Modeling And Measurements Of The Arc Plasma In A Mixture Of Gases

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Abstract. Radial distributions of Ar mass fractions and temperatures in plasmas produced in a wall-stabilized arc have been calculated. Modeling have been performed for many different mixtures of $Ar+N_2$ and three different arc currents. The obtained results show that the radial distributions of Ar mass fractions strongly depend on the chemical composition of the plasma. In plasmas containing large amount of Ar the distributions have local minima at the arc axis (in high temperature plasma regions), whereas in plasmas consisting mainly of nitrogen the distributions reveal maxima on the discharge axis. Those features seem to be connected with the dissociation of the nitrogen.

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INTRODUCTION

Wall-stabilized arcs are widely used sources of atomic and ionic excitation in the measurements of different parameters of many species [1-2]. In contrast to other light sources (hollow cathodes, barrier discharges) plasmas produced in cascade arcs can be assumed to be in the state close to partial LTE.

Many of interesting species supplied into the arc damage the stability of the arc operation, so in most cases they can be introduced into the plasma only as trace gases. Usually noble gases (mainly Ar or He, as they are much cheaper than others) are used as the working medium.

CALCULATIONS OF DEMIXING EFFECTS IN THERMAL ARC

Diffusion in a gas can be described by equations for the mass flux J_i, relative to the mass-average velocity, of each of the species i present. In a gas mixture containing q species, in the presence of a temperature gradient, the equations take the form

$$J_i \equiv m_i n_i v_i = \frac{n^2}{\rho} m_i \sum_{j=1}^{q} m_j D_{ij} d_j - D_i^T \nabla \ln T \tag{1}$$

where v_i is the diffusion velocity of species i relative to the mass-average velocity and T is the temperature. The D_{ij} are ordinary diffusion coefficients, and the D_i^T are thermal diffusion coefficients. The term d_j, given by

$$d_j \equiv \nabla x_j + \left(x_j + \frac{\rho_j}{\rho} \right) \nabla \ln P - \frac{\rho_j}{P\rho} \left(\frac{\rho}{m_j} F_j - \sum_{l=1}^{q} n_l F_l \right) \tag{2}$$

describes the diffusion forces due to gradients in mole fraction $x_j = n_j/n$ and pressure P, and due to external forces F_j. n and ρ are, respectively, the number and mass densities of the gas mixture, and n_j, ρ_j, and m_j are, respectively, the number density, mass density, and mass of the j-th species.

Murphy [3] has shown that in a mixture of two homonuclear gases that do not react with each other the treatment of diffusion can be greatly simplified if local chemical equilibrium is assumed. In this case, instead of considering the diffusion of individual species separately, one can consider the diffusion of gases. Here a gas, in this example nitrogen, is defined to consist of all the species that can be derived from that gas, for example N_2, N_2^+, N, N^+, N_2^+,

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and the electrons derived from the ionization of nitrogen molecules and atoms. It is possible to derive an expression for the mass flux of a gas, defined as the sum of the mass fluxes of all the species that make up the gas that has the form

$$\overline{J_A} \equiv \frac{n^2}{\rho}\overline{m_A}\,\overline{m_B}\,\overline{D^x_{AB}}\nabla\overline{x_B} - \left(\overline{D^{T1}_{AB}} + \overline{D^T_A}\right)\nabla \ln T \tag{3}$$

where $\overline{m_A}$ is the average mass of the heavy species of gas A, and $\overline{x_B}$ is the sum of the mole fractions of all species of gas B. The bar notation is used to denote that a variable refers to a gas rather than to a species. Gradients in the total pressure and external forces have been neglected.

Considering the equilibrium situation, in which the mass fluxes of the gases have vanished, the equilibrium mole fraction gradients of the two gases are calculated by setting $J_A = 0$ in Eq. 3, giving

$$\nabla\overline{x_B} = -\nabla\overline{x_A} = \frac{\rho}{n^2}\frac{\left(\overline{D^{T1}_{AB}} + \overline{D^T_A}\right)\nabla \ln T}{\overline{m_A}\,\overline{m_B}\,\overline{D^x_{AB}}} \tag{4}$$

Coefficients used in the calculations are shown in Figure 1.

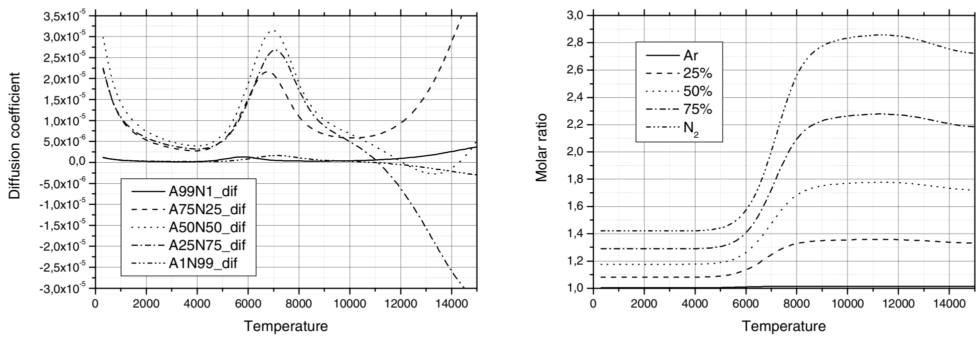

FIGURE 1. Coefficients used for resolving equation (4).

For calculation of the arc plasma properties some conservation laws should be applied:

Mass conservation

$$\nabla\cdot(\rho v) = 0 \tag{5}$$

Momentum conservation

$$(\rho v v) = -\nabla P - \nabla\cdot\tau \tag{6}$$

Energy conservation

$$\nabla\cdot(\rho v h) = \frac{j^2}{\sigma} - U + \nabla\cdot\left(\frac{\kappa}{c_p}\nabla h\right) + \frac{5k}{2ec_p}\,j\cdot\nabla h + \nabla\cdot\left[\left(\overline{h_A} - \overline{h_B}\right)\left(\overline{J_A} - \frac{\kappa}{c_p}\nabla\overline{Y_A}\right)\right] \tag{7}$$

Adding also the Maxwell's equations and Ohm's law we can calculate arc properties. For the first approximation we took 1D situation, where the arc has cylindrical symmetry and is in equilibrium. In such case we take into account equation (6) and (8) only, and the latter can be simplified to:

$$\frac{j^2}{\sigma} + \nabla\cdot\left(\frac{\kappa}{c_p}\nabla h\right) - \nabla\cdot\left[\left(\overline{h_A} - \overline{h_B}\right)\left(\frac{\kappa}{c_p}\nabla\overline{Y_A}\right)\right] \tag{8}$$

where $\overline{Y_A} = \frac{\overline{m_A}}{\overline{m_B} + \overline{m_A}}\overline{x_A}$.

In the end, there is a set of two equations, one for energy (8) and the second for mass ratio of the species (equation for $\overline{Y_A}$ derived from equation (4)). Solving this system of equations is not very complicated, because demixing doesn't change significantly the temperature curves, so the loop with solving the equation (8) with $\overline{Y_A}(r)$ set as constant and then solving (4) with the resulting $T(r)$ curve yields the results after just a few turnings.

Some of the crucial coefficients used in calculations of the temperature (eq. 8) are shown in figure 2.

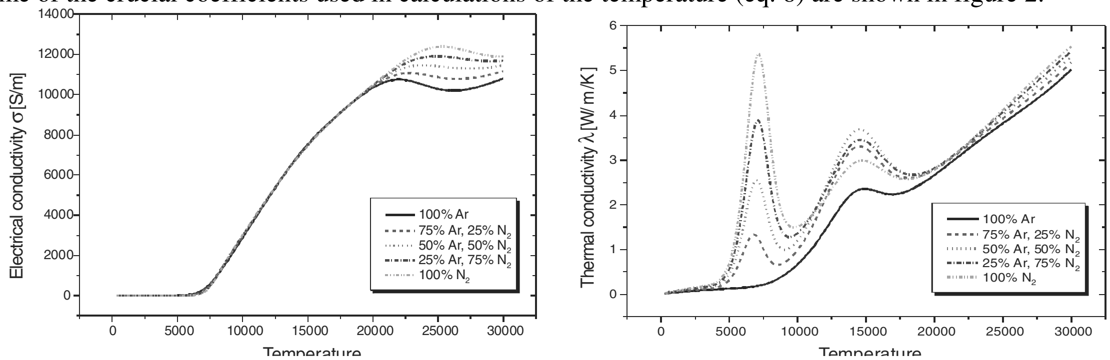

FIGURE 2. Thermal and electrical conductivity coefficients used for calculations.

RESULTS OF THE MODELING

The examples of the resulting temperature and mass ratio radial dependencies are shown in figure 3.

There is an interesting feature in both the temperature and mass ratio radial dependences (shown by arrows), clearly related to a region where the nitrogen molecule is dissociated. The dissociation changes significantly both the thermal and the electrical conductivity and uses much of the arc power, which in this case cannot be used to heat the plasma gas. The problem of energy used by dissociation of the nitrogen is also visible in the dependence (for constant arc current) of the electric field intensity on the ratio of the plasma gas species, which changes from about 1300 V/m for pure argon, to almost 2500 V/m for nitrogen. The electric field intensity (and, therefore, the power used by the arc to maintain the fixed current) increases significantly with the growing amount of nitrogen.

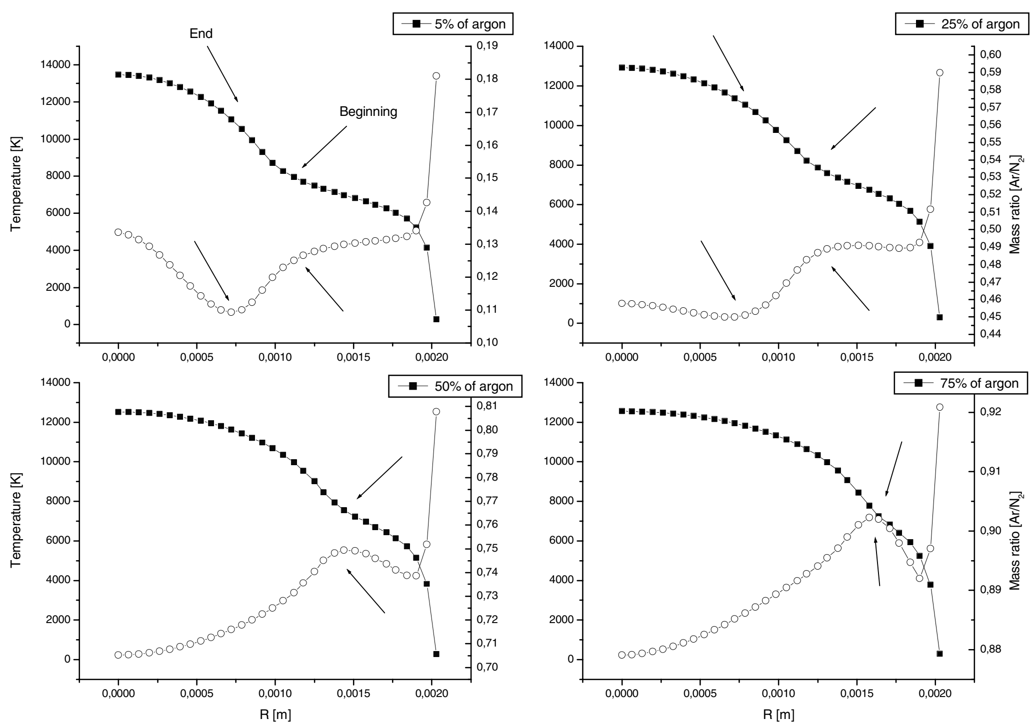

FIGURE 3. Examples of the results of he calculations, for arc current 40 A and different N_2/Ar mixtures.

The calculations were performed for the gas mixtures and arc currents similar to those used in experiment [5], in order to compare them. Two of the results for the mass ratio calculations and measurements are shown in Figure 4.

The features are remarkably similar, especially if we take into account that the simplified to “one and half” dimensions calculations cannot completely predict the results of side-on measurements, because they reflect the situation inside the plasma channel, and the experimental observations are taken in the region, where the channel walls do not exist.

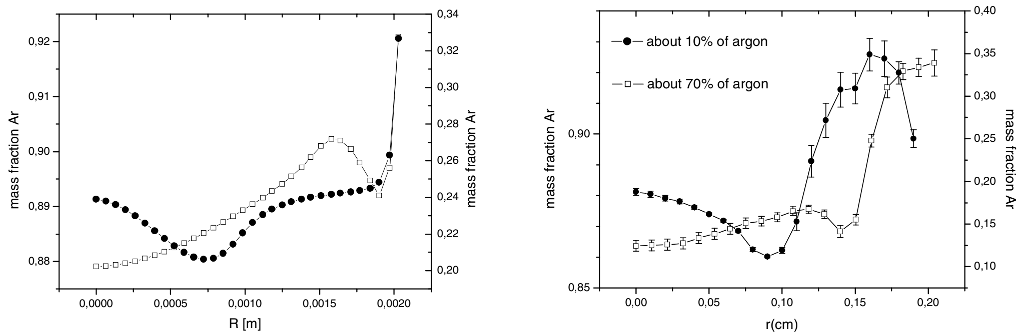

FIGURE 4. Comparison between the theoretical calculations (left) and the experimental measurements (right) [5]

CONCLUSIONS

The results of the calculations show, that the modeling of the cascade arc LTE plasma in the mixture of gases can be well done using the simplified model with the cylindrical symmetry (depending only on the distance from the arc axis) and still predict the complicated behavior of the demixing in the gas species. It shows also the high validity of the diffusion and transport coefficients of the mixture of gases, and their applicability not only for the temperature regions of the high-intensity welding arcs for which they were calculated, but also for much lower intensity Maecker-like arcs.

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