Control of arc plasma torches: compensation of operational enthalpy drifts

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Abstract. In arc plasma torches electrode wear is the main reason for slow changes in the electrical and thermal torch characteristics. Such effects hinder technological applications of this type of plasma torches whenever the enthalpy must be maintained at a fixed level, or varied as needed. To solve this problem, a new method and algorithm for torch control are proposed. The time evolution of the arc current, voltage and thermal power loss of the torch are recorded. The values measured are used to find the required value of the enthalpy.

The electric-arc plasma generators (plasma torches) are used to heat up gas jets to temperatures reaching 2 - 3x10^4 K and enthalpies up to 2 - 4x10^7 J/Kg. They have found numerous applications in machine-building, and chemical and metallurgical industries, where a basic requirement is to maintain a constant value, or, possibly to vary in a controlled way, the enthalpy (respectively, the temperature) of the plasma jet. Solving the problem of controlling this parameter is easy when the electrical (volt-ampere) and thermal characteristics of the plasma torches are known a priori. However, in cases of prolonged operation, the electrodes erosion results in unpredictable quantitative changes in the plasma torches characteristics.

The present work proposes a technique for plasma torch control under the conditions of prolonged operation and parameters changes. A basic prerequisite is that the torch operation control must be performed within a few seconds, since it is unacceptable to interrupt the technological process to determine the new parameters (which can also undergo changes).

The object of our studies was a plasma torch operating with nitrogen or air as a plasma-forming gas. The thermal characteristics of such a torch can be described by the semi-empirical relation [1,2]:

\[
h = \frac{IU(I)}{G} \left( \frac{1}{1 + e\left(\frac{I}{G}\right)^{0.34}} \right).
\]  (1)

where \(h(I,G)\) is the plasma enthalpy, \(I\) and \(U\) are the plasma torch current and voltage, \(G\) is the plasma-forming gas mass flow rate, \(e\) is a parameter depending on the plasma torch geometry and on the electrodes condition.
Depending on the electrodes geometry, the current and the flow rate, the volt-ampere characteristics (VAC) exhibit different behavior (figure 1). In the most general case they are non-linear; however, in narrow current intervals they may be assumed linear. They can also be described by semi-empirical relations [1,2], namely, for plasma-torches with cylindrical geometry of the channel $h_{cyl} = LI^{0.3}G^{0.45}$, while for plasma torches with step-wise widening along the anode channel they are $U_{step} = a(1 + bI)G^{0.22}$. For each particular design, these dependences only hold true in a given interval of parameters, with $U_{step}(I)$ describing the growing (linear) part of the VAC only.

The coefficients $a, b, L$ depend on the anode geometry and on the condition of the electrodes. Following prolonged plasma torch operation, their values change, which results in changes in the VAC (figure 2).

The following parameters are measured during operation: current, $I$, voltage, $U$, gas flow rate, $G$, heat losses in the plasma torch, $P$. In practice these are averaged values, with the characteristic time of averaging for $I, U$ and $G$ being a few tenths of a second. The measured enthalpy is determined by the expression

$$h_m = \frac{UI - P}{G}.$$  \hspace{1cm} (2)

Due to the specific nature of the measurements, measuring the plasma torch heat losses necessitates a longer period of time. In the boundary case of an operating plasma torch, stabilization of $h_m$ data takes several tens of seconds. The time needed in each concrete case depends on the plasma torch design and mass. Naturally, a transition to another temperature mode would take less time.

It is assumed that the values of $I, U, G$ are known at any given moment of time, while that of $h_m$, only if the mode has either been stable for the past 30 seconds, or has been varying slowly.

The plasma torch mode is chosen by choosing the values of $I, G$ so as the enthalpy should assume a given value $h_0$.

As a rule, the DC power supply of plasma torches operate as current stabilizers. This is why, if an arbitrary variation of the plasma torch mode of operation occurs, the current value remains constant, while the voltage and the enthalpy change.
A. Control of a plasma torch with known initial characteristics

Let the initial VAC evolve slowly, with the plasma operating point A\((I_0, U_0)\) undergoing a transition to A'\((I_0, U')\) (figure 2), while \(h_0\) changes to \(h'\). The parameter \(c\) in (1) changes its value to \(c'\); the coefficients \(a, b, L\) undergo similar changes. Making use of the values measured for \(I, U\) and \(P_i\) as substituted in (1) and (2), one can determine \(c'\).

In the simplest case (linear approximation), \(U(I)\) has the following form:

\[
U = a(1 + bI)G^a. \tag{3}
\]

It is assumed that \(\alpha=0.22\) [1]. Since it is also assumed that the flow rate is constant, its specific value is of no importance. The initial values of \(a\) and \(b\) are known. In order to obtain their values, one needs to make two measurements of \(U\) for different values of \(I\). However, one only knows the operating point A'. The procedure which we propose is as follows. As a first step one assumes that the parameter \(b\) has kept its value, \(b=b'\). Then,

\[
U' = a'(1 + bI)G^a. \tag{3'}
\]

By solving jointly (1) and (3') using \(c'\), one obtains the value of the current \(I'_1\) for which \(h = h_0\) under the assumptions made. One then changes the plasma torch current and measures the voltage value \(U'_1\) at current value \(I'_1\). One can then calculate the values \(a_1\) and \(b_1\), since two measurements have been performed at values of the current \(I\) and \(I'_1\), \(U = a_1(1 + b_1I)G^a\).

Using formula (1) once again, one calculates the current value \(I'_2\) that ensures enthalpy \(h_0\). One then changes the plasma torch current to \(I'_2\) and measures the new voltage value \(U'_2\). Making use of (1), one calculates \(h_1\) by substituting the values measured of \(I'_2\) and \(U'_2\) and checks if the conditions

\[
|1 - h / h_0| < \delta, \quad |1 - I'_1/I'_1| < \delta/2 \tag{4}
\]

hold true, with \(\delta\) being the permissible deviation from the specific mode by a reasonable value, namely, \(0.02<\delta<0.05\). In the case of one of these conditions not holding true, one determines new values \(a_2, b_2\) by using the operating points measured \((U'_3, I'_3)\) and \((U'_4, I'_4)\). These are then used to find a new current value \(I_2\), and the procedure just described is repeated until conditions (4) are fulfilled.

Once the operating mode is stabilized, one measures \(P_i\) and calculates \(h_m\) using (2). If \(|1 - h / h_0| > \delta\),
one finds the value of $c$ and, following the procedure described above, calculates the final value of the current that provides enthalpy $h_0$.

B. Control of a plasma torch with unknown characteristics

One turns on the plasma torch at a low value of the current and measures $I_0$, $U_0$, $P_1$ in this mode of operation. One then calculates the values of $h_m$ and $c$. Since no data is available for the value of $a$ and $b$, one assumes that $U(I)=U_0$. Equation (1) is then used to calculate the current necessary to ensure the enthalpy $H_0$ needed. One then proceeds in the manner described above. Figure 3 illustrates an example of controlling a plasma torch with unknown characteristics. The plasma torch is switched on at a current of 100 A and enthalpy of $4.35 \times 10^7$ J/kg. Following four consecutive steps, the torch reaches its operating mode $I = 220$ A and $h = 7.3 \times 10^7$ J/kg.

If the value of the current thus calculated differs substantially (by more than 20 %) from the currently measured one, it is recommended that the subsequent step of current variation, at which $U$ is measured and the consecutive values of $a$ and $b$ are calculated, should not exceed $0.2 I$. The choice of the current step depends on the type of plasma torch, its power and its operating current interval. One can thus achieve a smooth plasma torch control in the case of a strongly non-linear VAC, especially in the case of the presence of an extremum. Figure 4 presents the dependence of $H$ on $I$ for a concrete case. $h^*$ can be implemented at two different values of the current. Large steps of current variation can result in omission of $I_1$ and implementation of an operating mode with a large current $I_2$. This must not be allowed to take place, since larger current values lead to faster electrodes erosion. Figure 5 illustrates how the step size influences the final regime.

![Figure 4. Enthalpy dependence on the plasma torch current. $h(I_1)=h(I_2)$.](image)

![Figure 5. Current change at different step size.](image)

The procedure described can be extended to include the case of controlling the operating mode by way of varying the gas flow rate $G$. Unfortunately, sufficient data is not available for the $\alpha$ coefficient in a wide range of values of the basic parameters. It assumes different values in different types of plasma torches; its values remain constant in relatively narrow intervals of parameters variation [1, 2]. Further experiments would certainly allow us to solve this problem.

The algorithm described here gives a simple and efficient method for controlling the arc plasma torch enthalpy.

References

[1] Zhukov M F 1979 Fundamentals of linear-type plasma torch design (in Russian) (Novosibirsk: Nauka Publishers)

[2] Zhukov M F, Koroteev A S and Uryukov B A 1975 Applied thermal plasma dynamics (in Russian) (Novosibirsk: Nauka Publishers)