THE EFFECT OF GAS INLET LOCATION AND INTENSITY ON PLASMA TORCH CHARACTERISTICS

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Abstract

Results on investigation of voltage-current characteristics (VCC) were generalized employing method of dynamic similarity theory and presented for single-chamber plasma torch (PT). The research has been carried out under different flow rate and distribution of air into reaction chamber. The window of stable operation is: airflow rate was $80 \times 10^3$ kg s$^{-1}$, power between 250 and 450 kW.

The effect of injection intensity on plasma jet parameters has been established. The date may serve as a basic in developing of PT and electric arc discharged channels design.

1. Introduction

Arc discharged plasma is an effective method of treating surfaces, sputtering, etching, deposition of coatings and a range of other processes. Mainly all of plasma technological processes run at high temperature and velocity in PT or plasma discharge channels. The external simplicity of PT in reality is related with very profound physical phenomena of electromagnetic, thermal or dynamical nature. Although the evaluation of theory of electric arc is in a progress, the exact prediction method of integral arc discharges characteristics is unable because of a very complicated and different phenomena undergoing in the electric arc. Therefore a semi-empirical method prediction of integral PT characteristics is only available. It appeals on experimental establishment of critical dependences of geometric similar PT.

The analysis of similarity of physical processes undergoing in PT allowed creation general methods of projection of them [1]. This has been related with the consideration that despite to the complexity of the process, the number of working regime determinant parameters of PT is small and near to the number of primary criterions. So, non-dimensional equations have been indispensable for qualitative characterization of physical processes in PT. Consequently the voltage-current (U-I) characteristics have been measured in the DC plasma generator employing for different purpose and operating in atmospheric pressure air or nitrogen. The main aim of this work is to study, summarize and describe the VCC of PT. In this paper the results on investigation such PT parameters as VCC has been presented.

2. Theoretical consideration

During the process when under tangential injected gas the arc inside the plasma generator is reduced and stabilized, VCC became as rising [2,3]. When the mixed injection (radial and tangential) in different locations is employed, the electric arc is strongly turbulized and there
appears a possibility to heat much larger amount of gas in the PT of reduced dimensions. Thus the voltage drop in such plasma generator increases up to 80% and there appears the possibility for better control of plasma forming process. The characteristics of such plasma source can be described employing the system of differential equations of continuity, impulse conservation, energy, state and Maxwell's considering to Ohm's law [1,4,5]. The solution of equation system even in the simple occasions, when magnetization of particles, turbulent flowing, radiation or gravity does not exist, is extremely complicated. So the application of similarity theory is on a very high importance. Similarity criterions of physical phenomena could be found in two different ways: I) employing so called -theorems of finite difference theory or II) on the ground analysis of equations describing the pending phenomena. The level of fullness and reliability of solutions of similarity conditions in both cases depends on the fullness of initial information.

On the ground of proceedings of M. Shukov [1,6] and O. Yas'ko [7] schools, the power criterion \( N_r = \frac{I^2}{\sigma \rho w h d^3} \), the Reynolds number \( Re = \frac{\rho w d}{\mu} \), the Knudsen number \( Kn = \frac{\lambda}{d} \) and regime characteristics \( \frac{G_{ch}}{G} \) has been used for the generalization of phenomena in PT. Here \( I \) is current (A), \( \sigma \) - electrical conductivity (m m \(^{-1}\)), \( \rho \) - gas density (kg m \(^{-3}\)), \( G \) is mass flow rate (kg s \(^{-1}\)), \( w \) - gas velocity (m s \(^{-1}\)), \( d \) - anode diameter (m), \( \mu \) - viscosity (N s m \(^{-2}\)), \( l \) - distance (m) and \( \lambda \) - electron free track length (m). Then the VCC may be presented analytically according to equation:

\[
\frac{Ud}{I} = f(N_r, Re, Kn, \frac{G_{ch}}{G}, I).
\]  

In the case of the single-chamber PT with gas vortex stabilization, smooth surface of exhaust part of anode and free of auxiliary magnetic field, dimensionless arc voltage \( N_r = c_0 I^2 / (Gd) \) approximately may be defined through following criterions [6]: \( N_r = c_1 I^2 / (Gd) \), \( Re = c_2 G / d \), and \( Kn = c_3 / (pd) \).

\( c_0, c_1, c_2, \) and \( c_3 \) are dimensional combination of values reflecting physical properties (density, viscosity, electric conductivity etc.) repeating as constant, \( p \) is the pressure (Pa). The other possible criterion, such as Mach or Euler numbers are on the strength of \( Re \) and \( Kn \), so they doesn't enter to the number of characteristic parameters. Thus VCC of the mentioned above plasma source may be presented analytically in the following way:

\[
\frac{Ud}{I} = A (\frac{I^2}{Gd})^n (\frac{G}{d})^m (pd)^k.
\]

Subject to the plasma generator type, nature of plasmen gas, polarity of connection electrodes to power source and other parameters, the mentioned equation may have different expression.

Experiment has showed that exponent indexes \( n, m, \) and \( k \) varies only negligibly in the enough wide ranging. So, it is possible to consider them as constant values without making a significant error.

Particular values of exponent indexes have been determined in graph method. In that case it is more practical to take a priority for the system of logarithmic axis, what has been done in this work.

3. Experimental equipment and technical details

Two linear dc plasma torches of different configurations with hot cathode and step-formed anode were used. One of them 250 kW of power, with radial and tangential injection, was
designed especially for produce non-equilibrium plasma jet. The schematic presentation of the PT is shown in Fig. 1. It consists of a cathode junction 1 with tungsten cathode 2, cathode-coupled section for arcing 3, diffuser 4, 5, insulation rings, and step-formed anode 6. In the case when magnetic stabilization of flow is necessary, the coil 7 is useful.

By the selection of design pt the preference has been given to the pt with neutrals, fixed average arc length, and step-formed exit electrode. This allowed create the prosperity for arc shunting after a step and ensure the stability of medium length of electric arc in the wide range of gas flow and current variation. The mentioned plasma source also differs from the ordinary plasma sources with the slightly conical expanded solid step formed anode. The diffuser type anode serves for reducing of the drop of static pressure along the chamber channel. The total length of pt is 0.28 m, the diameter of tight part anode – 0.03 m, diameter after the step – 0.04 m. The diffuser part of the torch is isolated from the anode and makes two neutral sections separated between trough insulating rings of glass textolite. Each ring contains three blowholes of tangential air supply (g1, g3 and g5) for the arc stabilization.

One of the simplest and acceptable ways to influence on the arc for production of non-equilibrium plasma is the radial injection thin stream of cold gas circular into different cross section of rechargeable chamber. On the end of each conical section 12 radial blowholes of 2 \times 10^{-3} m diameter were bored for the radial air supply (g2 and g4). Blowholes for the g6 air injection have been made in the first side of the diffusive anode, before the step.

The other PT, described elsewhere in [8] 30 kw of power, consisting of cathode junction, insulation rings, intermediate anode, neutral section and step-formed anode, was designed and constructed especially to improve plasma spray quality and to obtain a possibility to introduce the stock and plasma forming gas directly into the arc. PT fitted with a 10^{-2} m diameter orifice tip is used to generate the nonequilibrium plasma jet. Air was injected only tangential in three different places (G1, G3, G5). The G7 under investigation is of the order of 0.54 – 1.27, G3 – 1 – 3.45, and G5 – 1 – 3.45 \times 10^{-3} kgs^{-1}. At the constant air flow G1, G3 and G5 is defined as a various. The current can be varied in the range of 150 - 200 A in the experiments described here. The voltage drop depends on the gas flow rate and gas composition and ranges from 180 to 250 V.

The mass flow of the source gases as air and the cathode protecting gases as nitrogen are regulated by mass flow controllers. The flow in the airlines was controlled by diaphragm and differential pressure gauge with electrical output signal. The nitrogen flow rate was controlled by critical jet up to maximum of 6.5 \times 10^{-3} kg s^{-1}.

Experimental installation, unless the pt, consists also of the power, gas and cooling systems and airing devices. The electric circuit has been closed with the transformer, rectifier, distributor, ohmic resistance, power net, arcing system and regulation-control devices with pc. The gas
supply system consists of nitrogen and airlines with compressors, valves and control devices. The cooling system has been composed of pump of 20 mpa pressure, water tanks of 20 m³, valves, and flow rate control devices. Pt parameters have been established of heat balance: the arc voltage, current, and heat loses to cooling water were measured. A set of quadruplicated copper-constantan thermocouples with a digital measuring device were used for measuring the temperature rise in the cooling water system. The water flow rate was measured employing volumetric method.

3. Results and discussion

The gas is injected at the cathode and anode side and is dissociated and ionised in the arc channel. We conclude that VCC of PT depend on following factors: a) arc chamber geometry; b) gas composition; c) flow and injection to produce desire arc. Estimating of influence of radial injection was performed under experimental investigation at constant and various values of radial flow rate. In the present study when the radial injection is not applied, VCC observed as increasing in the range of current of 300 - 600A (Fig. 2). That appears as a result of an increasing electric field intensity, linear depending on the current increment. It has been found that intensity of electric field and voltage drop linear increases with increasing of G in the range \( G_I = (45-80) \times 10^{-3} \) kg s\(^{-1}\) and \( G_{I,5} = (5-10) \times 10^{-3} \) kg s\(^{-1}\).

![Fig. 2. Plasma torch VCC with tangential air injection. Gas flow rate \( (10^{-3} \text{ kg s}^{-1}) \): \( G_N = 6.5 \), \( G_{I,5} = 24.5 \) and \( G_I \) accordingly: 1-23.0; 2-33.4; 3-42.5; 4-51.5; 5-59.5; 6-68.0; 7-78.0](image)

![Fig. 3. Plasma torch VCC with radial injection in the entrance of anode. Gas flow rate \( (10^{-3} \text{ kg s}^{-1}) \): \( G_N = 6.5 \), \( G_I = 40 \) for 1,2,3,4 and 5; \( G_{I,5} = 40 \); \( G_6 \) accordingly: 1-3.2; 2-4.3; 3-9.2; 4-14.1; 5-19.3; 6-3.0; 7-4.3](image)

Under application and increment of flow rate of radial injection \( G_2 \) from 0 to \( (12 \times 10^{-3}) \) kg s\(^{-1}\), the electric field intensity increases very much, but the further increasing of it is expedient only in the case of currents less than 400 A. Besides high current levels the arc shunting takes place, and the voltage become as decreasing. The shunting comes into the play also during the air injection into the middle of diffuser \( (G_2) \), when \( G_2 \geq 15 \times 10^{-3} \) kg s\(^{-1}\). The maximum effect has been reached after injection of gases into the entrance region of the anode 6 \( (G_6 \leq 5 \times 10^{-3} \text{ kg s}^{-1}) \). The effect of the radial injection location and intensity is apparently visible in Fig. 4. Experimental dates are given for the same of voltage, current and radial flow rate. Increasing \( G_2 \) 10-12% of
total flow rate, the intensity of electric field increases. The further increasing of $G_2$ values has no
effect to the electric field.

![Graph](image1)

**Fig. 4.** The influence of gas injection location and intensity on VCC. $G_2 = 40 \times 10^3$
kgs$^{-1}$. $G_3$: 11-13 - 35; 21-23 and 31,32 - 40 and 41-42 - 25. $G_5$, $G_4$ and $G_6$ values could be found in the table 1.

![Graph](image2)

**Fig. 5.** Dependence of increase arc voltage on the part of radial injection. 1-in the diffuser channel $G_2$; 2-in the exit of diffuser $G_4$; 3-in the anode entrance $G_6$; 4-after distribution along rechargeable chamber $G_1 = G_2 + G_4 + G_6$

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Table 1. $G$ values for the Fig. 4 legend

The flow rate and location of radial injection radial injection has a significant influence to the arc voltage (fig.5). Under the radial injection voltage intensive increases when $g_4$ increases till 7% of the total $g$ and then the $u$ slowly increases till $u = 1.3u_t$. The radial injection into the anode entrance part is effective only in the case of $g_6 < 5%$. The further increasing of $g_6$ leads to the arc shunting [9].

After analysis of the primary experimental results, VCC has been generalized. The dependence in Fig. 6 shows that VCC strongly depends on many of factors, which were established and showed in Fig. 7 and equation (3). The expression of $K$ in Fig. 7 is following:

$$K = \frac{Ud_2}{I}(Gd_2)^{0.78}.$$

(3)

The charts exposed in Fig 6 and 7 contain about 700 experimental dots.

After generalization the conclusive equation has been deduced it appears as follows:

$$\frac{Ud_2}{I} = 243\left(\frac{I^2}{Gd_2}\right)^{0.556} \left(\frac{G_2}{G}\right)^{0.06}.$$

(4)

In presented second case when the plasma torch of 30 kW was used, the flow rate of air was $\leq 2.2 \times 10^3$ kg s$^{-1}$ (the parameter $I^2/(Gd_2)\leq 1.5 \times 10^4$), the arc ends on the tight part of anode, and when it is $> 2.2 \times 10^3$ kg s$^{-1}$, the arc ends on the wide part of anode. The resumptive equation
for VCC in air is: \( \frac{Ud_2}{I} = A \left( \frac{I^2}{Gd_2} \right)^m \), where \( A=57.4, m=-0.42 \) for \( I^2/(Gd_2)<1.5 \times 10^4 \) (tight part of anode), and \( A=266, m=-0.58 \) for \( I^2/(Gd_2)>1.5 \times 10^4 \) (wide part of anode). The injection of dispersed particles directly into arc has only low influence.

![Graph 6. Generalized VCC in dependence of additional factors](image1)

![Graph 7. Generalized VCC in dependence on radial injection](image2)

So, the gas injection location and flow rate has an important influence to arc shape and dimensions. Under the adjustment of the location and flow rate of gas injection it is possible significant increase plasma torch power also change vcc character. This allows to increase the plasma flow temperature and efficiency.

References