Performance of water and hybrid stabilized electric arcs: the impact of dependence of radiation losses and plasma density on pressure

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Processes in the worldwide unique type of thermal plasma generator with water vortex stabilization and combined stabilization of arc by argon flow and water vortex have been numerically studied. Two–dimensional axisymmetric numerical model assumes laminar and compressible plasma flow in the state of local thermodynamic equilibrium. The calculation domain includes the arc discharge area between the near–cathode region and the outlet nozzle of the plasma torch. Radiation losses from the arc are calculated by the partial characteristics method for atmospheric pressure water and argon–water discharges. Thermal, electrical and fluid–dynamic characteristics of such arcs have been studied for the range of currents 150÷600 A under the assumption that radiation losses and plasma density depend linearly on pressure. It was proved that, taking this dependence into account, plasma velocity decrease while power losses from the arc by radiation and radial conduction increase with current. Outlet plasma temperature as well as electric potential drop remain practically unchanged.

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1 Introduction

Plasma generators with arc discharge stabilization by water vortex exhibit special performance characteristics; such as high outlet plasma velocities (≈ 7 000 m/s), temperatures (≈ 30 000 K), plasma enthalpy and, namely, high powder throughput during plasma spraying, compared to commonly used gas–stabilized (Ar, He) torches. In a water–stabilized arc, the stabilizing wall is formed by the inner surface of water vortex which is created by tangential water injection under high pressure (≈ 10 atm.) into the arc chamber.

The so–called *hybrid stabilized electric arc* utilizes combination of gas and vortex stabilization. In the hybrid H_2O-Ar plasma torch the arc chamber is divided into the short cathode part, where the arc is stabilized by tangential argon flow, and the longer part which is water–vortex stabilized. This arrangement not only provides additional stabilization of the cathode region and protection of the cathode tip, but it also offers the possibility of controlling plasma jet characteristics in wider range than that of pure gas or liquid stabilized torches.

The primary aim of this paper is to study the impact of pressure–dependence of radiation losses and plasma density on arc parameters. Comparison with our previous results will be discussed.

2 Description of the physical model

The following assumptions for the model are applied: 1) the numerical model is two–dimensional with the discharge axis as the axis of symmetry; 2) plasma flow is laminar and compressible in the state of local thermodynamic equilibrium; 3) argon and water creates a uniform mixture in the arc chamber; 4) only self–generated magnetic field by the arc itself is considered; 5) the partial characteristics method for radiation losses from the arc is employed; 6) cathode phenomena and space charge near the cathode are neglected. The complete set of conservation equations with temperature–dependent transport and thermodynamic properties can be written in the vector notation as follows:

CONTINUITY EQUATION:

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

MOMENTUM EQUATION:

$$\frac{\partial}{\partial t}(\rho\mathbf{u}) + \nabla\cdot(\rho\mathbf{u}\mathbf{u}) = -\nabla p + \nabla\cdot\boldsymbol{\tau} + \mathbf{j}\times\mathbf{B}\,,$$

$$\tau_{ij} = \eta\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_l}{\partial x_l}\right)\ , \tag{2}$$

ENERGY EQUATION:

$$\frac{\partial}{\partial t}(\rho c_p T) + \nabla\cdot(\rho\mathbf{u}c_\mathrm{p}T) - \frac{\partial p}{\partial t} =$$

$$= -\nabla\cdot(\lambda\nabla T) + \mathbf{j}\cdot\mathbf{E} + \mathbf{u}\cdot\nabla p + \frac{5}{2}\frac{k}{e}(\mathbf{j}\cdot\nabla T) - \dot{R} + \varPhi_\mathrm{diss}\ \ , \tag{3}$$

CHARGE CONTINUITY EQUATION:

$$\nabla\cdot(\sigma\nabla\varPhi) = 0\ . \tag{4}$$

Here $\mathbf{u}$ is the velocity vector, p is the pressure, $\boldsymbol{\tau}$ is the stress tensor, $\mathbf{j}$ is the current density, $\mathbf{B}$ is the self-generated magnetic field, T is the temperature, $\mathbf{E}$ is the electric field strength, k is the Boltzmann constant, e is the elementary charge of electron, $\dot{R}$ means the divergence of radiation flux (radiation losses), $\Phi_{\rm diss}$ is the dissipation work and Φ is the electric potential.

The transport and thermodynamic properties of argon and water plasma were calculated rigorously from the kinetic theory. For argon, the mass density ρ, the specific heat under constant pressure c_p and the sonic velocity were taken from [1], the thermal conductivity λ, the electrical conductivity σ and the dynamical viscosity μ from [2]. For water plasma, the transport and thermodynamic properties are based on the results published in [3].

For determination of the transport and thermodynamic properties of the mixture argon–water we applied linear mixing rules for non–reacting gases based either on mole or mass fractions of argon and water species [4]. The dynamical viscosity was calculated using the Armaly–Sutton mixing rule [5].

Radiation losses from the arc $\dot{R}$ are calculated by the partial characteristics method for plasmas containing atmospheric pressure water and the argon–water mixture [6]. Radiation from hundreds of emission and absorption oxygen atomic and ionic lines have been included in the determination of appropriate partial characteristics. On the other hand, the influence of atomic and ionic hydrogen lines, O_2, H_2 and OH molecules, and dissociation processes of H_2O have been omitted so far.

We also assume the density ρ and radiation losses $\dot{R}$ from the arc to be directly dependent on the pressure:

$$\rho(p,T) = \frac{p}{p_{\rm atm.}}\rho(p_{\rm atm.},T)\,, \qquad \dot{R}(p,T) = \frac{p}{p_{\rm atm.}}\dot{R}(p_{\rm atm.},T)\ . \tag{5}$$

The linear dependence of density on pressure follows from the equation of state for ideal gas; the linear dependence of the radiation losses is an approximation of the fact that radiation losses increase with operating pressure. Similar approach for the net emission coefficient has been applied by other authors [7].

The boundary conditions for the problem are represented in Fig. 1. The rectangular calculation region has been chosen with the dimensions of 3.3 mm for the radius and 58.32 mm (65 mm) for the axial coordinate of the hybrid (water) discharge. This domain represents the discharge region of the plasma torch with hybrid type of stabilization which is being investigated at the Institute of Plasma Physics AS CR. The task was solved numerically by the control volume method using the iteration procedure SIMPLER [8] with the compressible modification of the original code elaborated by J. Jeništa. A non–equidistant rectangular grid with 60 control volumes in the axial direction and 40 in the radial direction was used. Calculation was carried out for currents 150÷600 A and argon mass flow rate 22.5 slm (standard liters per minute). Mass flow rate for water–stabilized section of the discharge was taken for each current between 300 and 600 A from our previously published work [9], where it was determined iteratively as a minimum difference between numerical and experimental outlet values.

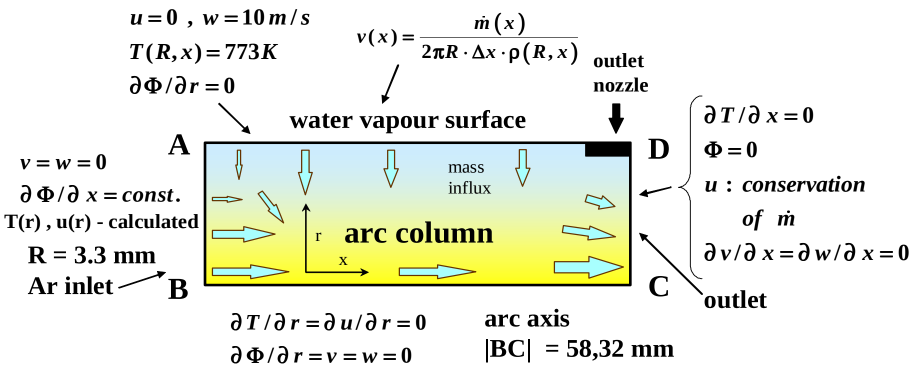

Fig. 1. Discharge area geometry for the hybrid torch. Dimensions of the outlet nozzle are $X = 5$ mm (axial direction) and 0.3 mm (radial direction).

3 Results of calculation

Relative changes of some arc parameters with respect to the arc current are depicted in Fig. 2. The relative difference shown here is defined as

$$\Delta_{\mathrm{rel}} = 100 \cdot [X(p) - X(p_{\mathrm{atm.}})]/X(p_{\mathrm{atm.}})\,,$$

where $X(p)$ is the value of the appropriate physical quantity for the pressure p and $X(p_{\mathrm{atm.}})$ is the corresponding value for atmospheric pressure. In the plots temperature, axial velocity and Mach number are taken at the point C in Fig. 1, i.e. at the axial outlet position; while overpressure and electric potential are related to the drops of these two physical quantities within the whole calculation region. We can see similar tendencies in both water and hybrid discharges. Overpressure generally increases within the discharge chamber with current. Since the plasma density increases with pressure due to its pressure–dependence the outlet velocity decreases. Mach number exhibits the same dependence as velocity, indicating that temperature field is practically unchanged. The amount of reabsorbed radiation in the discharge from both the water–stabilized and hybrid–stabilized arcs is only slightly influenced ($\leq 2\,\%$) by the pressure corrections (5). The power losses by radiation and radial conduction presented here thus increase with current. For the hybrid discharge $35 \div 20\,\%$ of radiation is reabsorbed, for the water discharge it represents $25 \div 14\,\%$ in the current range $150 \div 600$ A. Increase of the divergence of radiation flux due to pressure in the axial regions of the arc is not high enough to change considerably the temperature and electric potential drop. The overall pressure drop shows a peak at 400 A in both graphs and at 600 A in a case of the hybrid discharge. The reason for these small peaks consits in a slight change of the shape of temperature profile from a “bell–shaped–type” to a more “flat” one, i.e. with less pronounced arc core, a consequence of the pressure dependence of $\dot{R}$ and a nonlinear dependence of the partial characteristics on temperature. One can also notice that values of the relative differences of power losses and axial velocities are substantially higher in the hybrid discharge. Increase of plasma density due to the

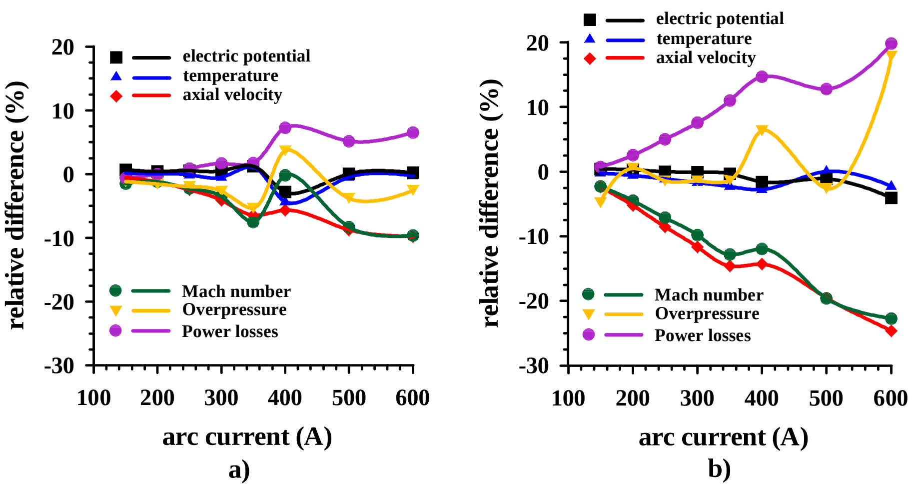

Fig. 2. Relative change of the arc parameters with respect to the arc current for a) water and b) hybrid discharges. Relative differences are related to calculations omitting the pressure corrections (5).

pressure correction (5) with the presence of relatively heavy argon atoms (M ∼ 40) implies higher decrease of the outlet velocity in the hybrid arc. On the contrary the presence of argon in water plasma creates the divergence of radiation flux more than twice higher than that of pure water discharge, resulting in higher relative difference of the power losses by radiation and radial conduction.

The following Figs. 3, 4 comprise contours of the overpressure and axial velocity for 600 A within the discharge region. Orientation of the plot axes corresponds to the domain shown in Fig. 1. The pressure corrections (5) increase overpressure in the hybrid discharge while the pressure field in the pure water discharge is changed not much. Axial velocities at the outlet decrease in both type of discharges, the higher impact of pressure correction is obvious in the hybrid discharge. The plasma flow in the water discharge is subsonic with the Mach number 0.76 at the outlet but the flow in the hybrid discharge is supersonic with the Mach number 1.28.

4 Conclusion

Two–dimensional numerical model of the discharge region of the water–stabilized and hybrid–stabilized electric arcs has been set up and solved for currents 150 ÷ 600 A. In the present paper we assumed the linear dependence of plasma density and divergence of radiation flux on pressure. Comparison of the present numerical results with our previous ones has been made. Our calculations, taking the pressure dependence (5) into account, proved that

– plasma velocity decrease while power losses from the arc by radiation and radial conduction increase with arc current,

– temperature and electric potential are practically uninfluenced by the pressure dependence,

– relative differences of the power losses and axial velocities are substantially higher in the hybrid discharge.

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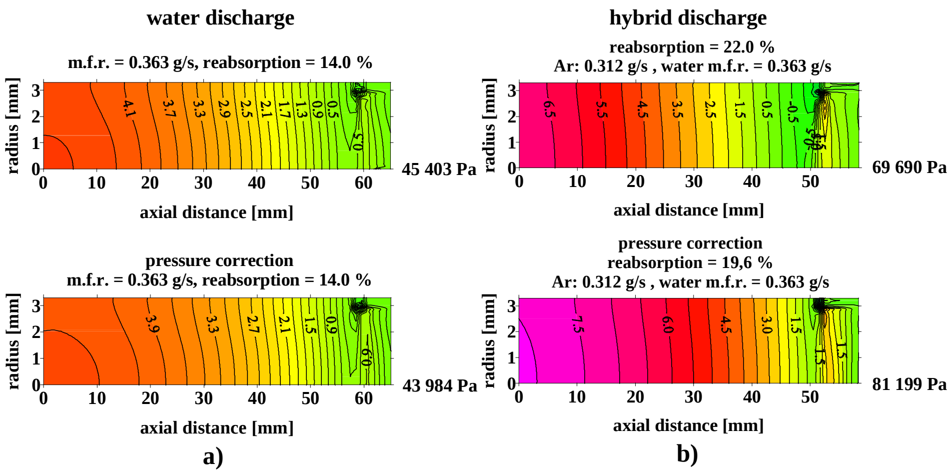

Fig. 3. Contours of the overpressure for a) water and b) hybrid discharges for 600 A with argon mass flow rate of 22.5 slm. 10^4 Pa corresponds to 1 in the plot.

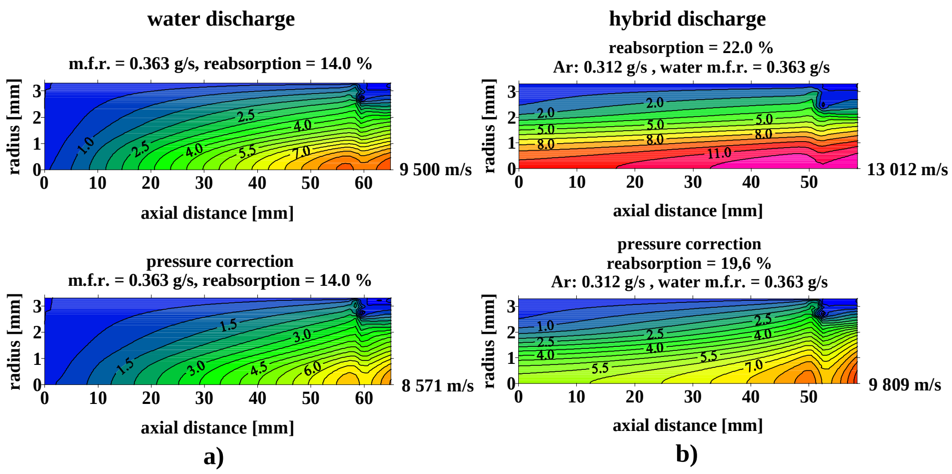

Fig. 4. Contours of the axial velocity for a) water and b) hybrid discharges for 600 A with argon mass flow rate of 22.5 slm. $10^3\ \mathrm{m\,s^{-1}}$ corresponds to 1 in the plot.

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