A Thermal Analysis of Characteristic Parameters in the Electrode–Region for Tubular Plasma Generators

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A thermal analysis of characteristic parameters in the electrode–region for tubular plasma generators is developed. Results of calculation on temperature of electrodes, evaporation rate and erosion rate for different electrode materials are presented as a function of arc current, pressure of arc chamber, width of arc root and velocity of water coolant. Some experimental data on electrode erosion in a tubular plasma generator is given. The effects of operating parameters on erosion rate are discussed in detail.

Keywords: electrode erosion, plasma generator, heat transfer.

INTRODUCTION

Tubular plasma generators have been proven to be a valuable tool in chemical and metallurgical processing, in the production of new materials, and in the destruction of toxic wastes. One of the remaining problems inhibiting further industrial application of plasma generators is the short lifetime of the electrodes. Some studies on electrode–region phenomena of plasma generators have been reported in the literature\[1\]-\[10]\]. The understanding of electrode–region phenomena is important in any thermal plasma generator, since the electrodes are partially responsible for the stabilization of arc and operating property of plasma generator, and the parameters in electrode–region are related to the electrode lifetime. The erosion mechanism of electrode may involve evaporation, flow or ejection of molten electrode materials and chemical reaction.

In this paper, a thermal analysis of characteristic parameters and a detailed calculation for the temperature on the surface of electrode, the evaporation rate and erosion rate of electrode materials in tubular plasma generators is presented on the basis of the energy balance between plasma and electrode. Some experimental results on erosion rate of electrode in tubular plasma generator are given.

MODEL FOR CALCULATION

The processes involved in the operation of the arc root in plasma generators are very complex and there are many factors that are related to electrode erosion. So some reasonable assumptions must be made before forming the model for calculation:

1) The arc root moves sufficiently fast over the cylindrical electrode so that the heating can be considered uniform in the circumferential direction.

2) The motion of the arc root covers a band of certain width (experimentally determined) and the probability of the axial location of the arc root within this band follows a normal distribution.

3) In the case of inert atmosphere, chemical reaction with the electrode materials can be neglected.

4) In the plasma generator, proper care is taken so that no excess loss of material occurs by molten metal ejection or runoff, the chief mechanism becomes evaporation.

1. Heat conduction within the electrode is governed by

\[
\frac{\partial T}{\partial t} = \frac{\lambda}{c_p} \nabla^2 T + \frac{1}{c_p} \frac{\partial \lambda}{\partial T} \times \left[ \left( \frac{\partial T}{\partial x} \right)^2 + \left( \frac{\partial T}{\partial y} \right)^2 + \left( \frac{\partial T}{\partial z} \right)^2 \right] + \frac{W'}{c_p}
\]  

(1)

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Where \( c \) is the specific heat, \( \lambda \) is the thermal conductivity of electrode material, \( \rho \) is the density of electrode material, \( W \) is the quantity of heat produced by Ohmic heating in electrode per unit time per unit volume, \( T \) is the temperature of electrode, \( t \) is time.

For the calculation of temperature in tubular plasma generators, a two-dimensional stable heat conduction equation can be used, the coordinate system for calculation of temperature of electrode is shown in Fig.1.

\[
Q = \left[ S(U_h + U_i) - \phi \right] + Q_R - Q_\phi - Q_m
\]

(for cathode) \( (3.1) \)

\[
Q = I[U_a + \phi + 5kT_e/2e] + Q_R - Q_e - Q_m
\]

(for anode) \( (3.2) \)

Where \( Q \) is the dissipated energy by thermal conduction on the cooled surface of electrode per unit time, \( I \) is the arc current, \( U_h \) is the cathode voltage fall, \( U_a \) is the anode voltage fall, \( U_i \) is the ionization potential of the gas medium, \( \phi \) is the effective work function of the cathode material, \( s \) is the fraction of ion current, \( s = I_i/(I_i + I_e) \), \( Q_R \) is the additional energy to the electrode by radiation per unit time, \( Q_m, Q_e \) are the dissipated energy by melting and evaporating of material on the surface of electrode per unit time, \( K \) is the Boltzmann’s constant, \( T_e \) is the temperature of electron.

4. The additional energy to the electrode by radiation of plasma is given as \[11\]

\[
Q_R = AI^{1.15} P_0^{0.5} F
\]

Where \( A \) is a coefficient, \( P_0 \) is the pressure of plasma gas, \( F \) is the inner area of electrode.

5. The specification of the ion current density is a uncertainty in the model of calculation. In this paper, we suppose that the ion current is given by the saturation value.

\[
J_i = 1/4(\pi n_+ + 2\pi n_{++})n_i
\]

Where \( n_+, n_{++} \) are the number densities of singly and doubly ionized gases, respectively, \( V_i \) is the mean thermal velocity of the ions. The number densities are calculated by applying Saha’s equation, \( J_i \) is the density of ion current.

6. The cathodic electric field \( E \) is determined by the MacKeown equation \[12\].

\[
E^2 = 4 \frac{U_h^{0.5}}{e_0} \left[ J_i \left( \frac{m_i}{2e} \right)^{0.5} - J_e \left( \frac{m_e}{2e} \right)^{0.5} \right]
\]

Where \( m_i \) is the mass of ion, \( m_e \) is the mass of electron, \( J_e \) is the density of electron current, \( e \) is the electronic charge, \( e_0 \) is the electric constant.

7. The Richardson–Schottky equation relating emission current density to cathode temperature and surface work function in the presence of electric field can be written as \[13\].

\[
J_e = BT^2 \exp \left[ - \frac{e\phi}{KT} \right] \exp \left( \frac{e(E/e\pi e_0)^{0.5}}{KT} \right)
\]

Where \( B = (2\pi em_e k_b)/h^3 \), and \( h \) is the Planck’s constant.