Evaluation of the mean argon plasma conductivity and temperature at the exit of an atmospheric DC arc plasma torch

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Abstract. A new long-life DC arc T-plasma torch [1] was studied. The well-known method of electric field strength measurements in a stabilized arc channel [2] was applied in a modified form as a consequence of the specific shape of the presumably diffuse anode spot attached to a gas vortex on the external surface of the anode unit. The electric field strength was determined assuming that the potential drop across the diffuse anode spot in the new plasma torch was small. This yielded a mean argon plasma conductivity \( \sigma \leq 118 \text{ Ohm}^{-1}\text{cm}^{-1} \) for arc current \( I \leq 180 \text{ A} \) which agrees with the independent experiment [2] thus affirming the correctness of the above assumption. The analysis of the known experimental and theoretical data on atmospheric argon plasma conductivity resulted in the selection of R.S. Devoto’s theoretical dependence \( \sigma(T) \) [3] as the most reliable one for \( T = 800 - 20000 \text{ K} \) at \( P = 1 \text{ atm} \), which allowed us to evaluate the mean argon plasma temperature at the exit of the plasma torch, namely, \( T \leq 19500 \text{ K} \).

1. Introduction
The new DC arc plasma torch with a tungsten rod cathode and a copper nozzle anode was described in [1]. Its main feature distinguishing it from others is the special design of the anode unit – see the schematic diagram in figure 1.

Here \( l_{AC} \) is the inter-electrode distance and \( l_{AN} \) is the anode channel length. The exit from the anode channel is implemented as a step of abrupt expansion that generates a gaseous vortex. In addition, it is deflected by the transverse flow of technologic gas that tends to deform the vortex and presumably adds to its twist. In such a situation and if \( l_{AN} \) is not too long, this vortex attracts an anode arc spot that expands to become diffuse thus lowering the anode material erosion by several orders of magnitude. Due to the shape of the working gas path, this device was named a T-plasma torch.

In contrast with conventional plasma torches with constricted anode spots having an erosion rate of \( m_A \sim 10^{-5} - 10^{-6} \text{ g/C} \) [4], in the T-plasma torch this parameter turned out to be some 4 - 5 orders of magnitude lower: \( m_A \sim 10^{-10} \text{ g/C} \) [1] which meant a high purity of the plasma and a substantial increase in the device’s design durability (about 10 000 hours at moderate arc currents \( I \sim 50 - 100 \text{ A} \)).

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2. Determination of the mean argon plasma conductivity

The mean electrical conductivity of arc plasmas is usually measured employing a stabilizing channel in a metallic inter-electrode insert operating under a floating electrical potential where the electrical field \( E \) is measured using small or large electrostatic probes. In the present version of the T-plasma torch such a technique appears problematic due to the small size of the discharge space while a similar outcome can be provided by the anode channel that can act as an arc column stabilizer when the anode spot of the discharge is attached to the external anode surface. This special feature of the present experiment allowed measurements of \( E \) in the anode channel.

In the T-plasma torch with an external diffuse anode spot, the arc positive column is divided into two parts: a free arc between cathode and anode and a stabilized arc inside the anode channel. The task is to measure the potential difference \( \Delta U_{AN} \) along the stabilized part of the arc column. It was done here using arc VA-characteristics for the same \( d_A = 2.5 \text{ mm} \) and \( l_{AC} = 2 \text{ mm} \) and for two different anode channel lengths \( l_{AN} = 4 \) and \( 8 \text{ mm} \). The location of the anode spot was determined by checking the state of the anode unit after each run of the plasma torch. The plasma pressure was kept atmospheric using rather small values of the argon flow rate \( Q_{Ar} = 2 \text{ l/min} \); according to [2] this condition corresponds to “ventilative” argon flow rates \( Q_{Ar} \leq 6 \text{ l/min} \) at which the arc VA-characteristics remain unchanged. The present experiment was arranged so that argon was supplied into the cathode unit and no gas was fed into the technologic channel. The VA-characteristics for two lengths of the anode channel were registered at currents \( I = 40 - 200 \text{ A} \). The results are presented in figure 2.

These curves were obtained by the point-to-point method with a pause of some 10 min. at the top arc current \( I = 200 \text{ A} \) to allow the anode spot to leave its trace on the anode surface. After-run inspections showed that for the long anode channel \( l_{AN} = 8 \text{ mm} \) arc traces could be seen at the anode channel inlet as a melted spot on the channel’s edge surrounded with a dark stain. Thus, in this case we had a free arc with the conventional constricted anode arc root. In the case of the short anode channel \( l_{AN} = 4 \text{ mm} \), an arc trace appearing as a dark ring around the anode exit was located on the external anode surface while the anode inlet remained clean. Moreover, in this latter case, the arc burned inside the anode channel and the arc positive column was stabilized by the anode’s cold wall.

The situation described is illustrated in figure 3 where a schematic diagram of the discharge space along with the axial voltage distributions is shown. Here line OG represents the arc voltage for the experiment with the long anode channel \( l_{AN} = 8 \text{ mm} \). Its voltage distribution appears schematically as graph ABCE. Line OF corresponds to arc voltage in the experiment with \( l_{AN} = 4 \text{ mm} \) and its voltage distribution is shown as graph ABCD. It is well known that for a conventional anode spot its voltage drop should be considerably larger than the one for a diffuse anode spot, which is reflected in figure 3; here the line CE is much longer than the short line beside point D representing \( \Delta U_{ADiff} \).

The mean electrical conductivity of the argon plasma was determined through the voltage difference \( U_D - U_C \) that was found as \( U_P - (U_G - U_{CE}) \), where \( U_{CE} \approx 6 \text{ V} \) is the voltage drop across the...
conventional anode spot that had been measured previously for the same discharge conditions [5]. In this operation the difference $U_D - U_C$ was considered to be equal to $\Delta U_{AN}$ assuming that the voltage drop across a diffuse anode spot is small: $\Delta U_{AD} \approx 0$. The resulting dependence $\sigma(I)$ marked with circles is shown in figure 4.

Note that the real $\sigma$ values should lie lower due to the effect of discharge current diversion into the copper anode body [6]. This effect could be more or less seriously evaluated for the inter-electrode inserts of [2] by using the physical concept in [6]. But here we have a conductive body collecting electrons by its entire internal surface which makes this parasitic current indefinitely large. In this situation and in view of our assumption $\Delta U_{AD} \approx 0$ we needed some independent check. It was found in the experimental data in [2] that were extrapolated from arc stabilizing channel diameters $d_A = 8$, 6, and 4 mm to $d_A = 2.5$ mm of the present work and yielded the data marked with triangles in figure 4. A general agreement in the conductivity magnitude that confirms the above assumption of a small potential drop across a diffuse anode spot seems evident. In more detail, the results in [2] show lower $\sigma$ values for the high current range $I \geq 150$ A where the discharge current diversion should be noticeable. Considering this possible effect in [2] to be less severe than that with big parasitic currents to the anode in our case, we corrected our results to the thick solid line in figure 4 that goes lower by $\sim 40\%$ at $I = 180$ A (accounting for the data [2]) and by $\sim 10\%$ at $I = 40$ A (just applying common sense). Now the mean argon plasma conductivity at the exit of the T-plasma torch can be evaluated as $\sigma \leq 118$ Ohm$^{-1}$cm$^{-1}$ for $I \leq 180$ A.

3. Evaluation of the mean temperature at the exit of the T-plasma torch
For this purpose, a reliable dependence of the argon plasma electrical conductivity at atmospheric pressure is necessary. It would be better if such dependence were experimental. The necessary information was found in [7-11]. Note that in [7] the final analytical function $\sigma(T)$ has been obtained as a result of strict numerical processing of argon plasma conductivity/temperature measurements similar to the ones made in [2]. As for the theoretical data, three works were analyzed published by R.S.Devoto [3], L.I. Grekov et al. [12] and P.P Kulik [13]. All these results are compared in figure 5.

It can be seen that R.S. Devoto’s curve [3] fits the experimental data better than the results of [12, 13].
Note that Baturin’s experimental function [7] nearly coincides with Devoto’s predictions, although in the paper [7] such a remarkable comparison is absent. It thus can be concluded that R.S. Devoto’s calculations [3] can be used as the sought after reliable temperature dependence \( \sigma(T) \) for argon at atmospheric pressure and temperatures in the range \( T = 800 - 20,000 \) K.

Figure 5 shows the boundaries of the present work’s data on argon conductivity as horizontal dotted lines. They indicate that the mean argon plasma temperature at the exit of the T-plasma torch lies in the range \( T \sim 1,000 – 19,500 \) K. Note that these temperatures characterize electrons (\( T_e \)) as well as heavy particles (\( T_{a,i} \)), as it has been determined previously that the argon plasma state in the atmospheric arc is very close to a local thermodynamic equilibrium [7].

4. Conclusions

The VA-characteristic method of electrical field strength measurements in the arc stabilizing channel was modified using an anode channel instead of a hole in the insulated inter-electrode insert.

Comparison of the present experiment with an independent one showed that the voltage drop across a presumably diffuse anode spot in the T-plasma torch should be small.

The analysis of the known literature data on \( \sigma_{\text{Ar}}(T) \) at atmospheric pressure showed that R.S. Devoto’s calculations [2] gave the most realistic function for \( T = (8 - 20) \cdot 10^3 \) K.

The present experiment showed that the mean conductivity of argon plasma at the exit of the T-plasma torch reaches about 118 Ohm \( ^{-1} \text{cm}^{-1} \) while its mean temperature does not exceed 19,500 K for arc currents \( I \leq 180 \) A.

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