Selection of coating material with the necessary emission characteristics (1-1.5 eV), satisfying the requirements of heat resistance and strength. As one of the possible materials, graphite / graphene intercalated with cesium [6].- Development of technology for depositing an emissive coating on the surface of heat-stressed elements.- Conducting a joint electric thermal physics calculation of the combined TTPC to evaluate the cooling effect and to reveal the features of the thermionic working process.The work is carried out under the guidance of prof. V.I. Yarygin.

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