

PARAMETRIC STUDY OF A WATER-SWIRL STABILIZED ELECTRIC ARC

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Abstract

A two-dimensional numerical model for an electric arc stabilized by water vortex has been proposed. The axisymmetric model includes the area between the cathode and the output nozzle of the arc. The production of water plasma, i.e. the rate of evaporation of water is determined both from radial conduction and radiation heat fluxes near the phase transition water - water-vapours and by assuming a uniform evaporation. The computer results refer to thermal, fluid dynamic, and electrical characteristics of such arcs for the range of currents 300 A - 600 A. The influence of non-uniform evaporation rate on the outlet discharge parameters is studied. It is found that the part of the power spent for evaporation is less than 2 % of the total input power. The calculated velocities, pressure drops and electrical potentials are in good agreement with experiments carried out on the water plasma torch PAL-160 operating at the Institute.

1. Physical model

The following assumptions are applied: The plasma flow is laminar and compressible, gravity effects and viscous dissipation are negligible. The plasma itself is in local thermodynamic equilibrium. Radiation effects are involved through the net emission coefficient, absorption of radiation in water vapours is omitted. The magnetic field is generated only by the arc itself. The set of governing two-dimensional equations is written, for a computer implementation, in an axisymmetric cylindrical system of coordinates.

The governing equations can be written in the vector notation as follows:

continuity equation:

$$\frac{\partial}{\partial t} \rho + \nabla \cdot (\rho \vec{u}) = 0 \quad , \quad (1)$$

momentum equations:

$$\frac{\partial}{\partial t} (\rho \vec{u}) + \nabla \cdot (\rho \vec{u} \vec{u}) = -\nabla p + \nabla \cdot \vec{\tau} + \vec{j} \times \vec{B} \quad , \quad \tau_{ij} = \eta \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_l}{\partial x_l} \right) \quad , \quad (2)$$

energy equation:

$$\frac{\partial}{\partial t} (\rho c_p T) + \nabla \cdot (\rho \vec{u} c_p T) - \frac{\partial p}{\partial t} = -\nabla \cdot (\lambda \nabla T) + \vec{j} \cdot \vec{E} + \vec{u} \cdot \nabla p + \frac{5}{2} \frac{k}{e} (\vec{j} \cdot \nabla T) - \Psi \quad , \quad (3)$$

charge continuity equation:

$$\nabla \cdot (\sigma \nabla \Phi) = 0 \quad , \quad (4)$$

where \vec{u} is the velocity vector, p is the pressure, T is the temperature, \vec{j} is the current density, \vec{E} is the electric field strength, Φ is the electric potential, k is the Boltzmann constant and e is the elementary charge of electron. The transport and thermodynamic properties of atmospheric pressure water plasma were taken from [1], the net emission coefficient Ψ for water plasma including self-absorption of radiation from [2].

The calculation domain and the boundary conditions are presented in Fig. 1. The radial inflow velocity along the DA is determined in two ways. First, the mass flow rate is assumed to be independent of the axial discharge coordinate and its value is obtained from experiments. Second, it is calculated from radial conduction and radiation heat fluxes (estimated by the method of radiation view factors) near the water - water-vapour phase transition.

The solution of the equations (1)-(4) was carried out using a compressible version of the control volume method SIMPLER [3]. The final steady state was reached as a time evolution of the initial state. A non equidistant grid with 15x15 points was employed in the calculations.

2. Discussion of results

The influence of nozzle temperature and nozzle length on the outlet arc parameters has been studied for the case of uniform evaporation rate. The lowering of nozzle temperature causes the constriction of arc, i.e. the increase of axial arc temperature, electric field strength, current density (see Fig. 2) and the decrease of overpressure and the Mach number. The increase of nozzle length results in the descent of electric field strength and current density, and in the increase of outlet velocity; these dependencies indicate the transition of arc parameters to the asymptotic case (long arc discharge stabilized by a wall).

In experiments, the value of evaporation mass flow rate \dot{m} was deduced under simplifying assumptions [5] from measured temperature profiles and from transport and thermodynamic coefficients of arc plasma assuming existence of LTE. We found such magnitudes of \dot{m} for which differences between numerical and experimental outlet quantities are minimal. The outlet axial velocity, temperature and the potential drop between the cathode and the nozzle were chosen for the comparison between numerical (at the point C of our computational domain) and experimental (2 mm downstream from the nozzle [6]) values. For each physical quantity we defined the relative error as $\Delta(rel) = |X(exp) - X(num)| / X(exp)$ ($X(exp)$ = experimental value, $X(num)$ = numerical value) and the resulting relative error is the sum of the three relative errors. The best-fit values of $\dot{m} = 0.265$ g/s (300 A) and $\dot{m} = 0.342$ g/s (600 A) were found. These values are slightly higher (5 % - 20 %) than the experimental values (0.204 g/s for 300 A, 0.325 g/s for 600A).

Tab. 1 compares the best-fit numerical results with the experimental ones (axial velocity, temperature, electric potential, pressure drop in the discharge chamber, Mach number, current density and electric field strength). Since the input power and \dot{m} increase with current, the magnitudes of all quantities increase as well. The plasma flow is mildly compressible with the Mach number ranging between 0.38 and 0.76. The higher differences occur in the temperature; the lower numerical values can be caused, in our opinion, by the fact

that we neglected the absorption of radiation in vapours and by a more complex discharge channel geometry. The input power $I \cdot \Phi$ increased more than twice for the 600 A arc with respect to the 300 A value. The power losses from the arc which are the sum of the radial conduction losses and radiation losses represent around 50 % of the input power. The ratio radiation losses/conduction losses ranges from 2 to 4. The values of the parameter ξ (3.1 % for 300 A, 1.43 % for 600 A) are in good agreement with experiments [5] which proved that only 1-2 % of radiation power is spent for evaporation of water (generation of the plasma gas itself). The evaporation is thus very inefficient process with 20-50 % of radiation power absorbed in vapours [5] and about 50-80 % in water and the walls of stabilizing chamber.

3. Conclusions

The proposed numerical model is able to explain the basic physical behaviour of an electric arc stabilized by water vortex and predict evaporation mass flow rates of water. The lower nozzle temperatures cause the constriction of arc; the longer nozzle is convenient for reaching higher outlet velocities. The conduction and radiation power losses represent around 50 % of the input power to the arc; the amount of heat flux spent for evaporation itself is 1.4 % - 3.1 % which supports the experimental observations.

References

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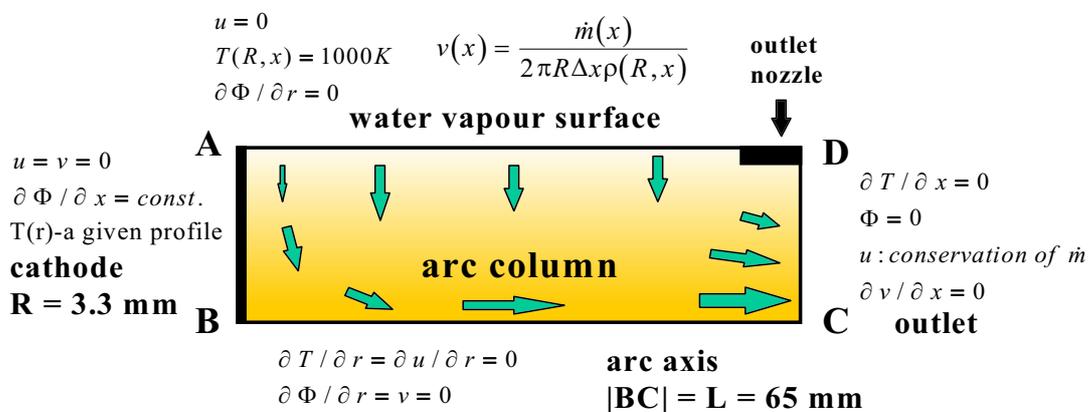


Figure 1. Boundary conditions. The dimensions of the outlet nozzle are 5 mm x 0.3 mm (x-r directions); $T_{\text{nozzle}} = 473 \text{ K}$.

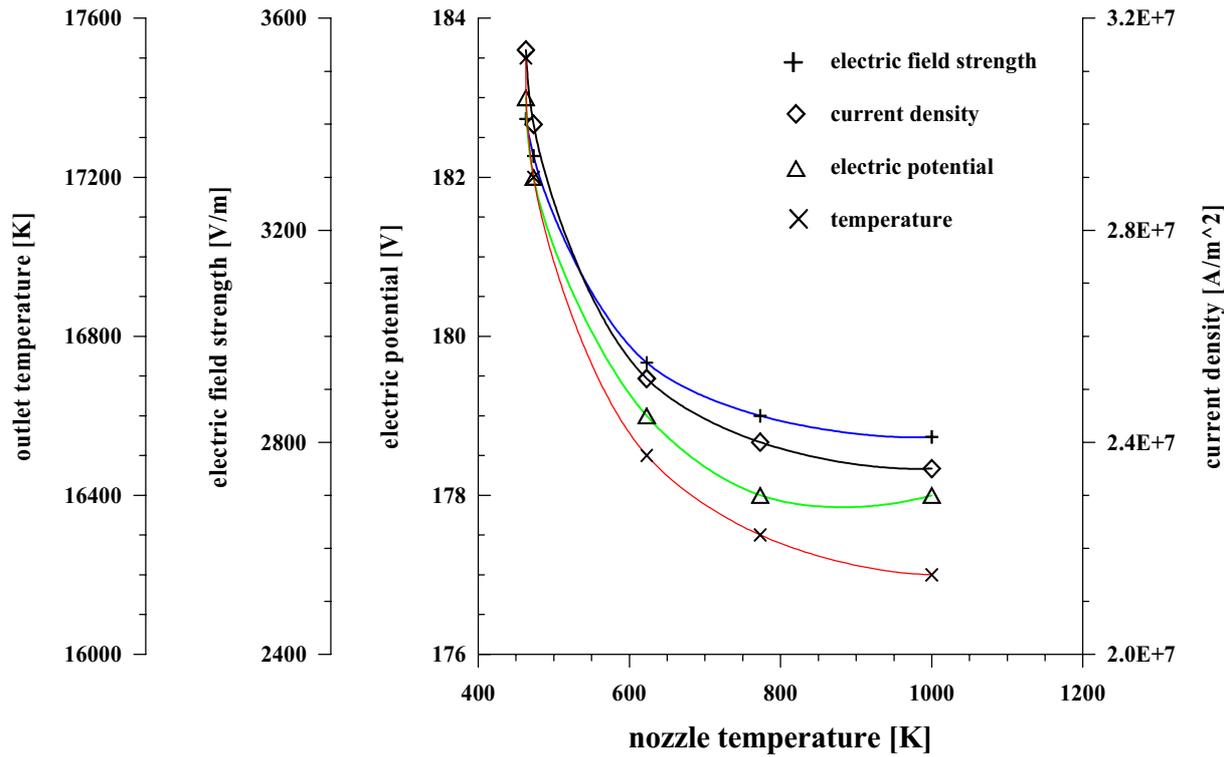


Figure 2. Arc temperature, electric field strength, electric potential drop in the discharge chamber and current density versus the nozzle temperature.

The values of the quantities are taken at the point **C** in Fig. 1.

I = 300 A		I = 600 A	
experimental	numerical	experimental	numerical
flow rate = 0.204 g/s	0.265 g/s	flow rate = 0.325 g/s	0.342 g/s
u = 2 494 m/s	2 630 m/s	u = 7 054 m/s	7 050 m/s
T = 19 000 K	16 800 K	T = 27 200 K	21 800 K
Φ = 185 V	184 V	Φ = 216 V	208 V
Δ p = 6 100 Pa	10 900 Pa	Δ p = 25 700 Pa	32 800 Pa
M = 0.317	0.381	M = 0.617	0.761
J (current density)	2.80 E07 A/m**2	J (current density)	4.07 E07 A/m**2
E (electric field strength)	3 190 V/m	E (electric field strength)	4 330 V/m
input power [W]	55 300	input power [W]	124 700
power losses [W]	23 800	power losses [W]	64 500
power losses [%]	43.10	power losses [%]	51.70
conduction losses [%]	8.600	conduction losses [%]	16.00
radiation losses [%]	34.50	radiation losses [%]	35.80
ξ [%]	3.061	ξ [%]	1.434

Table 1. Comparison between experimental and numerical values of the outlet axial quantities for currents 300 A and 600 A. The best-fit value of \dot{m} is 0.265 g/s for 300 A and 0.342 g/s for 600 A. The power losses from the arc are the sum of radial conduction losses and radiation losses. The parameter ξ determines the amount of radiation and conduction losses which is spent for evaporation of water.