Results of studies of the direct current generator of low-temperature nitrogen-propane plasma

M Kh Gadzhiev, A S Tyuftaev, M V Ilyichev, M A Sargsyan, D I Yusupov and E E Son

Joint Institute for High Temperatures RAS, Moscow, Russia
makhach@mail.ru

Abstract. The effect of propane-butane addition to the plasma-forming gas on the state of cathodes with inserts made from lanthanated tungsten and hafnium is investigated. With a small propane addition (1%), the restorative effect of the insert material is noted, and the propane consumption has an upper limit when it is introduced together with the plasma-forming gas (no more than ~ 73% of the plasma-forming gas consumption), below which the arc stability is not disturbed.

1. Introduction

Low-temperature plasma is widely used not only in science, but also in applied production and technical problems [1-10]. This wide application range is due to the fact that a plasma flow of various working gases with temperatures from hundreds to tens of thousands of degrees is created in the discharge gap of the low-temperature plasma generator (LTPG). Of all the existing types, the highest operating temperature can be provided by DC LTPGs, which is one of the simplest sources of low-temperature plasma (T <25 kK) [11-16]. However, the widespread practical distribution of plasma technologies is constrained by the lack of reliable arc plasma torches with a sufficient resource for long continuous operational time. The most common refractory metals used for the plasmatron cathodes inserts are lanthanated tungsten [17, 18] and hafnium [19]. Lanthanated tungsten is usually used when working with inert gases (nitrogen, argon, helium), and hafnium is used when working with air, since they have a lower work function than pure tungsten, which makes it possible to obtain the required thermal emission current at a lower surface temperatures. At a lower temperature of the electrode surface, thermal stresses decrease, and this contributes to a longer use of the cathode in the plasmatron. In regard to this, the aim of the work was to study the effect of adding propane-butane mixture to the plasma-forming nitrogen gas on the state of cathodes with inserts made from lanthanated tungsten and hafnium, expecting a restorative effect that the mixture would provide for the cathodes.

2. Methodology

As such plasma source, an LTPG with vortex stabilization and an expanding channel of the output electrode Figure 1 was developed, which provides high flow characteristics, high resource time, effective heating of the working medium by DC LTPGs, which is one of the simplest sources of low-temperature plasma (T <25 kK) [11-16]. However, the widespread practical distribution of plasma technologies is constrained by the lack of reliable arc plasma torches with a sufficient resource for long continuous operational time. The most common refractory metals used for the plasmatron cathodes inserts are lanthanated tungsten [17, 18] and hafnium [19]. Lanthanated tungsten is usually used when working with inert gases (nitrogen, argon, helium), and hafnium is used when working with air, since they have a lower work function than pure tungsten, which makes it possible to obtain the required thermal emission current at a lower surface temperatures. At a lower temperature of the electrode surface, thermal stresses decrease, and this contributes to a longer use of the cathode in the plasmatron. In regard to this, the aim of the work was to study the effect of adding propane-butane mixture to the plasma-forming nitrogen gas on the state of cathodes with inserts made from lanthanated tungsten and hafnium, expecting a restorative effect that the mixture would provide for the cathodes.
can be supplied together with the working gas (nitrogen) into the discharge gap, between the nozzle and the anode, and in the middle of the anode below the arc binding zone.

![Figure 1. Plasmatron design.](image)

To visualize the effect on the cathode of a small propane-butane addition to the plasma-forming gas, an experimental setup (Figure 2) and research methods described in detail in [19-21] were used. From the first viewing window, a clear image of the cathodes tip was projected (using a focusing lens) onto a Phantom Miro M110 high-speed black-and-white camera. From the opposite window, the arc image was projected (using a quartz focusing lens with a focal length of 220 mm) onto the input fiber of the Avaspec 2048 three-channel spectrometer.

The tip of the hafnium cathode was in the liquid phase during the experiment; once propane-butane mixture was added cathodes tip underwent a rapid destruction until a specific binding area of the cathode spot was reached. After that, a carbon layer started growing at the edges of the insert at a rate of $\sim 0.1$ mm/min, which, upon reaching a certain value, also collapsed and was carried away by the flow.

3. Results and discussion

The study of the state of cathodes with inserts from lanthanated tungsten and hafnium was carried out both for pure nitrogen and for nitrogen with the addition of up to 1% of propane-butane at arc currents 150–200 A Figure 3. The lanthanated tungsten cathode was heated to a temperature of 3200 K with an effective work function of 3.0 eV [23], and specific erosion of $\sim 5 \times 10^{-10}$ g/C [24]. The pure hafnium cathode was heated to a temperature of 3800K, for hafnium at these temperatures there are no well-measured or calculated values for its effective work function, but based on calculations in [25, 26], it can be assumed that it will be in the range of 2.2–2.6 eV, with specific erosion of $\sim 10^{-8}$ g/C. During operation, the tip of the lanthanated tungsten cathode was in a solid state, the most intense destruction
occurred at the moment of arc ignition (the first 100 ms). When propane was added, two processes took place simultaneously - the removal of the electrode material from the center of the cathode spot and the growth of material along the edge of the cathode spot. Upon reaching a certain value, the deposited material was destroyed and carried away by the flow.

![Figure 2. Experimental setup: 1 - Avaspec 2048 spectrometer; 2 - light guide; 3 - projected image of the plasma flow; 4 - focusing lens; 5 - plasma flow; 6 - quartz viewing windows; 7 - focusing lens "Nikon Nikkor 100-200mm"; 8 - high-speed camera Phantom Miro M110.](image)

Also, a study of the operation of the LTPG was carried out with the addition of the maximum possible ratio of propane-butane to a fixed nitrogen flow rate, at which the stability of the arc was not disturbed. The criterion for the stability of arc burning in our case is the fluctuation of the arc voltage of not more than ± 3 V. For the plasmatron design shown on Figure 1, with an arc current of 100 A and a nitrogen flow rate of ~0.45 g/s, the maximum possible propane-butane flow rate was ~0.33 g/s (not more than ~73% of the plasma-forming gas flow rate). Since a plasmatron with a self-aligning arc length was used, an increase in propane-butane supply leads to the development of pulsation phenomena associated with a high deposition rate of decay products on the electrodes Figure 4(a), which leads to an uneven cross-section of the gas discharge path, which in turn affects gas dynamics and the possibility of arc movement on the anode surface. When propane-butane is supplied with a plasma-forming gas into the discharge gap, the deposition of decomposition products occurs mainly on the electrodes (especially on the anode - Figure 4(a)). The supply of propane-butane to the anode after the arc attachment point leads to the deposition of decomposition products mainly not on the electrodes, but at the outlet from the anode Figure 4(b). When propane-butane is supplied together with the plasma-forming gas, decomposition products are deposited on the surface of the electrodes in the form of a melt, consisting mainly of carbon, and when it is supplied into the anode behind the arc attachment, deposition occurs at the outlet of the anode in the form of a powder. The phase composition of the carbon samples was analyzed by X-ray structural analysis on a DRON-2 setup (CuKα radiation). It was found that the samples consist of:

- graphite, represented by several components differing in the degree of three-dimensional ordering of the crystal structure;
- carbon with a turbostratic graphite structure, containing single chaotically oriented layers of graphite and packets of parallel, equidistant, but crystallographically unconnected layers;
• a significant amount of metal (copper) with a cubic face-centered crystal lattice;
• unknown impurity phases.

Figure 3. Photo of cathodes: (a) lanthanated tungsten before adding propane-butane; (b) lanthanated tungsten 1.5 min after adding propane-butane; (c) hafnium before adding propane-butane; (d) hafnium 1.5 min after adding propane-butane; (e) hafnium cathode without the addition of propane-butane; (f) hafnium cathode after 5 minutes of work with propane-butane mixture.
Figure 4. Photos of the decay products of propane-butane: (a) on the electrodes when supplied with a plasma-forming gas; (b) at the exit from the anode when supplied into the anode after the arc attachment point.

4. Conclusion
The effect of propane-butane addition to the plasma-forming nitrogen gas on the state of cathodes with inserts made from lanthanated tungsten and hafnium was investigated. It is shown that with a small addition of propane-butane mixture (1%) to the plasma-forming gas, the "restorative" effect of the electrodes is observed. The decomposition products of propane-butane are partially deposited on the anode, and the carbon ions formed as a result of the dissociation of propane-butane molecules and the ionization of carbon atoms under the action of the near-electrode potential drop are deposited on the water-cooled copper surface of the cathode, which increases the resource time of the electrodes. Also, depending on the design of the LTPG, the propane consumption has an upper limit when it is introduced together with the plasma-forming gas (no more than ~ 73% of the plasma-forming gas flow rate), below which the stability of the arc is not disturbed. In this case, the supply of propane-butane with a plasma-forming gas leads to a high rate of deposition of decomposition products on the electrodes, which can lead to a decrease in the stability of the arc burning over time.

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