THE EXPANSION OF THE EROSION ARC PLASMA FLUX INTO VACUUM

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Introduction. Lyubimov G.A. has proposed to explain the energy values observed in a vacuum-arc plasma jet that were exceedingly higher than the thermal ones a mechanism based on the hydrodynamic nature of the process /1,2/.The author /3/ has developed a one-liquid hydrodynamic theory of arcs in vacuum.It should be noted that the works /2,3/ employed a free parameter, viz.,the angle of jet expansion, and the values of the important parameters such as the fall of the cathod potential and the vapour flow rate that had been taken from the experimental data.This work describes the quasi-one-dimensional theory of the arc plasma jet into vacuum and the experimental data for the mass flow distribution in plasma.

Theory.The expansion of an arc plasma jet into vacuum at the absence of a magnetic field is described by the following one-liquid hydrodynamic equations set:

$$\rho v f = G = const, \quad I = f j = const \tag{1}$$

$$\rho v \frac{df}{dz} + \frac{dP}{dz} = 0 \tag{2}$$

$$\rho v \frac{dH}{dz} = jE, \quad j = \sigma E \tag{3}$$

where z is the current coordinate; $H = h + \frac{v^2}{2}$; h is the enthalpy, E is the electric field strength, G, I are the mass flow rate and the intensity of the arc current and σ is the conductivity. The equation of state was taken in the form $P = \frac{\varkappa - 1}{\varkappa} \rho h$; $\varkappa = \frac{C_p}{C_v} = const$; $f = \pi R^2$ is the area of the jet cross-section. The radial electric field compared with the longitudinal one in the arc could be neglected ($\frac{E_R}{E_z} \sim \frac{R}{L} \ll 1$, where L is the longitudinal dimension of the jet). Then the radially acting ion accelerating force will be $F_R \to 0$ and the jet boundary will expand with a thermal velocity $\frac{dR}{dz} = \frac{1}{M}$ where M is the Mach number. Hence, the angle of the jet expansion at $r \to \infty$ will be $\theta \to 0$ as during the expansion into vacuum under $r \to \infty$ is $M \to \infty$

It may be assumed that at short distances from the cathod the particles of the cathod material produced by the erosion move along the radii of a sphere sector, the semi-angle of which would be θ^*

By introduction of dimensionless parameters $x = r/r_0$, $\bar{H} = H/H_0$, $\bar{\sigma} = \sigma/\sigma_0$ where $r_0 = I / 2\pi a j_K$ is the radius of the cathod spot and $a = 1 - \cos\theta^*$ the equations (1-3) could be restricted to obtain two equations:

$$\frac{d\bar{H}}{dx} = \frac{2\,T(\lambda)^{1+m}}{K x^2 \bar{\sigma}} \tag{4}$$

$$\frac{d}{dx}\left[\sqrt{\bar{H}}\, z(\lambda)\right] = \sqrt{\bar{H}}\,\frac{T(\lambda)}{\lambda}\,\frac{2}{x} \tag{5}$$

where $\lambda = \frac{v}{C_*}$ is the reduced velocity, C_* is the critical sound velocity, $z(\lambda) = \lambda + \frac{1}{\lambda}$; $T(\lambda) = 1 - \lambda\frac{\varkappa - 1}{\varkappa + 1}$ are the gas dynamic functions, $K = 4\pi a T(1)^{1+m} \sigma_0 G \times r_0 H_0 / I^2$; $\bar{\sigma} = [\bar{H}\, T(\lambda)]^m$. One of the boundary conditions at $x = 1$ is $\bar{H} = 1$.

This case is similar to that for a gas flow from a spherical source into vacuum. Contrary to the adiabatic flow under the supply of heat,a sonic surface moves off the cathod radially.

When seeking the second boundary condition one should bear in mind that at the supply of heat to the gas flow in a supersonic nozzle a sonic cross-section,in contrast to the case of the spherical adiabatic source,moves to the direction of the diverging part of the nozzle.Its location $x = x_* > 1$ can be defined from the conditions of a monotoneous growth λ in the $x = x_*$ neighbourhood. Assuming that $\lambda = 1 + b(x - x_*)$ we find $x_* = (K\bar{H})^{-1+m}$

Then on the basis of the obtained transition through the sound velocity the equations set (4, 5) at $\eta = 1$, $\xi = 1$, $\lambda = 1$ will assume a self-modulated form independent of K provided that new variables $\eta = \frac{x}{x_*}$, $\chi = \frac{H}{H_*}$ had been introduced. The integration of the set should be carried out on both sides of $\eta = 1$.

Experiment. The mass flow distribution in the stationary arc was defined by the mass of the coat condensed onto tungsten wire probes 0.5 mm thick placed inside a metal cylinder across the vacuum arc plasma jet at various distances from the cathod. The diameter of the copper cathod was d_K = 6 mm. A diaphragm-anode with a hole of 10 mm was placed at the distance of 20 mm from the cathod between the latter and the wires. The mass of the condensate on the wires was determined by the method of the quantitative spectral analysis similar to /4/.

In the experiments the wires were placed in the metal cylinder, along its cross-section plane. The potential of the cylinder and the wires in relation to the plasma was a floating one. The arc current was I = 80 A and the arc life was t_p=3 s. The peak temperature of the wire within this period did not exceed that of the copper melting. In other experiments glass diaphragms with a central hole of 15 mm were interposed between the cathod and the anode at various distances from the cathod and across the flux. The distribution of the copper coating thickness on the diaphragms was assessed with the microphotometer by the intensity of the light flux passed through the diaphragm. The shape of the jet boundary when analysing the experimental data was defined by the constant of the fall in exponential dependence that approximated the thickness distribution of the copper coating both on the wire probes and the diaphragms.

Results. Figure 1 shows the calculated dependences of Λ and χ on η (curves 1,3), that of $\Lambda(\eta)$ at the adiabatic expansion /2/ and the function $\chi T(\Lambda)$ /4/ that is proportional to h. The values of Λ along the jet that had been calculated according to the dependence $\Lambda = \sqrt{\frac{M^2 \frac{\varkappa+1}{2}}{1+M^2\frac{\varkappa-1}{2}}}$ derived from the experimental dependence $M = ctg\,\theta'$ (when calculating η it was supposed that x_* =1 mm) are shown by triangles. The calculated limit velocity values V_∞ at $\eta \to \infty$ for vacuum-arcs in vapours of Cu, Ni, Zn at I = 100 A were 21.0, 13.2, 10.2 x 10^3 m/s accordingly.

Discussion. The substantial difference between the calculated data for the expansion of arc plasma jet into vacuum and for the adiabatic one may be seen from their comparison. Thus, at $\eta \approx 10^2$ the Mach number for the arc will be $M \approx 6.4$, for the adiabatic expansion $M \approx 54$ and $\chi T(\Lambda)$ differs from $T(\Lambda)$ derived under the adiabatic expansion by 200 times. The limit expansion velocity V_∞ calculated in this work, corresponds to the theoretical data /2/ which justifies the simplified approach adopted. The dependence of Λ along the jet obtained in the course of the experiments conforms well with the theoretical one what confirms the assumption of the thermal nature lying behind the jet expansion phenomenon.

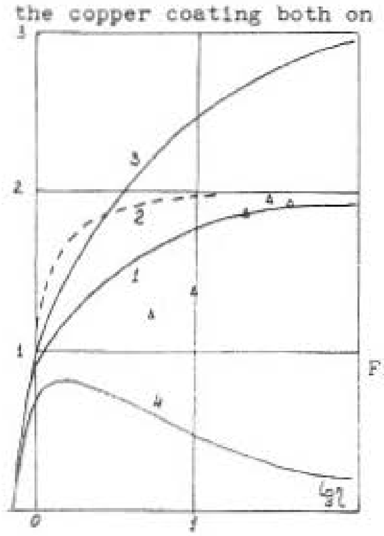

Fig. 1 The distribution of vacuum-arcs characteristics along the length

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