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Conditions for Plasma Jet Formation in a Laminar Plasmatron

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Abstract—The laminar plasma jet is an effective tool of plasma technologies for material processing thanks to great values of bulk temperature and high penetration of a plasma stream. However, laminar stream formation in an axial jet plasmatron is connected with a number of difficulties caused by physical restrictions. Conditions of formation of a laminar stream at the exit from a plasmatron nozzle with interelectrode inserts are found when using the most widespread plasma-forming gases. With use of a method of universal characteristics of arc and heat-transfer model of arc of jet plasmatrons, calculation of characteristics of the arc compressed by walls of the discharge channel is carried out; the necessary arc compression ratio in the stable laminar stream mode and its extreme values taking into account the permissible thermal load on walls of the discharge channel in the arc stabilization zone are defined. It is shown that reduction of the diameter of the plasmatron discharge channel reducing diameter of the laminar plasma stream exhausting from a plasmatron nozzle reduces the permissible values of the arc compression ratio. Influence of the cooling mode of walls of the plasmatron arc channel formed by interelectrode inserts on the arc compression ratio at separate water cooling of each interelectrode insert and at their joint cooling is shown. All calculations were carried out for the values of gas consumption and discharge channel length meeting a basic condition of laminar stream formation of $\mathrm{Re} < 150$. The arc current values necessary for a laminar plasma stream formation, depending on the discharge channel section and a plasma-forming gas consumption taking into account thermal properties of the gas environment, are determined. The method proposed in this article makes it possible to calculate an arc column temperature profile in the stabilization zone of a laminar plasmatron and can be used when developing plasmatrons with a stable laminar stream of set plasma-forming gas.

Keywords: arc plasmatron, laminar plasmatron, heat exchange model of arc

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INTRODUCTION

A laminar plasma jet is an extremely effective tool of modern plasma technology. The large values of mass-average temperature and high penetrability of a laminar jet in the surrounding gaseous environment offer great opportunities of its use in various fields of plasma technology. However, the formation of a laminar jet using an axial jet plasmatron runs up against fundamental, often impossible physical conditions. If there is a developed near-wall layer of the gas flow at the exit of the discharge channel and the plasmatron nozzle, even at a laminar flow pattern, then, from the point of view of hydrodynamic stability [3], the gas-dynamic structure in the form of concentric near-axial plasma flows in the laminar jet and external flow of the "cold" gas is unstable. The presence of high temperature gradients and the intense hydrodynamic perturbations at the interface of these flows lead to the decay of the laminar plasma jet immediately at the exit of the plasmatron nozzle.

The aim of the work is to develop a method for determining the values of the arc compression ratio in the stabilization zone necessary for the formation of a stable laminar jet at the plasmatron exit taking into account the allowable thermal load on the walls of the discharge channel and determining the arc current necessary to obtain a laminar plasma jet as a function of the cross section of the discharge channel and the consumption of the plasma-forming gas taking into account the thermal properties of the gas medium.

THE DEGREE OF ARC COMPRESSION BY THE WALLS AS AN INDICATOR OF THE APPEARANCE AND STABILIZATION OF A LAMINAR PLASMA JET IN THE PLASMATRON

An indispensable condition for the stability of the laminar jet at the exit of the plasmatron is the absence of the near-wall flow of the "cold" gas. The entire out-

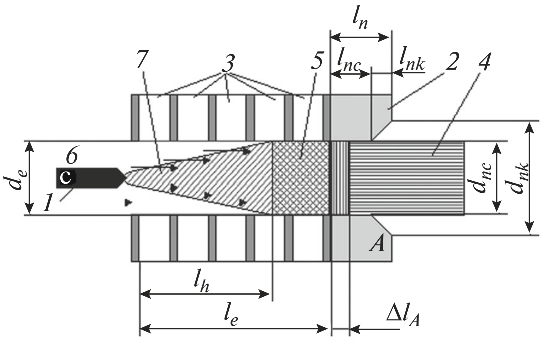

Fig. 1. Structure of the electric arc laminar plasmatron: (*1*) cathode; (*2*) anode; (*3*) interelectrode inserts (sections of the discharge channel); (*4*) laminar plasma jet; (*5*) region of laminar plasma flow; (*6*) gas flow in the discharge channel; (*7*) region of turbulent plasma flow. l_e—Length of the discharge channel; l_h—area of gas heating by the arc; d_{nc}—diameter of the cylindrical part of the nozzle channel; d_{nk}—diameter of the output section of the conical part of the nozzle channel; $\Delta_{\rm la}$—binding area of the anode spot; d_e—diameter of the plasmatron discharge channel.

put section of the discharge channel or the nozzle of the jet plasmatron should be filled with a laminar plasma jet formed by an electric arc column (Fig. 1).

If the value of the Peclet criterion Pe < 250, then the process of molecular heat conduction prevails over convective heat transfer in the gas layer between the column and the walls of the discharge channel, and to calculate the gas temperature in the layer, it is possible to accept the conditions

$$T_r = \Lambda^{-1} S_r(T), \; S_r = \frac{S(T_{\rm sa}) - S(T_w)}{\ln\left[\dfrac{S(T_{\rm sa}}{S(T_w)}\right]}, \tag{1}$$

where $T_w \approx 700$ K is the gas temperature at the input to the discharge channel, $T_{\rm sa}$ is the surface temperature of the arc column, S_r is the heat conduction function of the gas, and Λ^{-1} is the notation of the inverse function.

In accordance with the boundary layer theory, the thickness of the boundary layer on the wall of the discharge channel Δ_m is directly proportional to the gas viscosity in the compression layer

$$\Delta_m \sim \sqrt{\eta(T_r)}, \tag{2}$$

therefore, the degree of the arc compression required for locking the gas in the wall layer is determined by the condition

$$\delta_r = \frac{2r_a}{d_e}, \; \frac{1}{\Delta_r} = \frac{d_e}{2}(1 - \delta_r) < \Delta_m, \tag{3}$$

where r_a is the radius of the arc column and Δ_r is the thickness of the wall layer between the wall of the discharge channel and the surface of the arc column.

In other words, the arc column should fill the entire output section of the discharge channel; i.e., the arc in the output section of the channel should be in the compression mode by the walls. It is extremely difficult to ensure this condition in the presence of even small mass gas flows in the channel, since the degree of arc compression by the walls δ_r should be no less than such a value at which the thickness of the compression layer Δ_r is much less than the thickness of the dynamic boundary layer Δ_m on the wall of the discharge channel. In this case, the high gas viscosity in the compression layer due to the proximity of the $T_{\rm sa}$ isotherm completely blocks the cross section of the layer for any, even small, gas mass flow outside the arc column compressed by the walls. The entire gas mass flow at the exit of the discharge channel is captured by the arc column, thereby forming a steady laminar plasma jet at the channel exit. Such a jet drowned in the open space of atmospheric pressure gas is distinguished by a high penetrating power and low momentum dissipation rate because of the high gas viscosity at the jet boundary, and its surface behaves like a "solid" that is impermeable to the surrounding gas. Thus, if the value of the arc compression ratio, e.g., in argon (${}_{\rm Ar}\delta_r$), which ensures the stability of the laminar jet at the exit of the plasma jet is known from the experiment, for another gas, the required arc compression ratio can be calculated as

$$_{\rm gas}\delta_r = 1 - (1 - {}_{\rm Ar}\delta_r)\sqrt{\frac{\eta(T_r)_{\rm gas}}{\eta(T_r)_{\rm Ar}}}. \tag{4}$$

CALCULATION OF THE DEGREE OF ARC COMPRESSION AT THE EXIT OF THE DISCHARGE CHANNEL OF THE ARC PLASMATRON NECESSARY FOR THE FORMATION OF A LAMINAR JET

The results of the study of the electrical and thermal characteristics of a jet plasmatron generating a stable argon laminar jet longer than 0.5 m are presented in [1]. The discharge channel of the plasmatron had the diameter of $d_e = 6$ mm, and the arc current at which the steady mode of generating a laminar jet was achieved was $I = 162$ A. Using the method of arc universal characteristics and the conditions of the arc heat exchange model [2], it is possible to calculate the arc compression ratio ${}_{\rm Ar}\delta_r$ in a real laminar plasmatron [1] ensuring the formation of the laminar argon plasma jet. The calculations showed that the required degree of arc compression ${}_{\rm Ar}\delta_r$ for different gases in the plasmatron with a separate cooling system for the copper sections of the discharge channel with accuracy to the third digit after the decimal point is ${}_{\rm Ar}\delta_r = 0.962$ (Table 1).

Table 1. Degree of arc compression by the walls required for the formation of a stable laminar jet at the outlet of the discharge channel

Parameters	Gas					
	Ar	90% Ar + 10% H_2, wt %	N_2	Air	He	H_2
T_r, K	2664	2885	4643	3068	3917	3109
$\eta(T_r)$, 10^{-4} Pa s	1.1	1.154	1.3	1.009	1.421	0.486
S_r, kW/m	0.13	0.435	0.716	0.432	2.356	4.528
δ_r	0.962	0.961	0.959	0.964	0.957	0.975

Table 2. Maximum allowable degrees of arc compression by the walls of a discharge partitioned copper channel cooled with water (d_e = 6 mm)

Mode	Gas						
		Ar	90% Ar + 10% H_2, wt %	N_2	Air	He	H_2
A	I, A	290	296	279	280	384	142
	δ_r	0.984	0.925	0.845	0.956	0.878	0.469
B	I, A	337	481	449	430.4	844	355
	δ_r	0.987	0.969	0.907	0.974	0.949	0.665

CONDITIONS FOR THE FORMATION OF A LAMINAR PLASMA JET IN AN ARC PLASMATRON WITH A PARTITIONED DISCHARGE CHANNEL

To ensure the degree of the arc compression required for the formation of a stable laminar jet in the partitioned discharge channel of the plasmatron, its design and water cooling system should ensure heat removal under the intense thermal load on the internal surface of the discharge channel. In the arc jet plasmatron, this was implemented by applying a partitioned discharge channel with water-cooled copper interelectrode inserts (IEI) with a separate cooling system of sections, and in the spectral plasmatron [4], with an integrated water cooling system of sections (Fig. 2). Table 2 presents the results of calculations of the operating current of the plasmatrons of these two types with the discharge channel diameter d_e = 6 mm, which provides the maximum arc compression ratio allowed by the thermal load of sections.

For the known design of a copper discharge channel with separate water cooling of sections (type A—arc jet plasmatrons with IEI), the calculated values of the allowed heat load of sections q_{sc} = 20 W/mm^2 (argon), 30 W/mm^2 (nitrogen, air, 90% Ar + 10% H_2 mixture), and 50 W/mm^2 (helium, hydrogen). For the construction of a partitioned copper discharge channel of a spectrometric plasmatron with combined water cooling (type B, Fig. 2), the calculated values of allowed heat load of sections q_{sc} = 25 W/mm^2 (argon), 50 W/mm^2 (nitrogen, air, 90% Ar + 10% H_2 mixture), and 120 W/mm^2 (helium, hydrogen). The allowed thermal loads of sections are determined on the basis of experimentally obtained physical characteristics of plasmatrons processed using the method of arc universal characteristics. The calculations were carried out for the values of the gas flow rate and the length of the discharge channel satisfying the basic condition for the formation of a laminar jet Re <150 [1].

It follows from a comparison of the data given in Tables 1 and 2 that, using the arc compressed by the walls of the discharge channel with a diameter of d_e = 6 mm, a laminar jet can be produced in the plasmatron

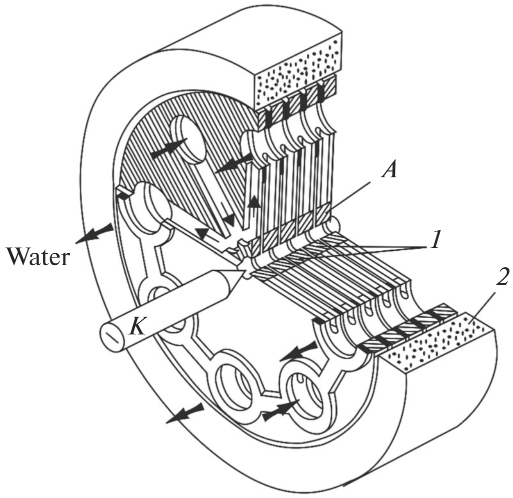

Fig. 2. Design of the discharge channel of the plasmatron with intense cooling of the sections [4]: (*1*) discharge channel; (*2*) plasmatron body. *K*—cathode; *A*—anode.

Table 3. Dependence of the maximum degree of arc compression by the walls of the discharge channel with different diameter

Type	Gas	Channel diameter d_e, mm				
		6	5	4	3	2
A	Ar	290 A/0.984	215 A/0.982	150 A/0.98	93 A/0.975	48 A/0.967
B	Ar	340 A/0.987	256 A/0.986	175 A/0.984	108 A/0.98	58 A/0.975
	Air	430 A/0.974	315 A/0.972	207 A/0.968	123 A/0.963	57 A/0.951
	90% Ar + 10% H_2	481 A/0.967	359 A/0.967	254 A/0.963	158 A/0.956	80 A/0.942

Table 4. Modes of formation of a laminar plasma jet by an arc in helium and nitrogen compressed by the walls of the discharge channel of type B plasmatron

Parameters	Gas			
	helium ($\delta_r = 0.958$)		nitrogen ($\delta_r = 0.9$)	
d_e, mm	10	8	10	8
I, A	1779	1360.5	874.5	651.5
q_{sc}, W/mm^2	102	117.7	40.5	44.0
T_{a}, 10^3 K	24.1	23.9	17.1	17.0
E, V/m	1799	2175	1454	1696

of type A construction only when working with argon. In the plasmatron of the type B, a steady laminar jet can be formed when working with argon, 90% Ar + 10% H_2 gas mixture, and air.

The decrease in the diameter of the discharge channel of the plasmatron and, as a consequence, the decrease in the diameter of the laminar plasma jet emitted from the plasmatron nozzle reduces the allowed values of the arc compression ratio. This leads to the decrease in the stability of the laminar jet with the decrease in the diameter of the channel. Table 3 shows the values of the maximum allowed degree of arc compression by the walls of the discharge channel of different diameters for the plasmatron under consideration. It follows from Table 3 that a steady laminar plasma jet can be formed by the arc compressed by the walls of the discharge channel in argon with any plasmatron design and any diameter of the discharge channel. When working in air, a laminar plasma jet can be obtained only at increased thermal loads of the discharge channel walls in plasmatrons of type B and only with the channel diameter larger than 3 mm. The formation of a laminar plasma jet in the Ar–H gas mixture is possible only in a plasmatron of type B with the channel diameter of ~4 mm or larger. It follows from the results shown in Tables 1–3 that the formation of a laminar jet using a jet plasmatron operating with nitrogen or hydrogen is very difficult, since it is not possible to obtain the necessary degree of arc compression by the walls in these gases with the allowed thermal loads of the discharge channel. When working with helium and carbon monoxide, a laminar plasma jet can be formed only in the discharge channel of a large-diameter plasmatron of type B at the elevated arc current values.

CHARACTERISTICS OF LAMINAR ARC PLASMATRONS WITH A PARTITIONED DISCHARGE CHANNEL

When working with helium and carbon monoxide, it is possible to form a laminar plasma jet in a large-diameter discharge channel and at elevated current values (Table 4). Only under these conditions is it possible to ensure the required degree of arc compression (Table 5) in a plasmatron of type B allowing increased limiting thermal loads on the copper walls of the discharge channel intensely cooled with water. Table 4 also shows the mean values of temperature and electric field strength of the arc column of a laminar plasmatron of type B calculated by the method of universal characteristics. Tables 5–7 shows the parameters of the laminar plasmatron calculated by the method of the arc universal characteristics necessary to produce a steady laminar plasma jet in argon, 90% Ar + 10% H_2 mixture, and air. It can be seen that the formation of a laminar argon jet is possible in a plasmatron of type A even with the channel diameter of 2 mm (Table 5), since the thermal loads on the channel walls do not exceed $q_{\text{sc}} = 20$ W/mm^2. The increased thermal loads on the walls of the discharge channel when working with the argon–hydrogen mixture (Table 6) and air (Table 7) require the use of a plasmatron of type B.

It follows from the condition for the formation of a laminar plasma jet dictated by blocking of the gas flow in the arc compression layer by walls in the stabiliza-

Table 5. Modes of formation of a laminar plasma jet by an arc in argon compressed by the walls of the partitioned copper channel of type A plasmatron

Parameters	Channel diameter, d_e, mm						
	10	8	6	5	4	3	2
I, A	346	246	164.5	128.5	97.5	69.5	44.0
q_{sc}, W/mm^2	8.825	8.78	9.39	10.02	11.34	13.8	18.96
T_a, 103 K	12.8	12.76	12.7	12.64	12.6	12.54	12.46
E, V/m	801.3	897.3	1076.2	1224.4	1461.2	1871.3	2707.4

Table 6. Modes of formation of a laminar plasma jet by an arc in Ar–H mixture compressed by the walls of the partitioned copper channel of type B plasmatron

Parameters	Channel diameter, d_e, mm				
	10	8	6	5	4
I, A	969.5	671.5	433.0	334.5	249.0
q_{sc}, W/mm^2	47.78	44.82	44.25	45.7	49.51
T_a, 10^3 K	15.9	15.89	15.87	15.85	15.84
E, V/m	1548.3	1677.6	1926.2	2146.1	2499.8

Table 7. Modes of formation of a laminar plasma jet by an arc in air compressed by the walls of the partitioned copper channel of type B plasmatron

Parameters	Channel diameter, d_e, mm					
	10	8	6	5	4	3.5
I, A	752.5	527.0	339.5	259.5	190.5	158.5
q_{sc}, Вт/mm^2	33.88	34.91	37.8	40.5	45.38	48.7
T_a, 10^3 K	14.41	13.86	13.22	12.87	12.53	12.34
E, V/m	1414.4	1665.1	2098.7	2451.3	2993.5	3378.7

tion zone of the laminar plasmatron that argon is the most acceptable gaseous medium. The formation of a laminar plasma jet in a plasmatron of type A working with argon is characterized by wide possibilities in controlling the diameter and power of the jet at the average output temperature of ~12000 K. At the same time, the creation of a plasmatron is not associated with problems of large thermal loads on the walls of the discharge channel, and the required arc current when operating in argon is significantly lower than that in plasmatrons working with other gases. In addition, the penetrating ability of a laminar argon jet in the surrounding medium of atmospheric pressure at the exit of the plasmatron significantly exceeds the capabilities of a jet of another chemical composition. This property of the argon jet is associated with low values of the thermal conductivity at relatively high viscosity of argon, which ensures low energy dissipation rates of the jet as it moves in the atmosphere. Of practical interest is the use of plasmatrons that generate a laminar argon-hydrogen plasma jet. The temperature and enthalpy of a 90% Ar + 10% H_2 gas jet (Table 6) significantly exceed the characteristics of an argon jet (Table 5). However, in this case, it is necessary to use a special design of the partitioned discharge channel of a plasmatron of type B, and the minimum diameter of the discharge channel of the plasmatron should not be less than 4 mm. In this case, the arc current is significantly higher than that in the plasmatron running on argon.

The problem of the formation of a laminar air plasma jet is the choice of the cathode material that is operable at the elevated operating currents of the compressed arc. In addition, the plasmatrons that form this stream should withstand the increased thermal loads on the walls of the discharge channel, already reaching q_{sc} = 50 W/mm^2 at the channel diameter of 3.5 mm (Table 7).

The formulated conditions for the formation of a stable laminar jet in arc plasmatrons with a partitioned discharge channel and the results of calculations of the characteristics of the compressed arc of a laminar plasmatron explain why the production of laminar plasmatrons lead to positive results only in the case of argon plasma. For example, in [1], the possibility of the formation of an arc in the discharge channel with the diameter of 6 mm of a laminar argon plasma jet having high penetrating power (the length of the jet at the plasmatron output was up to 0.5 m) was proved. The arc current of $I = 162$ A and the average mass temperature of the jet of $T_{\mathrm{st}} = 11870$ K necessary for this were close to the values given in Table 5.

CONCLUSIONS

A method for calculating the universal characteristics of the arc has been developed, and within the arc heat exchange model, the conditions for obtaining the degree of compression of the arc column at the exit of the discharge channel of the arc plasmatron necessary for the formation of a stable laminar plasma jet of the given chemical composition have been determined. Achievement of the required value of this parameter in the stabilization zone of the plasmatron laminar jet is a necessary condition for obtaining low values of the Reynolds number, which should not exceed 150. The calculated characteristics of the arc and the formulated conditions for achieving the required degree of its compression make it possible to determine the arc current required to obtain the laminar plasma jet for the given values of the diameter of the discharge channel and the mass flow of the plasma-forming gas of different chemical compositions taking into account the thermal characteristics of the gaseous medium. The proposed method makes it possible to calculate the temperature profile of the arc column in the stabilization zone of the laminar plasmatron and can be used in the development of plasmatrons with a steady laminar jet of the given plasma-forming gas.

CONFLICT OF INTERESTS

The authors declare that they have no conflict of interest.

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