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Modelling of Electric Processes in Circuits of Arc Plasma Torches
Part 1. Approximations of Static Characteristics of Arc Plasma Torches

Abstract: The article discusses selected structural and operational properties of DC and AC arc plasma torches. References cited in the article contain generalised analytical expressions identifying experimental current-voltage characteristics of typical arc plasma torches. Values of coefficients in formulas approximating static current-voltage characteristics depend not only on the type and the polarity of the plasma torch but also on values of criterial factors. The study discusses separately DC plasma torches and single-phase AC plasma torches.

Keywords: electric arc, arc plasma torch, current-voltage characteristics of arc

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Introduction

Arc plasma torches are usually used in welding engineering, metallurgy, plasma chemistry, the processing of untypical waste, etc. The advantages of arc plasma torches include short start-up times, fast chemical reactions, the low consumption of working gases, high energy concentration and small dimensions of reactors. Technological processes involving high-power plasma are often performed using AC plasma torches (usually powered by alternating current having a network frequency of 50 Hz). The above-named plasma torches are characterised by simple designs of discharge chambers, simple power supply systems, high reliability and relatively small dimensions. The transfer of heat from the AC arc to the working gas is more effective in comparison with the transfer of heat from the DC arc. Similar to DC plasma torches, the above-named solution involves the application of appropriate choking coils, aimed to stabilise discharges. As a result, the design of such plasma torches is simpler, whereas the devices themselves are cheaper and easier to operate. However, inductive reactance (applied in the system) worsens the power coefficient. As a result, it is necessary to compensate for reactive power using capacitor batteries or follow-up capacitors. In comparison with the use of direct current in plasma torches, the use of alternating current in such devices leads to various problems including difficulties ensuring arc burning continuity (as a result of current passing through the zero value), the reduced use of supply source power, fluctuating plasma parameters (related to changes in current) as well as difficulties ensuring the symmetric load of the network and difficulties performing control and measurements [1]. Because it is usually necessary to reduce the fluctuations of output parameters, such plasma torches are provided with a mixing chamber to equalise the parameters of the hot gas stream.

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One of the advantages of AC plasma torches is nearly the same active life of all electrodes. Both the materials of the electrodes and the manner in which they are cooled depend on the type of plasma-forming gas. The use or inert gases, nitrogen or hydrogen requires the application of electrodes made of high-melting materials (e.g. tungsten and its alloys). Such electrodes are referred to as hot and their operation involves the thermionic emission of electrons from motionless electrode spots. In turn, the use of oxidising gases involves the application of tubular electrodes made of copper and intensively cooled with water. These electrodes are referred to as cold and their operation involves the autoemission of electrons from moving electrode spots (usually in periodic motion). Shifts of electrode spots can be forced by eddy gas flows, external magnetic fields or rotating (disc or cylindrical) electrodes. The above-named solutions minimise the erosion of materials and, consequently, translate into the longer active life of electrodes. Plasma torches are considered technically usable if they guarantee continuous operation for a minimum of 200 hours.

Nearly every DC plasma torch can be powered by alternating current and operated as a single-phase device. Three DC plasma torches can be connected to work in the three-phase network. The primary issue of the aforesaid adaptation is the ignitions of arc discharges. There are several ways in which such processes can take place [1, 2]. Applicable solutions usually involve the use of an additional low-power, high-voltage and high-frequency generator connected in parallel or in series with electric arc. To facilitate ignition and ensure the continuous and stable operation of AC plasma torches it is sometimes necessary to use additional low-power DC plasma torches as the injectors of plasma into the area of primary discharge. The above-named solution is particularly necessary in three-phase plasma torches with rail electrodes [3].

The stabilisation of arc discharges using choking coils characterised by high inductivity and connected in series is costly and, in addition, may worsen the parameters of the supply network. It is more effective to connect (in parallel) either a low-DC high-voltage generator or a low-current and high-frequency generator [4]. As regards times of the deionisation of arc in air, the most effective is the high frequency (even above 1 MHz) of the auxiliary generator. The use of auxiliary power supply sources reduces ignition voltage and, consequently, affects the shape of the static and dynamic characteristics of arc.

Selected structural properties and characteristics of DC plasma torches

In general, plasma torches are divided into plasma torches with internal and those with external arc. The above-presented division takes into account the location of arc in relation to an element containing at least one electrode and supplying the working gas [1, 2]. Plasma torches with external arc (and also those with partly external arc) are usually used in welding engineering and electrometallurgy. In the aforesaid applications, the charge constitutes one of the electrodes (usually the anode). In plasma torches with internal arc, electric discharges take place in a special chamber or a channel. The effect of the flowing gas on the arc column can be longitudinal, transverse or diagonal. The foregoing affects the design of discharge chambers and creates various conditions as regards the supplying of the plasma torch. Longitudinal flows may stabilise discharges, whereas transverse flows may have the entirely opposite effect. The flow of gas is tasked with the creation of conditions enabling the intense absorption of heat, which simultaneously reduces the cross-sectional area of the column and increases its average temperature. The foregoing may not only be accompanied by the stabilisation of thermal conditions but also by the stabilisation of the geometrical dimensions of the column. Various activities aimed to intensify heat exchange include the use of intensified gas streams, the use of channels and nozzles of decreased diameters or the application of intensively cooled constrictors. The most popular DC plasma torches, i.e. linear ones, feature the self-adjusting arc length, an edge and the sectional inter-electrode insert. The current-voltage characteristics of the above-named plasma torches are presented in Figure 1. The use of eddy gas flows and external magnetic fields makes it possible to reduce the erosion of anodes and improve discharge stability. The diaphragm in the whirl chamber protects the cathode against the effect of heated gases (becoming very chemically active). If heated gases are neutral, the above-presented division of the chamber does not take place.

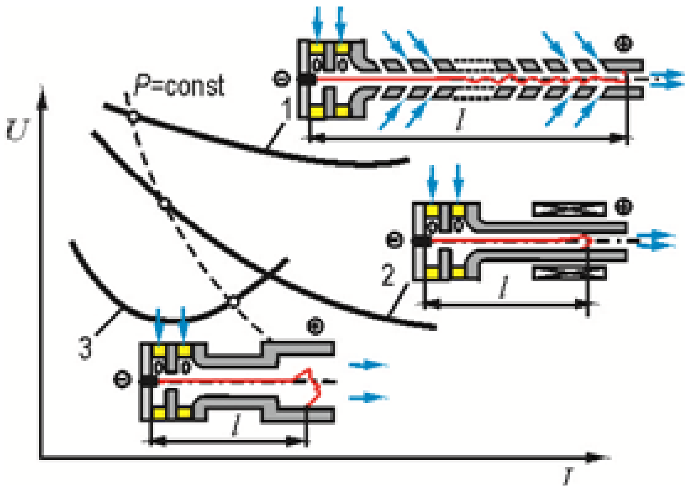

Fig. 1. Current-voltage characteristics of arc in the three types of linear plasma torches [1, 5]: 1 – plasma torch with the inter-electrode insert, 2 – plasma torch with the self-adjusting arc length and 3 – plasma torch with the edge in the electrode extension area

The general formula for the effective characteristic of the linear DC plasma torch is the following [6]

$$\frac{Ud}{I} = A_u\left(\frac{I^2}{\dot m d}\right)^{\alpha_u}\left(\frac{\dot m}{d}\right)^{\beta_u}\left(\frac{l}{d}\right)^{\gamma}(pd)^{\delta} \qquad (1)$$

Another popular and equivalent form is the following: [7]

$$U = A_u\left(\frac{I^2}{\dot m d}\right)^{\alpha}\left(\frac{\dot m}{d}\right)^{\beta}\left(\frac{l}{d}\right)^{\gamma}(pd)^{\delta} \qquad (2)$$

where $\alpha = \alpha_u + 0.5$, $\beta = \beta_u + 0.5$. The transformation of formula (2) enables the obtainment of the following form (more comfortable in terms of further analyses):

$$U = \frac{A_u l^{\gamma} p^{\delta}}{\dot m^{\alpha-\beta} d^{\alpha+\beta+\gamma-\delta}}\left(\frac{1}{I}\right)^{-2\alpha} \qquad (3)$$

The plasma torch has the power characteristic with efficiency η:

$$\tilde\eta = \frac{1-\eta}{\eta} = B\left(\frac{I^2}{\dot m d}\right)^{k}\left(\frac{\dot m}{d}\right)^{l}\left(\frac{l}{d}\right)^{m}(pd)^{n} \qquad (4)$$

where U – arc voltage, I – arc current, $\dot m$ – resultant gas mass stream, d – arc chamber diameter, A_u, B, α, β, γ, δ, k, l, m, n – parameters dependent in structural properties of the plasma torch, the type of plasma-forming gas and the use of technological plasma equipment $\eta = (1+\tilde\eta)^{-1}$ [5], – thermal efficiency.

Individual factors in formula (1) are connected with the following criteria [7]:

1. l/d – criterion of geometric similarity. If the value of the quotient is low, characteristics $U(I)$ decrease. If l/d is high, the shape of the characteristics is parabolic. Optimum arc length $l = 12d\sqrt{\dot m d}$ corresponds to the highest value of effective power,
2. $I^2/(\dot m\ d)$ – energy-related criterion identifying the intensity of heat emission in gas as a result of electric energy transformation $I^2R = I^2l/(\dot m\ d)$,
3. $\dot m\ /d$ – criterion characterising the flow of gas in the plasma torch channel,
4. pd – criterion related to gas breakdown voltage.

The shapes of the static characteristics presented in Figure 1 reveal that exponent $\alpha < 0$. In cases of plasma torches with the self-adjusting arc length, the adopted values of exponents are $\gamma = 0$ and $m = 0$. Exemplary values of the parameters of functions approximating plasma torch characteristics are presented in Table 1 [8]. The approximation of measurement data using power functions is characterised by certain limitations in relation to shapes of

Table 1. Values of coefficients in the formula approximating the current-voltage characteristic of the DC plasma torch (2) along with the ranges of changes in relation to combinations of physical parameters

Plasma torch type and polarity	Gas		α	β	δ	$\frac{I^2}{\dot{m}d}$	$\frac{\dot{m}}{d}$	pd
		V	-	-	-	$\frac{A^2 s}{kg \cdot m}$	$\frac{kg}{s \cdot m}$	$\frac{N}{m}$
Single-chamber plasma torch, normal polarity	Air	1290	-0.15	0.30	0.25	$1{\cdot}10^7$-$4{\cdot}10^{10}$	0.1-20	$(5\text{-}35){\cdot}10^2$
Single-chamber plasma torch, reversed polarity	Air	1970	-0.17	0.15	0.25	$1{\cdot}10^7$-$4{\cdot}10^{10}$	0.1-20	$(5\text{-}35){\cdot}10^2$
Double-chamber plasma torch, normal polarity	Air	1360	-0.20	0.25	0.35	$1{\cdot}10^6$-$4{\cdot}10^{10}$	$5{\cdot}10^{-2}$-26	$1{\cdot}10^3$-$8{\cdot}10^5$
Double-sided plasma torch	Air	3060	-0.17	0.12	0.25			
Single-chamber plasma torch, normal polarity	H_2	$9.7{\cdot}10^3$	-0.20	0.5	0.36	$8{\cdot}10^8$-$7{\cdot}10^{11}$	0.04-0.25	$(1\text{-}3){\cdot}10^3$

characteristics. Typically, it is possible to come across results of detailed tests concerning a single plasma torch with various current excitations, various gases and various gas mass streams. For this reason, criterion 1 is ignored in approximations. In addition, the control of power through changes of arc lengths is preferred in plasma torches used for melting, i.e. mounted in walls or covers of plasma furnaces. In turn, in stream plasma torches the above-named solution can be difficult and, for this reason, changes of the gas mass stream are preferred in such cases.

The designation of values selected from the last three columns of Table 1 as K_1, K_2 and K_4, leads to the formation of the following dependence

$$I^2 p^2 = K_1 K_2 K_4^2 \tag{5}$$

Parameter l/d is simplified and is not used in the formula. The foregoing leads to the choice of the rational value of supply current, additionally depending on gas pressure. Plasma torches with the edge of the anode enable the obtainment of higher efficiency than that obtainable using the previously discussed devices.

Experimental tests [9, 10] revealed that an increase in the arc length or in the gas mass stream leads to a similar result, i.e. to the shift of characteristics $U(I)$ towards higher voltage values. The comparison of the two plasma torch operation states (expressed by formula (2)), leads to the determination of the following proportions:

$$\frac{U_2}{U_1} = \left(\frac{l_2}{l_1}\right)^{\gamma} \tag{6}$$

and

$$\frac{U_2}{U_1} = \left(\frac{\dot{m}_1}{\dot{m}_2}\right)^{\alpha} \left(\frac{\dot{m}_2}{\dot{m}_1}\right)^{\beta} = \left(\frac{\dot{m}_2}{\dot{m}_1}\right)^{\beta-\alpha} \tag{7}$$

which enables the simple forecasting of various machine operation states.

In comparison with welding arc, plasma torches are characterised by relatively long plasma columns. As a result, values of supply voltage are significantly higher than those of near-electrode voltage drops. For this reason, when calculating plasma torch operation states, their individual values are ignored. However, the mathematical models of arc are used to describe dynamic processes in the column with equilibrium plasma. For this reason, in detailed tests, the above-named areas are modelled separately, using connected elements of various mathematical descriptions [11].

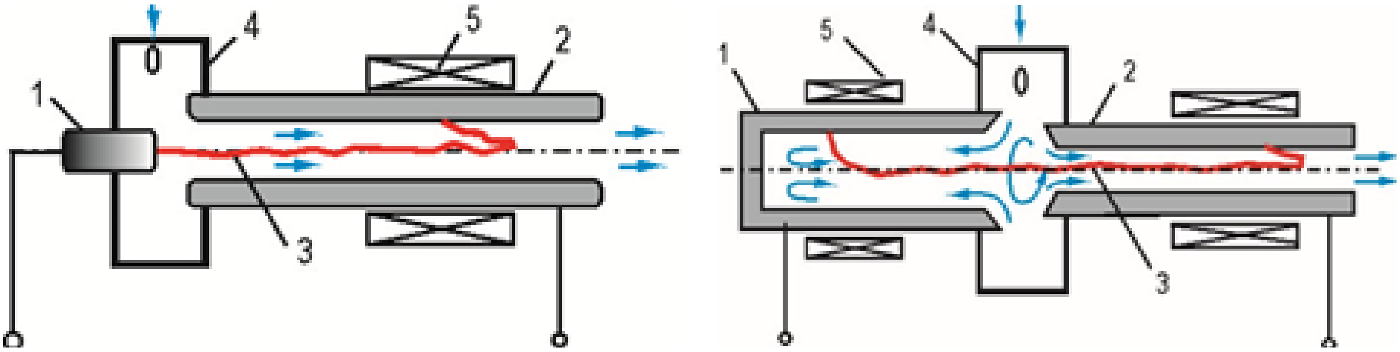

Fig. 2. Schematic diagram of single-phase plasma torches with gas stabilisation and the self-adjusting arc length: a) with the internal pin electrode and b) with two tubular electrodes (1-cathode, 2 – anode, 3 – electric arc, 4 – swirl chamber and 5 – magnetic coil) [12]

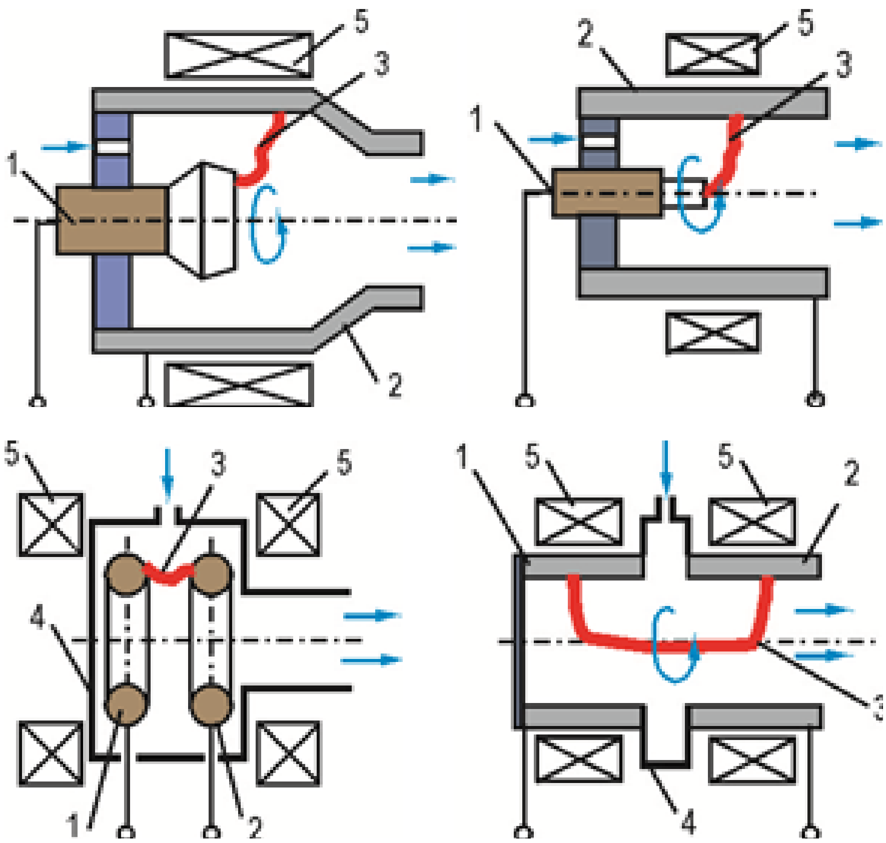

Fig. 3. Schematic diagrams of plasma torches with magnetic discharge stabilisation: a) coaxial system with the cold internal electrode, b) with the hot internal electrode, c) with cold ring electrodes and d) with cold tubular electrodes (1-cathode, 2 – anode, 3 – electric arc, 4 – swirl chamber and 5 – magnetic coil) [12]

The knowledge of the static characteristics of arc is insufficient when modelling the dynamic processes taking place in the plasma torch. In relation to the above-named issue, the most important knowledge is concerned with the function of the damping of physical processes in the plasma column. Many researchers are satisfied with the approximation of the aforesaid function in the form of a time constant (having a very low value and being very difficult to determine precisely). In terms of static characteristics, it is assumed that the value of exciting current is constant or changes very slowly. During the investigation of arc with alternating excitation, values of measured electric parameters are affected by the quality of the operation of the actual current source. Because of the fact that the authors do not provide information on the subject, it should be assumed that these are nearly ideal sources of sinusoidal current.

Selected structural properties and characteristics of single-phase plasma torches

In their design, single-phase plasma torches are similar to DC ones. The type of applied gas affects the structure of electrode nodes. Figure 2 presents two structural variants of linear plasma torches. The first one is preferred in relation to chemically inert gases, whereas the second one is applied during operation with air. Schematic diagrams in Figure 3 present plasma torches which can be operated using any gas.

The current-voltage characteristics of single-phase plasma torches may adopt the form similar to (2), yet expressed using root-mean-square current I_{RMS} and root-mean-square voltage U_{RMS}

$$U_{RMS} = A_u \left(\frac{I_{RMS}^2}{\dot{m}d} \right)^{\alpha} \left(\frac{\dot{m}}{d} \right)^{\beta} \left(\frac{l}{d} \right)^{\gamma} (pd)^{\delta} \tag{8}$$

The appropriate coefficients of the approximation (based on [5]) are presented in Table 2.

Publication [1] discusses the double-chamber plasma torch. The burning of primary arc is accompanied by high-frequency discharge. The families of current-voltage characteristics contain fragments very similar to hyperbolic curves. Publication [12] presents ranges of values of physical parameters in relation to the double-chamber plasma torch, i.e. I = 50-5000 A, $d = (5\text{-}76)\cdot10^{-3}$ m, $\dot{m} = 1\cdot10^{-3}\text{-}3.5$ kg/s and $p = (1\text{-}1000)\cdot10^{5}$ Pa.

Changes of the chemical composition of gas affect the values of coefficients and exponents in formulas as well as the static and effective characteristics of plasma torches [13]. The effect of gas pressure on discharge depends on the chemical composition of the former. For instance, the above-named effect is weak as regards helium and strong in terms of nitrogen [14].

The disadvantages of single-phase plasma torches include the pulsation of the gas stream, difficulties obtaining high temperatures of gas, the necessity of using additional sources of ionisation (DC auxiliary arc, high-frequency discharge) and the possible asymmetry of the three-phase network load [15].

Concluding remarks:

1. The application of the similitude theory in the generalisation of the experimental static current-voltage characteristics of arc enables the modelling of plasma torch properties within wide ranges of changes in relation to structural and operating parameters.
2. Simplified approximations of the static current-voltage characteristics of arc burning in various plasma torches involving the use of various gases do not facilitate taking into account the operation of additional ionising systems. The major parameter which remains undefined is the value of discharge ignition voltage.

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Table 2. Values of coefficients in the formula approximating the current-voltage characteristic of the single-phase plasma torch (2) with the self-adjusting arc length along with the ranges of changes in relation to combinations of physical parameters

Plasma torch type and polarity	Gas	A_u	α	β	δ	$\frac{I^2}{\dot{m}d}$	$\frac{\dot{m}}{d}$	pd
		V	-	-	-	$\frac{A^2 s}{kg \cdot m}$	$\frac{kg}{s \cdot m}$	$\frac{N}{m}$
Single-chamber plasma torch, alternating current + high-frequency generator	Air	3930	-0.18	0.28	0.20	$1\cdot10^{7}\text{-}4\cdot10^{10}$	0.1-20	$(5\text{-}35)\cdot10^{2}$
Double-chamber plasma torch, alternating current + high-frequency generator	Air	2150	-0.15	0.16	0.20	$1\cdot10^{6}\text{-}4\cdot10^{9}$	$5\cdot10^{-2}\text{-}26$	$1\cdot10^{3}\text{-}8\cdot10^{5}$

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