Proposal of an Experimental Methods for Electron Transpiration Cooling Effect

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Proposal of an Experimental Methods for Electron Transpiration Cooling Effect

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Abstract. We present an analysis of the current state of electron transpiration cooling (ETC) effect studies as applied to high-temperature aerodynamics of hypersonic vehicles. The possibility of experimental study of the ETC effect using the plasma-dynamic device at the Ioffe Institute is considered. The distribution of vertical component of the electric field and gas temperature distribution across the glow discharge is measured. The region of homogeneity of plasma parameters is determined.

1. Introduction
Heat protection system problem for space and hypersonic vehicles is one of the major issue proposals for aerospace industries [1]. Passive mechanisms for hypersonic leading edge protection from heating are attended by increasing in the weight of the vehicles, resulting in a decrease in orbital payload mass. In recent times decades alternative methods of thermal protection based on the use of MHD flow-control have been discussed, for example in [2,3]. However, on the best part of the down-path of the re-entry payload and the hypersonic aircraft surface heating is carried out by the effect of radiation. Under such conditions, passive methods of heat protection can not provide the sufficient intensity of heat removal. Electron transpiration cooling (ETC) is a recently proposed active heat protection technique which affects directly to the heated surface of the hypersonic vehicles. ETC is based on thermionic emission of electrons, and involves cooling of the surface due to energy removed by electron transpiration.

Practical implementation and experimental studies of such ETC systems is technically challenging. Recent progress is only presented in several theoretical works connected with numerical simulation and engineering development. In the 1960s the first works describing the use thermo-electric materials on the nose of re-entry vehicles appeared [4,5]. In these works, an theoretical analysis and experimental study of a new design of a thermoelectric current generator for aircrafts were carried out.

Meanwhile, the possibility of using thermo-electric materials for active heat protection by ETC is not discussed in [4,5]. By that time the aircrafts couldn’t reach hypersonic velocity, so the technology was not developed. Since 2014 and up to the present time studies have been conducted on the numerical simulation of the ETC effect [6-11]. Calculations of the efficiency of energy removal by electron transpiration under various external conditions (the composition of the medium, the velocity of the incoming flow, and various geometric parameters of the model) are carried out. It was shown in [11] that ETC can be a usable approach for decreasing the surface temperature of hypersonic vehicles by up to 50%.
2. Description of the experiment

In our opinion, realization of experimental studies of various physical aspects of ETC effect is essential as for the numerical simulations so for this problem at large. At the moment investigational study focused on detection of temperature variation caused by ETC effect under conditions close to hypersonic flight have been started at the Ioffe Institute as part of the RFBR project 18-38-00346 mol.a.

Experimental studies are proposed to be carried out on the plasma-gasdynamic setup in the air under the pressure of 2-7 kPa. The scheme of the setup is shown in Fig.1 The stationary glow discharge is ignited between two conical copper electrodes (1 - cathode, 2 - anode) arranged vertically at a distance of 100 mm in the working chamber with an inner diameter of 300 mm and a height of 400 mm. The chamber walls and the cathode 1 had a common potential which is equal to zero. The anode 2 is located on the non-conductive plate closing the lower end of the working chamber. The arrangement of electrodes (anode at the bottom, cathode on top) and their shape were determined by the necessity for spatial stability of the discharge. Gas discharge glow is sustained by a DC voltage source.

The discharge glow has the shape of a body of revolution. Its cross-section increases at the vertical direction from anode to cathode. The diameter of the central part of the discharge in the measuring cross-section is approximately 60 mm. An external power supply provides the discharge current of 1.1 A with a voltage between the electrodes of 650 V (at 4 kPa). The gas temperature at the discharge axis is approximately 1400 K, the ionization degree dont exceed $10^{-6}$. The setup allows to use the discharge energy as an intensive source of heating.

![Figure 1. Experimental setup. 1 - cathode, 2 - anode, 3 - sliding rod.](image)

On the opposite side of the working chamber a double probe is placed on the sliding rod 3. The probe is mounted at the sliding rod therefore the plasma parameters at the different distances from the discharge axis can be measured. The probe consists of two parallel platinum electrodes with a diameter of 0.5 mm and a length of 10 mm with the distance of 8 mm between them. The electrodes of the probe are connected to the input of the current meter, which is a precision differential amplifier. The input circuit of the amplifier included a constant voltage source 40 V, which provides the ion current saturation regime. In this case, the probe current is proportional to the concentration of ions. Measurements carried out without 40 V voltage source provide the axial distribution of vertical electric field in discharge plasma.

To study the ETC effect, it is planned to create a model, which is a flat plate with the size of about 1x1 cm with a thermoelectric material surfaced on it. This model is fixed on a movable road which allows it to be placed in various areas of the discharge with different gas temperatures and thus change the intensity of thermionic emission. Two electrodes are xed on the plate, which are inside a quartz capillary about 400 mm long inside the movable rod. The electrodes are connected to resistors with resistance values 2 kOhm, which is the input load of
the current meter. The temperature of the plate gets equal to the temperature of the external environment after a durable disposal in the glow discharge plasma. The heat being removed by electron emission from surface lead to plate temperature decrease. The temperature of the plate can be measured by using: contact method - by using a thermocouple; noncontact method - by using spectral pyrometry. These experimental methods allow to nd out the temperature value, and register the the dynamics of temperature variation with time.

Currently, borides of rare-earth elements are widely used in radioelectronics and emission electronics. The abundance of their use is due to their unique physical properties, such as high mechanical and chemical resistance, high (more than 2000 C) melting temperature, and low (2-3 eV) work function. One of the most commonly used materials for the manufacture of thermal cathodes is lanthanum hexaboride (LaB$_6$), the work function of which is 2.66 eV. It has high resistance to chemical attack and a melting point of about 2470 K, which makes its use promising for thermal protection by ETC. According to estimates from [6], the current density obtained at the temperature available in the installation is of the order of 1 mA/cm$^2$. The current meter designed for probe measuring system is capable of registering currents of the order of $10^{-6}$ A. This circumstance will allow us to make measurements with high accuracy, and also makes it possible to investigate materials with different work functions.

The presence of a plasma medium near the emitting electrode can significantly reduce the thermal emission current density. In [8], a detailed analysis of the effect of the near-electrode space charge layer on the magnitude of the electron cooling effect is performed. It is shown that taking into account this effect can reduce the calculated thermal emission current density by more than 5 times. However, as shown in [11], with an increase in the speed of supersonic flight from 4 km/s to 8 km/s, it is possible to overcome the limitation of the space charge and to achieve a 50% decrease in surface temperature. Thus, thermal emission current estimations using the Richardson law should be treated with great caution. This fact is an additional proof of the importance of ETC experimental studies.

3. Properties of glow discharge
The internal structure of the glow indicates the presence of regions with differing plasma electrical parameters. The most indicative object demonstrating discharge structuring is the cathode of the discharge gap (the upper electrode in Fig. 1). The part of the surface adjoins the vertex of the cone has a bright glow. This luminous region occupies less than half the surface of the cathode, and its transverse dimension coincides with the diameter of the inner brightest region of the discharge. The cross-sectional area of this region like the size of the luminous surface of the cathode, varies in proportion to the discharge current. There being of a bright cathode glow allows us to state that the central part of the glow is a glow discharge.

The determination of the glow discharge properties in an important stage in the preparation for the experiments described above. For this purpose, a number of studies were carried out aimed at measuring the plasma parameters. The gas temperature and the vertical component of the electric field were measured. The technical features of the setup permit measurements only in the cross section of the discharge (see Fig. 1). Figure 2 shows the distribution of the vertical component of the electric field of a discharge obtained with an electrostatic voltmeter. The distance X is measured from the axis of the discharge gap. It can be seen that in the central part of the discharge ($|X| < 10$ mm), the vertical component of the electric field changes by no more than 10%. Figure 3 shows the distribution of the gas temperature. The temperature was measured with a chromel-alumel thermocouple attached to a sliding rod. It is evident that in the central part of the discharge ($|X| < 10$ mm) the gas temperature is practically constant. The distribution of charged particles concentration was also measured. It has a very similar radial profile with a slight change in value near the axis.
4. Conclusions

The contemporary aerodynamic investigations demonstrate a high interest in the development of a fresh approaches to solving the problem of aircraft thermal protection, as shown by the example of the ETC method. An analysis of the content of these works shows that there are no fundamental physical limitations for the application of the ETC method. The experimental research methods proposed in this paper will allow performing quantitative measurements of the ETC effect and determining the effectiveness of using this method of thermal protection in hypersonic flight. Measurements of glow discharge plasma parameters are presented. Experimental data shows that the central region of the glow with characteristic size of about 20 mm has nearly identical values of plasma parameters.

Acknowledgments

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References

[1] Ivett A. Leyva 2017 Physics Today 70 30
[2] Bobashev S V, Mende N P, Popov P A, Sakharov V A 2011 Tech. Phys. 55 1760.
[3] Bobashev S V, Golovachev Y P, Kurbatov G A, Mende N P, Sakharov V A, Chernyshev A S, Schmidt A A 2009 Tech. Phys. 54 33.
[4] Touryan K J 1965 AIAA Journal 3 652.
[5] LeBlank A R, Grannemann W W 1964 Proc. IEEE 52 1302.
[6] Alkandry H, Hanquist K M, Boyd I D 2014 AIAA Paper 2014-2674.
[7] Hanquist K M, Boyd I D 2015 AIAA Paper 2015-235.
[8] Hanquist K M, Haray K, Boyd I D 2016 AIAA Paper 2016-4433.
[9] Hanquist K M, Haray K, Boyd I D 2017 Journ. of Thermophys. Heat Trans. 31 283.
[10] Hanquist K M, Boyd I D 2017 AIAA Paper 2017-0900.
[11] Hanquist K M, Haray K, Boyd I D 2017 J. Appl. Phys. 121 053302.