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PLASMATRON CONSTRUCTION

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Abstract. This article discusses the calculational and constructional basis of linear DC arc discharge plasma jets. The aim is to construct an arc discharge plasmatron with the simultaneous experimental determination of exponents and coefficients for criterial equations used to calculate the construction parameters. As a result, a specific 50 kW plasmatron with minimized outer diameter has been designed and built. New coefficients of the criterial equations have been determined to calculate the constructional parameters for plasmatrons with a smooth anode and those with a stepwise anode. The principal construction of the plasmatron and experimentally determined and calculated characteristics are presented. The conformity of these data is rather good.

Key words: DC arc linear plasmatron, DC arc V-A characteristics, criterial equation of DC plasmatron.

In the metallurgy, mechanical engineering, chemical and other industries several types of plasmatrons are used to produce low-temperature plasma. However, linear arc discharge DC plasmatrons are most widespread. In terms of technology, plasmatrons with possibly small outer diameter appear to be preferable. Thus, one could use metal tubes for placing plasmatrons into the desired location.

Unfortunately, it has not been proved yet neither theoretically nor experimentally that the commonly used criterial equations [1], describing the behaviour of electrical arc in a plasmatron, will work properly if the design of the plasma jet will be changed slightly.

Thus, the objective of this work is to construct an arc discharge plasmatron and simultaneously experimentally determine the exponents and coefficients for the criterial equations used to calculate the constructional parameters.

Recent successful theoretical and experimental research on the stabilization of electrical arc by gas vortices and magnet fields allows one to calculate the plasmatron characteristics and to construct plasmatrons with the given parameters.

The processes in the electrical arc, burning under the specific conditions of a plasmatron, are very complicated and diversified. Currently, no exact methods for the calculation of integral characteristics for an arc discharge plasmatron are available. Therefore, a semi-empirical method is used for the calculation of plasmatron's integral characteristics, based on the similarity theory and experimental determination of criterial relationships for geometrically similar plasmatrons [1,2]. These criterial relationships can be used for designing plasmatrons with a number of conditions satisfied. These include the following:

1. The combustion chambers of plasmatrons must have similar geometry.
2. The performance temperatures of the inner surfaces of electrodes must be identical.
3. Similar electrodes must be made of the same material and switched on at the same polarity.
4. The working gas of the plasmatron must be the same and the temperature of the input gas must not differ from it.
5. The condition of kinematic similarity must be satisfied

$$\frac{v_l}{v_z} \approx \text{const},$$

where v_l is the tangential velocity of the gas vortex and v_z is the axial velocity.

The similarity criteria known from the classical aerodynamics are also used

$$M = \frac{v}{a}, \quad k = \frac{c_p}{c_v}, \quad Re = \frac{\rho v d}{\mu}, \quad Pr = \frac{\mu c_p}{\lambda},$$

where M is Mach number; v and a are gas velocity and sonic speed respectively; k is the coefficient equal to the ratio of gas heat capacities at constant pressure c_p and at constant volume c_v; Re is Reynold's number; ρ is density; d is diameter; μ is viscosity; Pr is Prandtl's number; and λ is thermal conductivity.

In addition, criteria reflecting the specific processes of a plasmatron must be used. Among these, the following are the most important:

– the criterion of the interaction of the exterior magnetic field and electrical current

$$S_B = IB/\left(\rho v^2 d\right),$$

where B is the induction of the magnetic field, I is the current of the arc,

– the electrical field criterion

$$S_l = \sigma E d^2 / I,$$

where σ is electrical conductivity, E is electrical field intensity,

– the voltage criterion

$$S_U = \sigma U d / I,$$

– the energy criterion

$$S_i = I^2 \Big/ \left(\sigma \rho v h d^3\right),$$

where h is the characteristic enthalpy of the jet,

– the Reinolds number as

$$Re = 4G/(\pi \mu d),$$

where G is the gas flow rate,

– the Knudsen number

$$Kn = \lambda_e / d,$$

where λ_e is the free path length of an electron in the gas.

The use of the Knudsen number is necessary since for the arc with unfixed length, the volt-ampere (V-A) characteristic is essentially dependent on the discharge voltage, which in turn is a function of the Knudsen number.

The most significant integral characteristics of an electrical arc are the efficiency characteristic and the V-A characteristic, which shows the dependence of voltage on current with the rest of significant parameters remaining constant.

The criterial equation of the V-A characteristic for a single chamber arc plasmatron is generally written as follows [3]:

$$U = A\left(\frac{I^2}{Gd}\right)^{\alpha}\left(\frac{G}{d}\right)^{\beta}(pd)^{\gamma}, \tag{1}$$

where A, α, β, and γ are the experimentally determined constants.

The general form of the criterial equation of the plasmatron efficiency is [3]

$$\frac{1-\eta}{\eta} = K\left(\frac{I^2}{Gd}\right)^{m}\left(\frac{G}{d}\right)^{n}(pd)^{q}\left(\frac{l}{d}\right)^{\varphi}, \tag{2}$$

where η is the efficiency, K, m, n, q, and φ are the experimentally established constants, and l/d is the relative length of the working chamber.

Our specific purpose was to construct a plasmatron with a minimized outer diameter and without any gas, water or electricity supply links on its outer surface. We chose two modifications of the so-called single chamber linear plasmatron operated by air. In the first modification, the length of the electrical arc is randomly changing (the so-called plasmatron with a smooth anode). For both cases, the operating gas is air, the cathode material hafnium and the anode material copper.

Traditionally, a tangential vortex ring with the diameter four to five times greater than that of the output electrode is used in gas vortex stabilized plasmatrons. Figure 1 shows the layout of such a plasmatron with this type of the vortex ring and a smooth anode.

To reduce plasmatron's diameter, we used a different vortex ring. Here, the gas passes through a four-path coil with a right angle profile. The axis of the coil coincides with that of the plasmatron and at the outlet from the vortex ring, the gas velocity vector consists both of tangential and axial components (the angle between the gas velocity vector and the plasmatron axis is 83°). Such a design allowed us to reduce the outer diameter of the plasmatron.

Figure 2 shows the layout of the plasmatron.

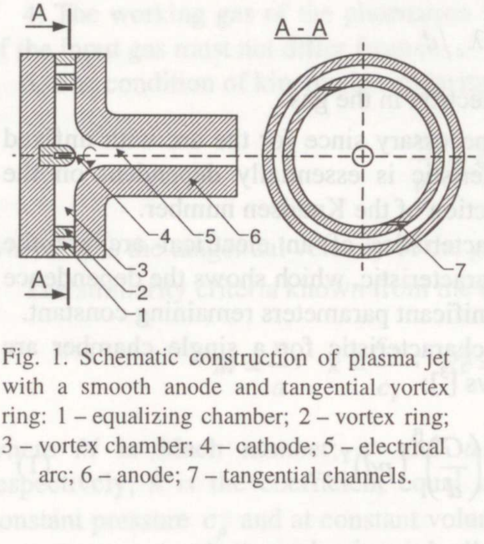

Fig. 1. Schematic construction of plasma jet with a smooth anode and tangential vortex ring: 1 – equalizing chamber; 2 – vortex ring; 3 – vortex chamber; 4 – cathode; 5 – electrical arc; 6 – anode; 7 – tangential channels.

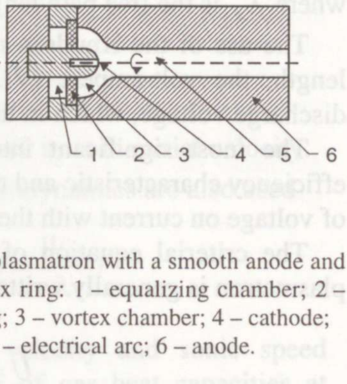

Fig. 2. A plasmatron with a smooth anode and axial vortex ring: 1 – equalizing chamber; 2 – vortex ring; 3 – vortex chamber; 4 – cathode; 5 – electrical arc; 6 – anode.

Since for this plasmatron design, the constants of the expressions (1) and (2) are not known, we used initially the corresponding formula of a plasmatron with the tangential vortex ring.

In the case of smooth anode, the equation of the V-A characteristic is [3]

$$U^{+} = 1290\left(\frac{I^2}{Gd}\right)^{-0.15}\left(\frac{G}{d}\right)^{0.3}(pd)^{0.25}, \qquad (3)$$

and the efficiency equation [3]

$$\frac{1-\eta}{\eta}=5.82\cdot10^{-5}\left(\frac{I^2}{Gd}\right)^{0.256}\left(\frac{G}{d}\right)^{-0.256}(pd)^{0.3}\left(\frac{l}{d}\right)^{0.5}. \tag{4}$$

These equations are valid for a wide range of parameters.

In addition, we take into account the condition that at the tip of the plasmatron nozzle, the gas velocity does not exceed the sonic speed

$$d_{kr}=2\left(\frac{G}{\pi\rho_{kr}a_{kr}}\right)^{0.5}, \tag{5}$$

where a_{kr} is the sonic speed at the gas temperature in the outlet of the nozzle.

Let us select

$$d=1.3\,d_{\mathrm{kr}}=2.6\left(\frac{G}{\pi\rho_{\mathrm{kr}}a_{\mathrm{kr}}}\right)^{0.5}. \tag{6}$$

It has been found experimentally that the optimal ratio of the plasmatron channel length to the diameter is

$$\frac{l}{d}=20. \tag{7}$$

In the calculations, the pressure of the working gas p and both the initial and final temperatures T_a and T_l should be given first for defining the critical parameters. On this basis, the critical gas density and velocity both at the initial and final temperature can be found in the respective handbooks. These are necessary data for the calculation of the vortex ring openings and the channel diameter.

In addition to the above Eqs. (1)–(4), we used the expression of the electrical power of the plasmatron

$$U\cdot I=N \tag{8}$$

and the expression for gas enthalpy

$$G\left(h_l-h_a\right)=N\eta,$$

where h_l is the gas enthalpy at the final temperature and h_a is the gas enthalpy at the initial temperature or

$$G\cdot\Delta h=IU\eta. \tag{9}$$

Thus we obtain a system consisting of six equations (3), (4), (6)–(9), which allows us to calculate the main parameters of the plasmatron.

For the calculation, we need the expected power of the plasmatron N or the gas flow rate G, the temperatures T_a and T_l, and the pressure p, which also defines the plasmatron power.

Since the system of equations can not be solved analytically, we used the approximation method. The data on the dependencies of gas enthalpy, density and sonic speed on the temperature and pressure were taken from [4].

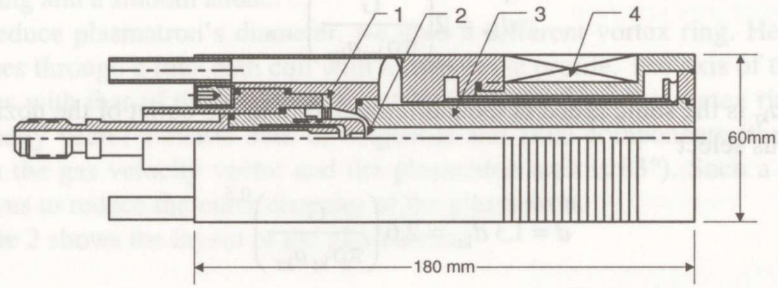

Fig. 3. A real plasmatron with a smooth anode and axial vortex ring: 1 – vortex ring; 2 – cathode; 3 – anode; 4 – magnet coil.

Supported by the above system of equations, we calculated and built a smooth anode 30 kW plasmatron. Its cross-section is given in Fig. 3. However, tests showed that its real parameters are not in conformity with the calculated figures. Namely, the voltage of the arc was significantly higher. Evidently, the reason lies in the fact that our plasmatron is geometrically not exactly identical with the plasmatron type, which the calculations are based on. The main difference can be found in the vortex rings, which has been considered above. Therefore we determined experimentally new coefficients A, α, β, and γ for the criterial equation of the V-A characteristic (1) and obtained:

$$U = 3870\left(\frac{I^2}{Gd}\right)^{-0.19}\left(\frac{G}{d}\right)^{0.5}(pd)^{0.25}. \qquad (10)$$

New parameters of the plasmatron have been calculated, using Eq. (10) instead of Eq. (3). We obtained $N = 27.4$ kW, $p = 10^5$ N/m^2, $T_a = 300$ K, $T_l = 4000$ K.

The parameters calculated were $G = 2.18$ g/s, $I = 128.3$ A, $U = 213.6$ V, $\eta = 0.6$, $d = 7.0$ mm, $l = 140$ mm.

With Eq. (10), we calculated the characteristics of this plasmatron for two different flow rates of gas: 2.18 and 2.9 g/s.

The results are illustrated in Fig. 4. The points measured experimentally are also shown in this figure. As can be seen, the conformity of the measurement results with the calculated values is good (the difference does not exceed 6%).

Measured efficiency was $\eta = 0.64$. This was determined from the measurements of the heat carried away by the cooling water and is evidently higher than the calculated values due to neglecting other (relatively low, but difficult to determine) losses. Thus, the efficiency value can be regarded as matching well with the calculated values.

As we can see from the results, the efficiency of the plasmatron with a smooth anode is relatively low (0.6). The efficiency coefficient of the stepwise anode is significantly higher since the length of the electrical arc is fixed. The anode layout of such a plasmatron is shown in Fig. 5.

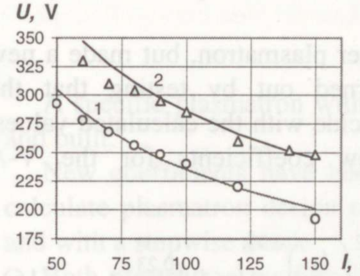

Fig. 4. V-A characteristics of the plasmatron with a smooth anode: 1 – G = 2.18 g/s; 2 – G = 3.1 g/s.

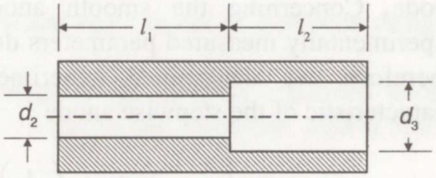

Fig. 5. A stepwise anode.

For the calculations of a plasmatron structure with a stepwise anode, we used a system of equations principially similar to that of the smooth anode, except for the equation of the V-A characteristic, which has the following form for the stepwise anode [3]:

$$U = 4.55\left[1 + 4.6\cdot 10^{-5}\left(\frac{I}{d_2}\right)\right]\left(\frac{G}{d_2}\right)^{0.22}\left(\frac{l_2}{d_2}\right)^{0.95}\left(pd_2\right)^{0.23}. \quad (11)$$

In addition, we applied the condition where the voltage of the plasmatron with a stepwise anode must remain lower than that of the respective plasmatron with a smooth anode. If it is not the case, the fixation of the arc behind the step will disappear, and the plasmatron will start to work as the one with a smooth anode.

With an additional condition

$$U \leq 0.84U_s, \quad (12)$$

where U_S is calculated using Eq. (10), we obtain

$$U = 0.84 \cdot 3870 \cdot \left(\frac{I^2}{Gd}\right)^{-0.19} \left(\frac{G}{d_2}\right)^{0.5} (pd_2)^{0.25} \tag{13}$$

Thus we obtained a system of equations (4), (6), (8), (9), (11), and (13) for the calculation of the plasmatron with a smooth anode under experimentally found supplementary conditions

$$d_3 = 2d_2 , \tag{14}$$

$$l_3 = 3d_3 . \tag{15}$$

This system has been solved in the same way as for the smooth anode, using the approximation method. With this system, we calculated the plasmatron with a stepwise anode for the capacity $N = 50$ kW.

In building, we used the housing of the former plasmatron, but made a new anode. Concerning the smooth anode, it turned out by testing that the experimentally measured parameters do not coincide with the calculated values. Therefore, we determined experimentally new coefficients for the V-A characteristic of the stepwise anode

$$U = 11.2 \left[1 + 2.47 \cdot 10^{-5} \left(\frac{I}{d_2}\right)\right] \left(\frac{G}{d_2}\right)^{0.22} \left(\frac{l_2}{d_2}\right)^{0.95} (pd_2)^{0.23} . \tag{16}$$

Then we calculated the new plasmatron with a stepwise anode, using Eq. (16) instead of Eq. (11).

As a result, the parameters given were $G = 5.8$ g/s, $p = 10^5$ N/m^2, $T_a = 300$ K, $T_l = 3600$ K.

The parameters calculated were $I = 130.6$ A, $U = 342.6$ V, $N = 44.7$ kW, $\eta = 0.76$, $d_2 = 10$ mm, $l_2 = 58$ mm, $d_3 = 20$ mm, $l_3 = 60$ mm.

Using Eq. (14), the V-A characteristic of this plasmatron has been calculated for the gas flow rate 5.8 g/s.

Figure 6 shows the calculated V-A characteristic and the experimentally determined points. As can be seen, the conformity of the experimentally determined points with the calculated values is rather good in the rising part of the characteristic (the difference does not exceed 6%). This is the region of the normal operation of the plasmatron, and the criterial equations used describe only this region.

The measured value of the efficiency coefficient is 0.8. In the case of the plasmatron with a smooth anode, the measured efficiency value is somewhat higher for the reasons mentioned above. As the results show, the efficiency coefficient of the plasmatron with a stepwise anode is essentially greater than that of the plasmatron with a smooth anode.

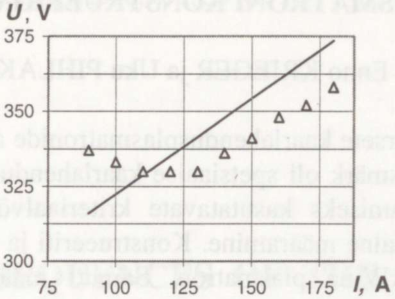

Fig. 6. V-A characteristic of the plasmatron with a stepwise anode: $G = 5.8$ g/s.

CONCLUSIONS

A specific plasmatron with the minimized outer diameter has been designed and built.

New coefficients have been determined for the criterial equations used to calculate plasmatron design parameters, in particular, for those with a smooth and with a stepwise anode.

Both plasmatron modifications have been built and the calculation formulas have been checked for different operational regimes. The conformity of the results with the calculated values is rather good (the error does not exceed 10%).

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PLASMATRONI KONSTRUEERIMINE

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On käsitletud lineaarsete kaarlahendusplasmatronide arvutamise ja konstrueerimise aluseid. Töö eesmärk oli spetsiaalse kaarlahendusplasmatroni konstrueerimine ja selle arvutamiseks kasutatavate kriteriaalvõrrandite astendajate ja kordajate eksperimentaalne määramine. Konstrueeriti ja valmistati minimeeritud välisläbimõõduga 50 kW-ne plasmatron. Samuti määrati nii sileda kui ka astmelise anoodiga plasmatroni arvutamise kriteriaalvõrrandite koefitsientide ja astmenäitajate väärtus. Plasmatroni arvutuslikud ja eksperimentaalselt määratud karakteristikad on heas kooskõlas.