# Preliminary Study of Mixing of Plasma Species in a Hybrid-Stabilized Argon-Water Electric Arc

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This paper focuses on numerical simulation of mixing of plasma chemical species in the discharge and near-outlet regions of the worldwide unique type of thermal plasma generator with hybrid stabilization of electric arc by axial argon flow and tangential water vortex. Results of simulation for 300-500 A indicate inhomogeneous mixing of argon and oxygen-hydrogen species for all currents. The argon diffusion mass flux is driven mainly by the concentration and temperature space gradients.

**Keywords:** arc discharge, combined diffusion coefficients, inhomogeneous mixing, mass fraction

## 1 INTRODUCTION

The so-called hybrid stabilized electric arc, developed at IPP AS CR, v.v.i. in Prague, utilizes a combination of gas and vortex stabilization. In the hybrid argon–water 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 stabilized by water vortex. The arc is attached to the external water-cooled rotating disk anode at a few millimetres downstream of the torch orifice. At present, this arc has been used for plasma spraying, pyrolysis and gasification of waste and production of syngas from biomass [1].

In our experimental configuration water species are created by evaporation from a water column in the tangential direction, while argon is flowing axially into the discharge chamber where argon species are mixed with the water ones (Fig. 1). Recently it was proved from spectroscopic experiments made in IPP AS CR, v.v.i., [2] that argon and water plasma components are mixed only partially within the discharge chamber and, in addition, that mixing of individual components depends also on arc current. Since the studied plasma in the hybrid stabilized electric arc is quasi-laminar with steep radial temperature and velocity gradients [3] it can be expected that mixing and demixing processes will be important.

Here we present a novel numerical model of the hybrid-stabilized argon-water electric arc including the plasma species mixing model using the so called "combined diffusion coefficients method" [4, 5]. It has already been successfully applied by some authors to describe mixing of species in different arc discharges [6, 7]. Diffusion processes due to gradients of mass density, temperature, pressure, and an electric field are considered in the present model.

## 2 ASSUMPTIONS AND PHYSICAL MODEL

The following assumptions for the model are applied:

1) argon-water plasma itself is in local thermodynamic equilibrium, 2) the model is axisymmetric (2-dimensional), 3) the plasma flow is turbulent and compressible, 4) gravity effects are negligible, 5) the magnetic field is generated only by the arc itself, 6) the partial characteristics method for radiation losses is employed, 7) transport and thermodynamic properties for argon-water plasma mixture are calculated rigorously from the kinetic theory [8, 9] and they depend on temperature, pressure and argon mass fraction, 8) the combined diffusion coefficients are also functions of temperature, pressure and argon mass fraction.

Radiation losses from the argon-water arc are calculated by the partial characteristics method [10]. Continuous radiation, discrete radiation consisting of thousands of spectral lines, molecular bands of $O_2$, $H_2$, OH and $H_2O$ have been included in the calculation of partial characteristics [11]. Broadening mechanisms of atomic and ionic spectral lines due to Doppler, resonance and Stark effects have been considered. The partial characteristics are function of temperature, pressure and an average argon mass fraction, determined from the ratio of mass flow rates of argon to water plasmas.

Turbulence is modelled by Large eddy simulation (LES) with the Smagorinsky subgrid-scale model with the constant values of the Smagorinsky coefficient ($C_S$ = 0.1) and the turbulent Prandtl number ($Pr_t$ = 0.9). The Van Driest damping function near the walls is employed to suppress turbulence [12].

The resulting set of conservative governing equations for density, velocity, energy and argon mass fraction (continuity, momentum, energy and species equations) was solved numerically by the LU-SGS method [13] coupled with Newtonian iterative method. The same method was successfully applied for calculation under the assumption of homogeneous plasma mixing. To resolve compressible phenomena accurately, the Roe flux differential method [14] coupled with the third-order MUSCL-type TVD scheme [15] is used for convective term. The electric potential is calculated using the Tridiagonal Matrix Algorithm (TDMA) enforced with the block correction method.

The computer program is being elaborated in the Fortran language. The task has been solved on an oblique structured grid with nonequidistant spacing. The total number of grid points was 38 553, with 543 and 71 points in the axial and radial directions respectively. Calculation domain is shown in Fig. 1.

## 3 DETAILS OF THE SPECIES MIXING MODEL

Only one species equation is required in the combined diffusion coefficients method, say for the species of gas A (argon), with the equation for argon species flux [16]:

$$\frac{\partial}{\partial t}(\rho f_A) + \nabla \cdot (\rho \vec{u} f_A) = -\nabla \cdot \vec{J}_A \quad ,$$

$$\vec{J}_A = -\Gamma_f \nabla f_A + \Gamma_f \frac{f_A}{M_A} \nabla M_A - \Gamma_f \frac{f_A}{M} \nabla M +$$

$$\Gamma_P \nabla(\ln P) - \bar{D}_{AB}^T \nabla(\ln T) - \Gamma_E \nabla \Phi - \frac{\mu_t}{Sc_t} \nabla f_A \,,$$

where $\rho$ is the mass density, $f_A$ is the mass fraction of species A (gas A = argon), $\vec{J}_A$ is the argon diffusion mass flux, $\Gamma_f, \Gamma_P, \Gamma_E$ are the transport coefficients for the ordinary, pressure and electric field diffusions respectively, $M_A$ is the average molecular weight of argon, $M$ is the average molecular weight of all particles of gas mixture, $\bar{D}_{AB}^T$ is the combined temperature diffusion coefficient, $\mu_t$ is the eddy viscosity, $Sc_t$ is the turbulent Schmidt number ($Sc_t$=1). The last term accounts for the diffusion of the argon species due to turbulence. The water species mass fraction $f_B$ can be easily calculated from the closure condition $f_A + f_B = 1$.

## 4 RESULTS

Mixing of plasma species has been studied so far for 300–500 A and for 22.5 and 40 slm (standard liter per minute) of argon. The very first results of the model are illustrated in Figs. 2-4, showing the contours of the argon mass fraction, temperature and the combined ordinary diffusion coefficient for 300 and 500 A. We can conclude that:

- Mixing of argon and water plasma species is inhomogeneous under the studied conditions.
- Temperature and ordinary (concentration) diffusions are the most dominant contributions in the argon mass diffusion flux. Diffusion due to pressure gradients is lower and due to the electric field is practically negligible.
- Argon species are dominant in the central regions of the arc, water ones in arc fringes. Argon mass fraction in the central arc region also increases with current and argon mass flow rate. One of the reasons for this dependence is obvious from the plots: the combined ordinary diffusion coefficient decreases with temperature in the arc core (500 A), preventing thus higher mixing of argon and water

plasma species. The combined temperature diffusion coefficient (not shown) exhibit the same temperature dependence.

- These first results agree with our former experiments carried out 2 mm downstream of the nozzle orifice: calculated radial temperature profiles exhibit very good qualitative and quantitative agreements with the measurements. Qualitative agreement was also obtained for the radial argon mole fraction profiles.

## 5 CONCLUSIONS

The results confirmed inhomogeneous mixing of argon and water plasma species in the discharge region calculated by the combined diffusion coefficients method. Argon mass fraction in the axial region of the discharge increases with current and argon mass flow rate. Diffusion of species is influenced by highly nonlinear dependence of the combined diffusion coefficients on temperature, pressure and argon mass fraction.

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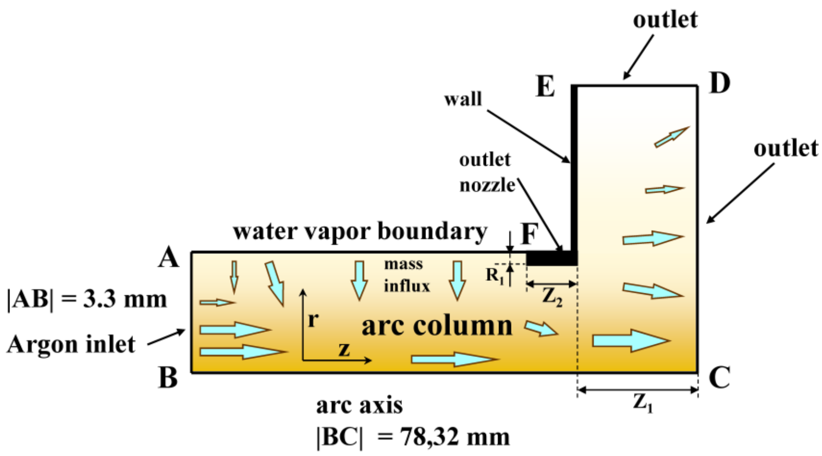


*Fig. 1: Calculation domain for our problem. Argon flows axially through the AB line (+z direction) while water evaporates along the water vapor boundary AF (-r direction)*

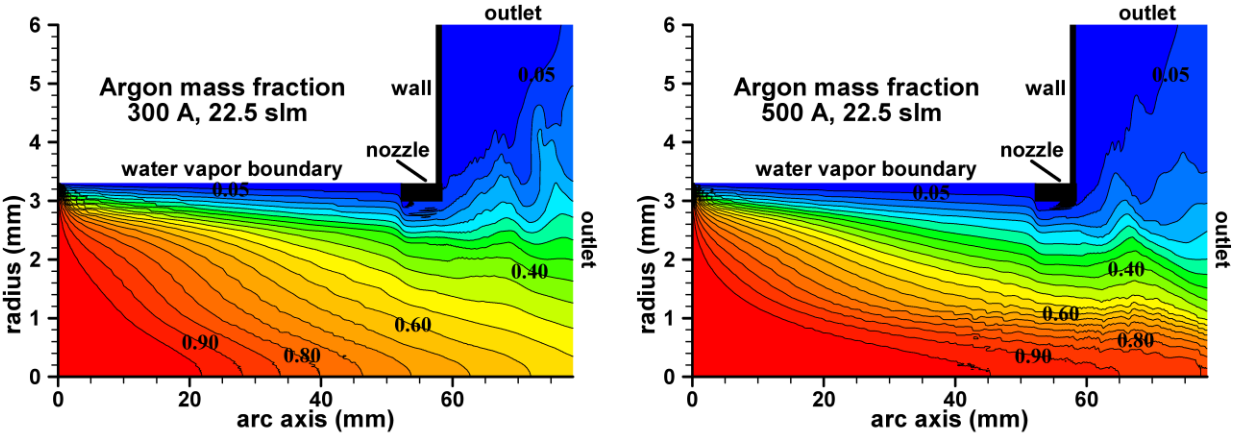


*Fig. 2: Isopleths of argon mass fraction for 300 A (left) and 500 A (right) discharges. Water mass flow rates are 0.228 $g \cdot s^{-1}$ (300 A) and 0.329 $g \cdot s^{-1}$ (500 A); argon mass flow rate is 22.5 slm for both currents. The increase of argon mass fraction in the centre of the arc for higher current is clearly visible. Contour increments are 0.05*

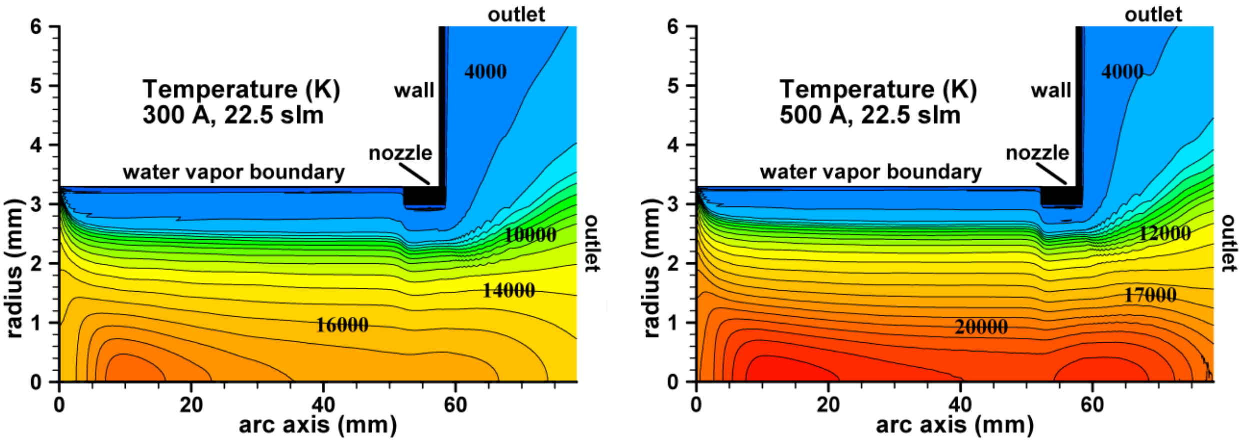


*Fig. 3: Isotherms for the same conditions as in Fig. 2. Temperature in the arc core and the temperature gradients in arc fringes are higher for higher curren*

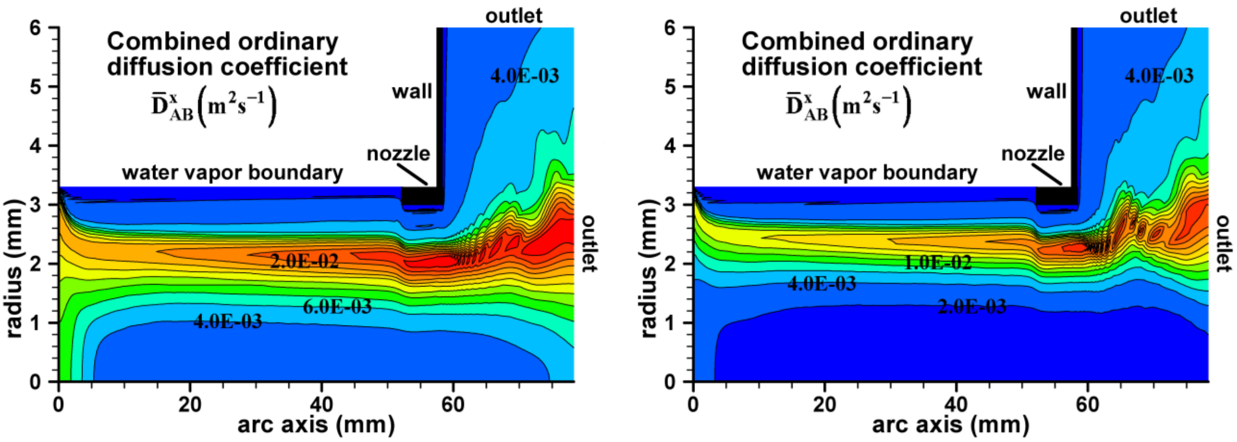


*Fig. 4: Combined ordinary diffusion coefficient for the same conditions as in Figs. 2, 3 (left—300A, right—500A). The arc core for 500 A shows the lower values of the coefficient compared to 300 A*