

ELECTRICAL CHARACTERISTICS OF A LOW-POWER PLASMA TORCH

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In this work it is reported measurements of the electrical characteristics of a low-power plasma torch used to produce diamond films. The torch operates with Ar/H₂ mixtures at pressures less than 0.5atm and currents up to 12A. A simple model of the gas flow and electric arc is developed and compared with the experimental data.

A schematic diagram of the plasma jet experiment is shown in figure 1. The system comprises a stainless steel vacuum vessel and an arc chamber composed of two concentric electrodes: an inner cathode with a molybdenum tip and an outer copper cathode. The exit diameter of the torch at the neck is 4mm (figure 2). Both electrodes are water cooled and are electrically insulated by a ceramic flange. The pressure in the evacuated vessel is about 50mbar and the pressure at the admittance orifice of the arc chamber is in the range 200–350mbar depending on the gas fluxes. In operation, a plasma jet is formed below the torch exit nozzle, and a film is deposited on a substrate positioned axially in the jet.

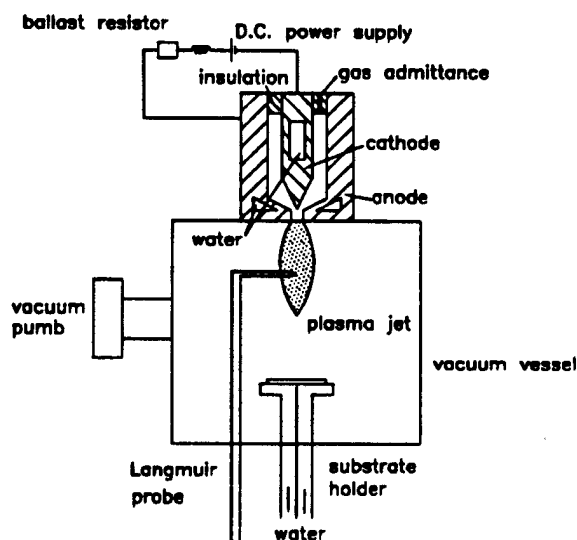


Figure 1. The plasma jet experiment.

To run the torch, pure argon is admitted to the arc chamber, and breakdown occurs at around 1000V. Hydrogen is then added to the flow. As illustrated in figure 3, the torch appears to operate initially in a glow discharge mode, with voltages over 300V, and a V-I characteristic with a slight positive slope. There is a relatively large heat loss to the walls of the arc chamber in this mode of operation, and measurements in the plasma jet indicate that the electron temperature is in the range 0.07 – 0.47eV and the electron density is 10^{16}m^{-3} – 10^{18}m^{-3} [1].

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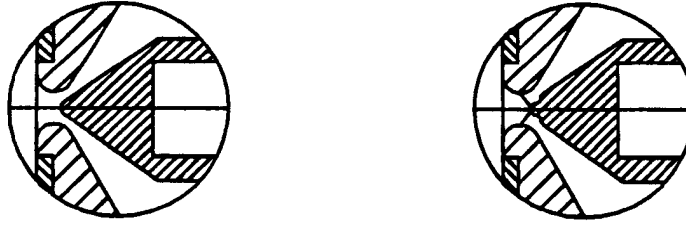


Figure 2. Detail of arc region: the cross section on the right shows the effect of arc erosion

When the current reaches about 8A there is an abrupt change to an operating mode with lower voltage, indicating a transition to an arc discharge. In the arc discharge mode the voltage is around 150V, the V-I characteristic has a negative slope (figure 3), and heat loss to the chamber wall is reduced. Substrate temperatures in the glow discharge mode are around 650°C, but are in excess of 1000°C in the arc discharge mode. The arc erodes the molybdenum cathode tip significantly after a few hours of operation. The form of this erosion is illustrated in figure 2.

A simple model of the arc in the plasma torch, based on one-dimensional thermodynamic relations, is outlined below.

Isentropic flow with constant total enthalpy per unit mass $H = h + v^2/2$ is assumed for the cold flow to the arc region, at which point the enthalpy of the flow is increased. It is assumed that the cross-sectional area of the arc is much less than the total flow area, and that the flow is heated over a region where there is negligible change in channel dimensions. In this situation, mass and momentum conservation yield

$$p_1 + \rho_1 v_1^2 = p_0 + \rho_0 v_0^2 \quad (1)$$

where the subscripts "0" and "1" refer to flow conditions before and after passing through the arc region respectively. The electrical input to the arc results in a change of the total enthalpy of the flow given by [2] $\dot{m}(H_1 - H_0) = VI$, where $\dot{m}$ is the mass flow, V and I are the arc voltage and current respectively.

Using the relation above and equation (1), the flow conditions immediately can be determined for a given arc electrical power input. To determine the relationship between V and I it is assumed that a fraction f of the total mass flow enters the arc and is heated to the arc temperature, and that the arc is cylindrical with diameter equal to the same fraction f of the effective channel width w_{eff} . According to Steenbeck's principle [3], f is adjusted for minimum arc voltage. The pressure in the arc is assumed to be equal to the pressure in the main flow after it is heated, and the specific enthalpy of the arc h_{arc} can be found from

$$\dot{m}f(h_{arc} + v_{arc}^2/2 - H_0) + Q = \dot{m}(H_1 - H_0) + L \quad (2)$$

The first term on the left hand side represents energy convected out of the arc, Q is the heat transferred to the flow from the arc, and L represents energy lost to the walls. It is assumed that Q and L can be defined by fractions θ and η of the known terms such that equation (2) becomes

$$f(h_{arc} + v_{arc}^2/2 - H_0)(1 + \theta) = (H_1 - H_0)/(1 - \eta) \quad (3)$$

v_{arc} has little effect on the predictions provided the corresponding Mach number is low; for the calculations here, the velocity of the main flow was used, i.e., $v_1 = v_{arc}$.

Once h_{arc} is known, the arc temperature and the electrical conductivity σ can be determined, and V and I can be found from the arc resistance $4l_{eff}/\pi f^2 w_{eff}^2$, where l_{eff} is the effective

arc length. The effective dimensions w_{eff} and l_{eff} were determined using the conical surface indicated by lines across the flow region in figure 2. In addition to the arc resistance, an electrode voltage drop of 26.5V was assumed, with an electrical power dissipated in the electrodes of $\Delta V \times I$ where $\Delta V = 8.8V$ is the sum of the work functions of the cathode and anode metals. A chemical equilibrium approximation was used to calculate the cold flow and plasma transport properties [4, 5].

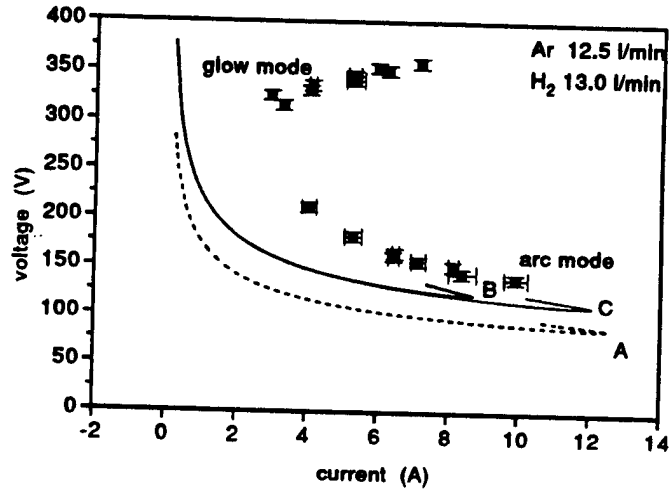


Figure 3. V-I characteristics: experiment and model predictions

Figure 3 compares measured voltage-current characteristics with the model predictions for three cases: (A) $\theta = 0$ and $\eta = 0$, (B) $\theta = 0.5$ and $\eta = 0$, (C) $\theta = 0.5$ and $\eta = 0.2$. Figures 4 and 5 show model predictions of the flow pressure, temperature and Mach number, and the arc temperature and diameter. The predictions correspond to case (C) of figure 3. The flow is driven from a constant stagnation pressure in the reservoir, and the curves reach a maximum current as the static pressure approaches zero. The solution after the turn-around represents a rather cold high-velocity flow which may not exist in practice.

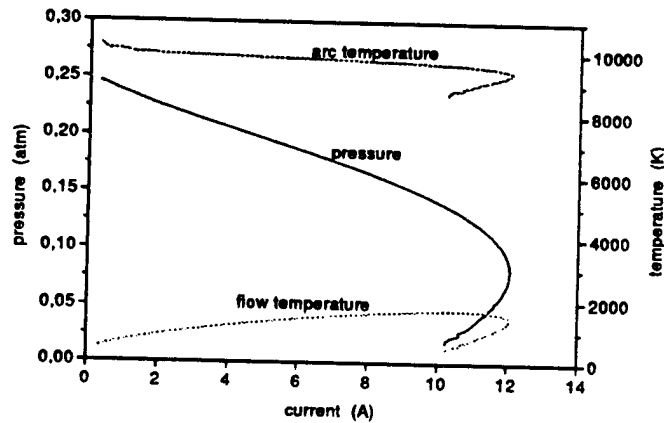


Figure 4. Calculated pressure at the arc location, and temperatures in the arc and flow, as a function of current.

Figure 6 shows the predicted and measured effect of altering the gas mixture. Model parameters for the calculated curves correspond to case (C) in figure 3. For higher proportions of

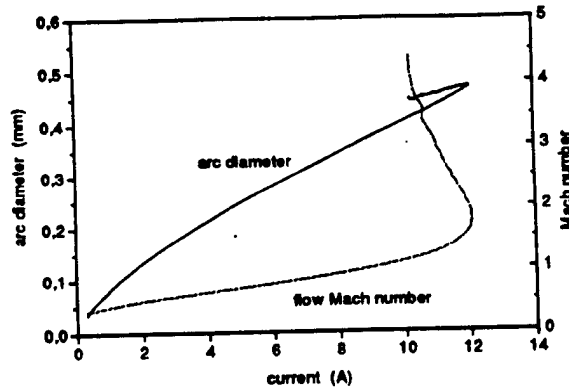


Figure 5. Calculated arc diameter and Mach number in the gas flow as a function of current.

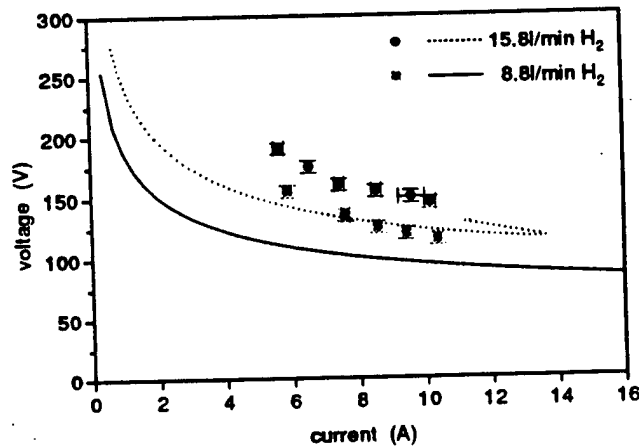


Figure 6. Electrical characteristics for two hydrogen fluxes, with a fixed argon flux of 12.5 l/min.

hydrogen, the voltage is observed to increase. The same trend is predicted by the model.

The model presented here is a first attempt at a treatment of the characteristics of plasma torches which may be useful when a rapid predictive capability is required. Initial results are encouraging, despite the gross simplifications used to derive the model.

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