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Development of a hot channel for a DC plasma torch

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A design of a hot graphite channel for a DC plasma torch has been created, which provides heating of a graphite target to a temperature above 3000 K without the occurrence of „mechanical" erosion due to the creation of a more homogeneous stationary gas flow of argon and nitrogen by a DC plasma torch. It turned out that one screw chamber is sufficient in argon, and in molecular gas (nitrogen) it is necessary to use a screw chamber together with dividers.

Keywords: plasma torch, atmospheric entry, graphite, homogeneous gas flow, mass loss rate.

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Under the operating conditions of the space flight upon entry to the atmosphere the vehicle external coating is subjected to non-stationary (quickly increasing — over some tens of seconds) homogeneous air flow that heats the surface to 3000–4000 K [1,2].

Simulation of the atmosphere entry conditions for such vehicles requires a generator of atmosphere pressure hot air, it can ensure the required heating of the model surface. It is important that upon entry into the atmosphere the flow around the vehicle is spatially homogeneous, ensuring at each point of its surface a monotonous (without pulsations) increase in the heat flux density over time. In principle, such flow around can be simulated using high frequency and ultra-high frequency and plasma generators creating a diffusion discharge. But provision of the required power level for air-flow of rather large models is associated with use of expensive and complicated equipment [3,4]. It seems advantageous to use the DC plasma torches with more simple power supplies. But such hot air generators are characterized with a principle instability of the generated flow through space and over time. This is due to the discharge nature when a relatively narrow hot (at temperature over 8000 K to reach the required level of gas conductivity) discharge cord — arc column — moves chaotically in the flow of the rest „cold" gas due- to interaction with the own magnetic field (Fig. 1). As a result of flow around by such gas jet of the obstacle — target — the heat flux density distribution over the heated surface appears to be chaotically pulsating thus resulting that in the surface material the large nonstationary thermoelectromotive forces are generated due to- alternating thermal expansions-compressions of the surface material grains (including in direction normal to the surface). This results in breakage of the weak places (grain boundaries) of the material, especially non-metal, grains release and their erosion by the flow. The mass loss by the target material due to this mechanism will be called as „mechanical" erosion unlike to other mechanisms of mass loss: evaporation (sublimation) and chemical erosion (oxidation) [2]. In the video footage this looks like release of a large number of brightly glowing microparticles (Fig. 2). Besides, at large heating rates (even by homogeneous gas fow) the thermo-stressed state occurs on the heated surface, it is due to the material expansion along the surface, with large tension stresses perpendicular to the surface at some distance from it. As result surface areas can chip off.

The direct frontal (at angle 90°) nonstationary action of the jet hot core — plasma itself — on the surface of the blown results in a pulse heating of this region to temperature of the material sublimation (when equilibrium vapor pressure becomes equal to or greater than external pressure). In this case the additional applied energy is spent for the material evaporation — its sublimation.

This paper objective is creation of the attachment to the plasma torch to ensure the target heating to 3000–4000 K without occurrence of the „mechanical" erosion due to suppression of spatial pulsations in the generated flow of the heated gas and equalization of the transverse temperature field of the flow.

For the flow temperature field equalization in the channel first of all the temperature of the channel internal surface of such attachment shall be increased to maximum possible level, this possible when, for example, graphite is used. Upon significant temperature increasing of the channel internal surface the radial profiles of the temperature, density and rate significantly re-arrange. The relatively low evaporation rate of the graphite ensures long-time operation if the inert gases (argon, nitrogen) are used. If air is used the operation time is determined by the rate of chemical erosion of the graphite, and in any case it exceeds the characteristic time of the atmosphere entry of the space vehicle. So, the required attachment is uncooled graphite channel that is continuation of the water cooled copper channel of the plasma torch (anode).

Let's discuss behaviour of such straight graphite channel (sectioned to increase the heat-resistance), connected to the plasma torch, after approaching the stationary thermal

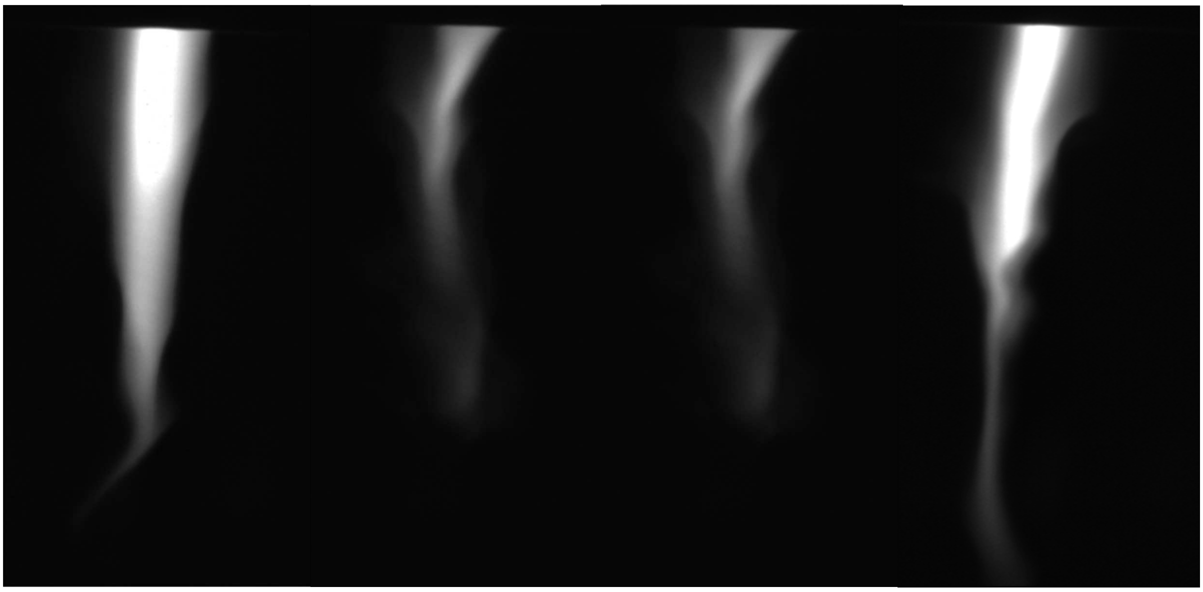

Figure 1. Video footage in series of the argon plasma jet in open space from a plasma torch at arc current of 150 A and flow 0.8 g/s. Video shooting rate 1 kHz.

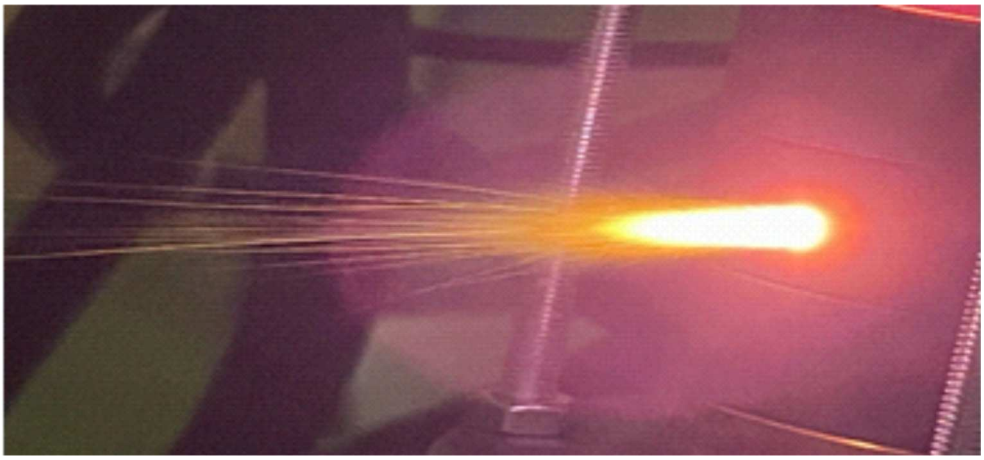

Figure 2. View of argon plasma jet from outlet during pyrometry, diameter 3 mm in graphite channel at arc current 150 A and flow 0.8 g/s.

conditions. Temperature of the channel internal surface can not exceed the sublimation temperature of the carbon. At channel beginning its internal surface is effectively cooled by the radiation into closed cavity with cold surface — zone of anode, interelectrode insert and cathode of plasma torch. The farther from the anode, the less spatial angle of radiation into this cold cavity is, and the higher the temperature of the channel internal surface is. At significant distance from the anode the effect of temperature (energy content) decrease of flow arises due- to the heat losses of the channel. At large power of the flow in region, where the temperature achieved the sublimation temperature, wall material evaporation begins. Therefore, the channel profile will have a barrel-like form at the region of high heat losses with radius decreasing at the exit due- to soot condensation. The temperature through the length of the channel external surface will initially increase, and then decrease.

This design was tested in three electrode (cathode with insert made of lanthanated tungsten–interelectrode insert–anode) plasma torch with channel diameter (internal) 8 mm with vortex gas supply, efficiency $\sim 60\%$ for work gas argon and $\sim 80\%$ for nitrogen, this ensures the formation at outlet of a weakly diverging $(2\alpha = 12^\circ)$ plasma jet with diameter $D = 5-12$ mm with enthalpy $5-50$ kJ/g, and bulk temperature $5-10$ kK, at full electric power of arc discharge $5-50$ kW, and plasma gas flow $1-3$ g/s [5,6]. The following parameters were selected as main monitored parameters: a) actual temperature of heated practically isothermal graphite sample, grade MPG-6

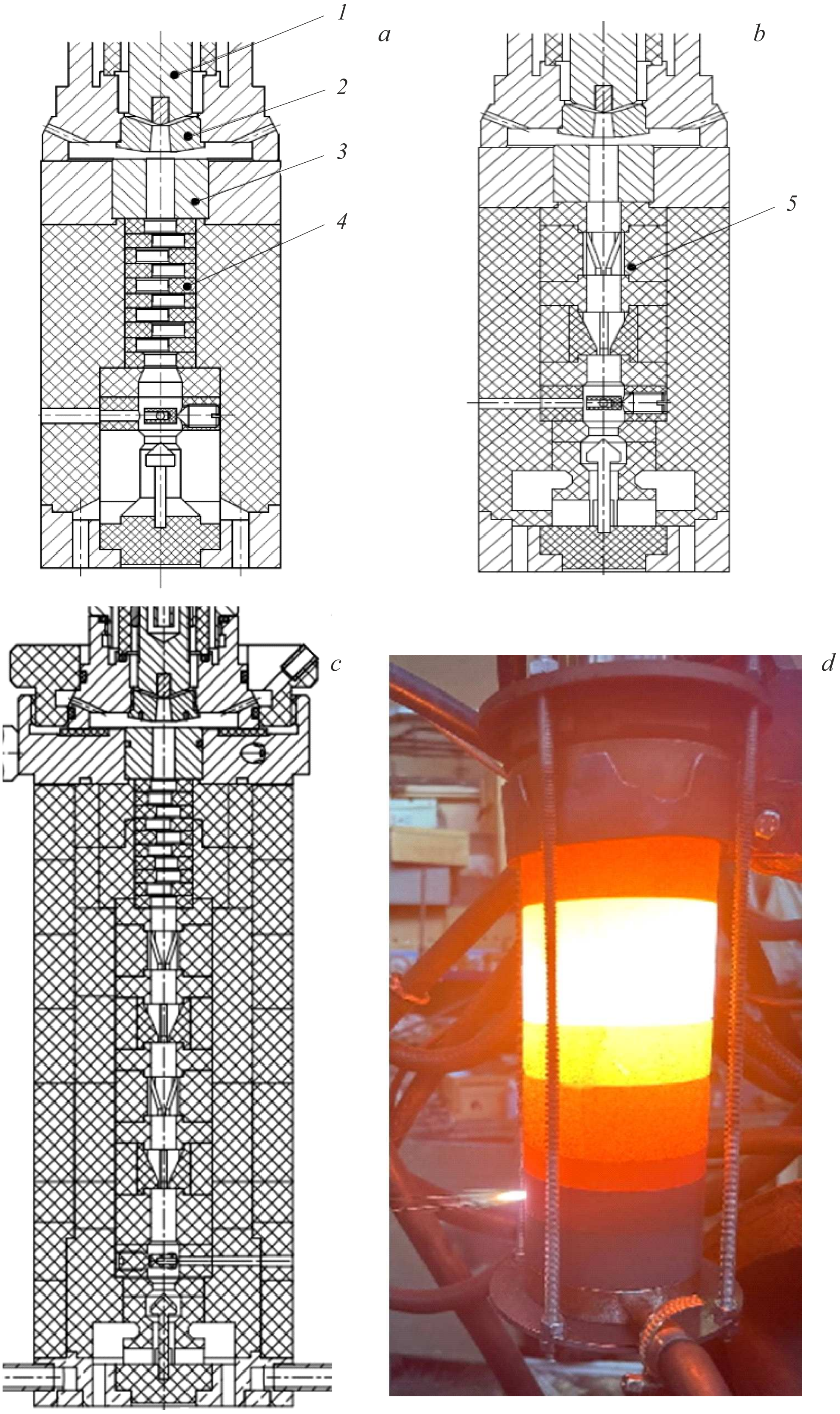

Figure 3. Tested plasma torch designs with hot graphite channels. *a* — screw chamber, *b* — channel with dividers, *c* — channel with screw chamber and dividers, *d* — general view of heated long graphite channel. *1* — cathode, *2* — nozzle, *3* — anode, *4* — screw channel, *5* — wedge divider.

(Ø 8 × 4 mm) with black body model in it — dead-end drilling (Ø 2 × 6 mm); b) its mass loss.

The sample was located in the chamber with internal diameter 10 mm at end of the graphite channel (Fig. 3). To improve the uniform heating the sample is secured in three sharp graphite screws in the chamber with divider below — mushroom knob.

The temperature was measured using a brightness pyrometer Raytek 1M working at wavelength 1 μm (field of view size 0.6 mm, error 0.3% of measured value), through hole Ø 2.5 mm in a side wall of the channel. The maximum temperature measured by pyrometer is 3300 K. Mass of sample and all other elements of the hot path was measured before and after each test. Arc current range is 150–450 A, gas flow range is 0.8–1.5 g/s.

The first tests with argon showed that there was large erosion of some graphite elements as result of oxygen presence in the argon, as well as of the air ejection presence. Transfer to highly pure argon (oxygen content $2 \cdot 10^{-5}$%) and appropriate design improvements ensure the erosion level about 10^{-4} g/(cm$^2 \cdot$ s) at the sample temperature over 3300 K (pyrometer off-scale reading), which, howsoever, probably exceeds the evaporation rate of carbon under such conditions. High-speed shooting of the plasma jet at outlet of the graphite channel 25 mm long (Fig. 1) showed that the generated gas flow is highly heterogeneous and nonstationary. it appeared to be that residues of the discharge arc cord intensively pulsate with frequency over 10 kHz, as result the local regions of high heating periodically occasionally occur on the target surface. It is shown (Fig. 2) that many glowing microparticles permanently exit through the optical hole, and on the top surface of the sample approximately in the center a cavity 1–2 mm deep is formed — result of the „mechanical" erosion.

It became clear that without such pulsations suppression it was impossible to ensure the graphite erosion comparable to the evaporation rate. Two methods of action on the flow were selected. The initial consideration is the assumption that location in flow of the heated elements subjected to the frontal flow around has no effect. It is possible to affect the flow only by surfaces oriented at small angle to the flow direction. This can be either screw channel (Fig. 3, *a*) or extension from side walls of narrow flow dividers (Fig. 3, *b*) oriented at angle 10–20° to the flow direction, or these two methods combination (Fig. 3, *c*). Fig. 3, *d* shows also the general view of the long graphite channel (about 120 mm), heated for 3 min to bright glow (to 1100°C) in middle portion.

The screw design showed that simplified design of the screw channel out of set of washers with cylindrical drilling (Ø 8 mm), shifted from axis by 4 mm, and installed with successive rotation by 90° one after another, turned out to be fully functional. At that the system of formed neckings of the channel cross-section facilitates the backflow zones occurrence. The washers heating temperature increases with distance from the cold copper channel of anode (with decrease in radiation on the cold copper of the plasma torch).

In case of the design with flow dividers four or six narrow wedges with angle of inclination to axis 10–25° are installed in split holder and fixed from top and bottom in radial direction with the appropriate inserts. This limits the possibility of oscillations of the hot arc cord and improves the flow mixing due to necking the channel cross-section and formation of vortex backflow zones. Such design also showed good performance. When the dividers are installed just after the plasma torch outlet the significant „burning" of wedges is observed. Probably, the combined use of these approaches, see Fig. 3, *c* is optimal.

When working with argon and using only screw graphite insert without dividers for the sample temperature about 3000 K the sample mass loss rte below 10^{-5} g/(cm$^2 \cdot$ s) (0.05 μm/s) was obtained.

When working with nitrogen such screw insert was insufficient, the dividers shall be used. On the design with the screw insert (one screw turn) and with dividers (Fig. 3, *c*) for the sample temperature below 2300 K mass loss was not observed, and at $T = 2800$ K value $1.5 \cdot 10^{-4}$ g/(cm$^2 \cdot$ s) was obtained, i.e.further design improvement is necessary. The matter is that in the molecular gas nonuniformity of the flow thermal effect on the target surface is significantly higher due- to larger dissociation degree of gas as compared to the ionization degree, at rather close values of dissociation energies of molecules and ionization energies of atoms (9.8 and 14.5 eV respectively for nitrogen [7]). Length increasing of the screw insert to 40 mm (with two screw turns) decreased the mass loss rate of sample from $1.5 \cdot 10^{-4}$ g/(cm$^2 \cdot$ s) when working with screw chamber with six washers (with one flow turn) to $5 \cdot 10^{-5}$ g/(cm$^2 \cdot$ s).

So, the design of plasma torch with hot graphite channel behind it was suggested and tested to ensure the target heating to temperature over 3000 K without the „mechanical" erosion occurrence due to generation of more homogeneous and uniform hot gas flow, this ensures start of the study of graphite behaviour in air.

Conflict of interest

The authors declare that they have no conflict of interest.

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