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THE INFLUENCE OF LORENTZ FORCE ON THE FLOW REGIME OF HYBRID-STABILIZED ARGON–WATER ELECTRIC ARC

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Abstract: The paper compares two numerical models of plasma flow in the arc chamber of a hybrid argon–water plasma torch. The models contain set of equations for the continuity, momentum and energy. The equation for momentum of the first model takes into account also the Lorentz force. This force acts on a moving electrically charged particles (ions and electrons) in a magnetic field. The second model neglects an influence of Lorentz force. A numerical analysis was performed with the solver Fluent. The influence of Lorentz force on the velocity, pressure and temperature fields is discussed in the paper.
Keywords: Lorentz force, hybrid-stabilized argon–water electric arc, Fluent

1. INTRODUCTION

In the paper is presented a comparison of two CFD models of flow in a plasmatron chamber with a hybrid stabilisation of arc. The hybrid stabilisation is a combined stabilisation by a helicoidal gas stream (in the vicinity of cathode) and by liquid water (in a mean part of a plasmatron chamber). The advantages of the hybrid stabilization compared with other solutions are explained in [1]. The first of compared CFD models takes into account the action of Lorentz force. This force acts on electrically charged plasma, which flows through the plasmatron chamber exposed to an electromagnetic field. The CFD model calculates also a magnetic induction necessary for an estimation of Lorentz force.

There are always tendencies to exclude parameters having marginal influence on a final result. That is the reason why a simplified CFD model omitting the influence of Lorentz force was created. This model has not implemented a calculation of a magnetic induction. The results of calculations obtained by both models are compared each other and conclusions about a significance of Lorentz force on the final flow field are made.

2. DESCRIPTION OF THE DEVICE

Research was carried out on a model plasmatron with a hybrid stabilisation of electric arc WS®P (Figure 1), developed in the Institute of plasma AS CR in Prague [2]. The plasmatron works with gas argon and water.

A plasmatron chamber is depicted in the Figure 1. In a short cathode part is an electric arc stabilized by the flowing argon. In the next section is the arc stabilised by water injected tangentially along the plasmatron wall. It is evident that argon enters the chamber in axial direction respect to the cathode. Liquid water enters the chamber through the openings made along a perimeter in a tangential direction. The helicoidal flow with a stabilization effect is created. Due to generated Joule heat the temperature in the plasmatron increases. The consequence is an ionization of gases and consequently the formation of plasma. A part of liquid water is evaporated due to high temperature and it is mixed up with flowing argon. It becomes a component of flowing plasma.

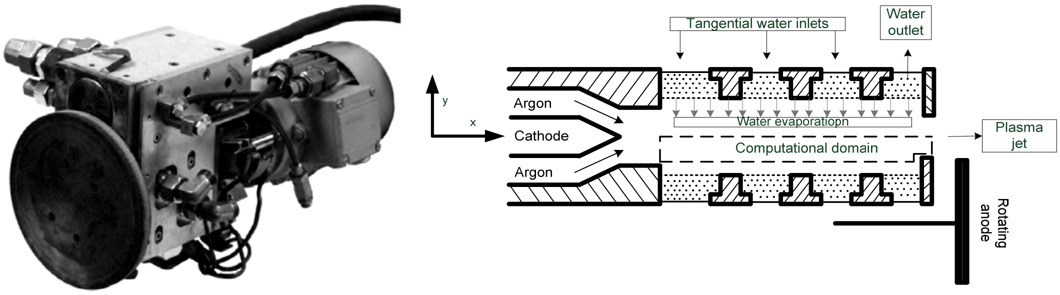

Figure 1. Plasmatron WS®P with a hybrid stabilisation of electric arc [2] (left).
Scheme of the arc chamber of the plasmatron

The plasma stream is accelerated towards the orifice of a plasmatron jet. In the region of the arc dominates especially an axial component of velocity. A part of the argon is mixed up with water and flows outside of plasma jet. The electric arc occurs in the surroundings of plasma which is also a moving conductor of an electric current. In the arc and also in its vicinity a magnetic field is also induced. Lorentz force acting on the electrically charged plasma partially accelerates the plasma flow and changes the form of flow field. Because of high temperatures the heat transfer due to radiation occurring especially in radial direction is meaningful.

3. CFD MODEL, FLOW EQUATIONS AND BOUNDARY CONDITIONS

The calculation domain is depicted by the hatched line in the Figure 1. It contains the whole region of the electric arc up to the jet orifice. The CFD simulation was carried out with the software Fluent. A standard 2D, axisymmetric and steady model of flow was applied. According [1] the tangential components of flow are unimportant and that's why they were neglected. A local thermodynamic equilibrium of flowing medium was assumed.

The calculation domain contains a relatively small part of a chamber and it is assumed that the liquid water doesn't occur inside the domain, only the vapour. That is the reason why the helicoidal flow of liquid water providing stabilising effect was not simulated numerically. It is also assumed that evaporated water flows in the radial direction on the outer boundary of the domain. Experiments showed that the mixture water-argon is not homogenous [1]. However, for the sake of simplicity we carried out the calculations with a homogenous mixture of water and argon.

The flow is described by the equations (1) to (9). The mass conservation has following form (1):

$$\nabla \cdot (\rho \mathbf{u}) = 0 \tag{1}$$

where ϱ – mixture density, $\mathbf{u}$ – velocity vector.

Momentum equation has following form (2):

$$\nabla (\rho \mathbf{u} \cdot \mathbf{u}) = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \mathbf{j} \times \mathbf{B} \tag{2}$$

where p - pressure, $\boldsymbol{\tau}$ – stress tensor, $\mathbf{j}$ – current density vector, $\mathbf{B}$ – vector of total magnetic induction.

It should be noted that the flow regime was laminar. In the paper [1] is mentioned that the results obtained on the base of laminar flow regime are similar to those obtained with a model of turbulence LES.

Relation (3) is an energy equation:

$$\nabla \cdot [(e + p)\mathbf{u} - \lambda \nabla T] = \mathbf{j} \cdot \mathbf{E} + \Phi_{dis} - \dot{R} \tag{3}$$

where e – total energy, λ – thermal conductivity , T – thermodynamic temperature, $\mathbf{E}$ – electric field intensity vector, Φ_{dis} – dissipation of energy due to viscous friction, $\dot{R}$ - radiation of heat.

For the internal energy holds (4):

$$U(p, T) = e(p, T) - 0{,}5\, \rho |\mathbf{u}|^2 \tag{4}$$

Current density is given by (5):

$$\mathbf{j} = \sigma\left(-\nabla\Phi + (\mathbf{u}\times\mathbf{b})\right) \tag{5}$$

where σ – electric conductivity, Φ – potential of electric field, **b** – vector of magnetic induction induced due to currents in a conductor.

Magnetic induction has a dominant component in a tangential direction (in the direction of axis y) for which holds (6):

$$b(r) = \frac{\mu_0 I}{2\pi r} \tag{6}$$

where μ_0 – permeability, r – chamber radius, where the induction is calculated, I – total electric current flowing through the cross section of the radius r.

For the intensity of electric field holds (7):

$$\mathbf{E}(r) = -\nabla\Phi \tag{7}$$

where Φ – potential of an electric field.

Heat transfer due to radiation was modelled by an approach of NEC (net emission coefficient) according (8):

$$\dot{R} = 4\cdot\pi\cdot\varepsilon_{\mathbf{n}} \tag{8}$$

where ε_n - net emission coefficient (NEC). NEC is given by:

$$\varepsilon_n = \int_0^\infty B_\lambda(T)\cdot k_\lambda^/(T,p)\cdot\exp\left(-k_\lambda^/(T,p)\cdot R_p\right)d\lambda \tag{9}$$

where B_λ - Planck function, $k_\lambda^/$ - total absorption (including induced emission), λ - wave length, R_p - distance from the axis of a discharge. Detailed information about the approach of NEC can be found in papers [3], [4].

Material properties are intensively changing in the dependence on the pressure and temperature. Because of low pressure close to 1 atm in the calculation domain, it is not necessary to consider the pressure dependence of material properties, only the temperature dependence is taken into account. Material properties were calculated for both mixture components on the base of a kinetic theory of gases in the AV ČR. The whole approach to a calculation of material properties is described for example in the paper [5]. Transport properties of the mixture argon and water (for a corresponding mass ratio of both components) were calculated by applying a mixing rule in a range 0 to 50000 K.

Boundary conditions were mass flow rate of argon in the entry (in the vicinity of the cathode), mass flow rate of vapour in the peripheral part of the electric arc, temperature profile in the entry in the vicinity of the cathode, assumed temperature of water, difference of electric potentials between the entry and output and the axis of symmetry along a plasmatron chamber.

4. RESULTS OF CFD SIMULATIONS

The CFD simulation was carried out for two different cases. The first one takes into account also the Lorentz force while the second one doesn’t take into account the action of Lorentz force. Both cases correspond to the flow regime at potential difference between input and output of 146 V, electrical current 300 A, argon mass flow rate $\dot{m}_{Ar}$ = 0,312 g/s and vapour mass flow rate $\dot{m}_W$ = 0,286 g/s. In the case with the Lorentz force was evaluated the distribution of the Lorentz force per unit volume in the calculation domain (Figure 2). For both cases were evaluated distributions of axial velocity (Figure 3), pressure (Figure 4) and temperature (Figure 5) inside the calculation domain. It is evident from the Figure 2 that the magnitudes of Lorentz force are relatively small. The calculation domain has a radius 3,3 mm and a length 58 mm, so its volume is a very small value. This is the reason why the total Lorentz force is also small in magnitude.

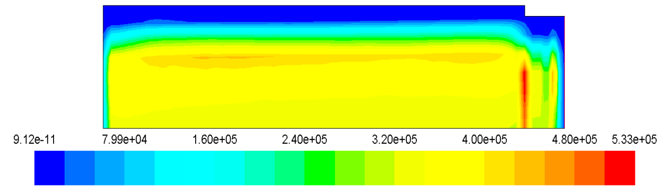

Figure 2. Distribution of Lorentz force per unit volume [N/m3] in a calculation domain.

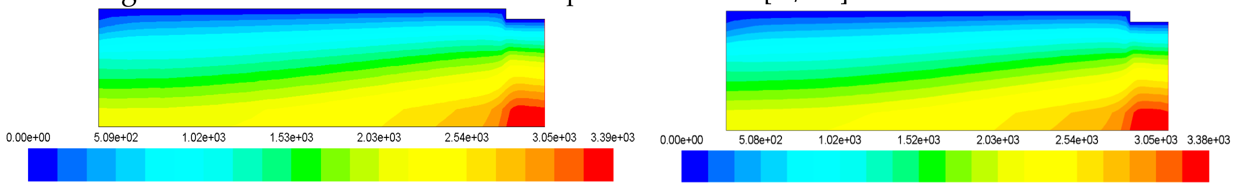

Figure 3. Axial velocity in [m/s] with (up) and without (down) Lorentz force.

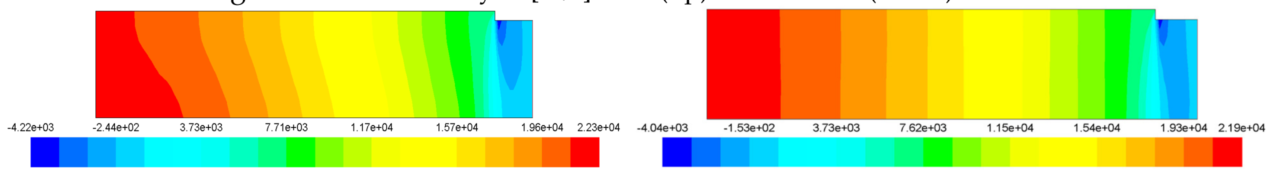

Figure 4. Pressure distribution [Pa] with (up) and without (down) Lorentz force.

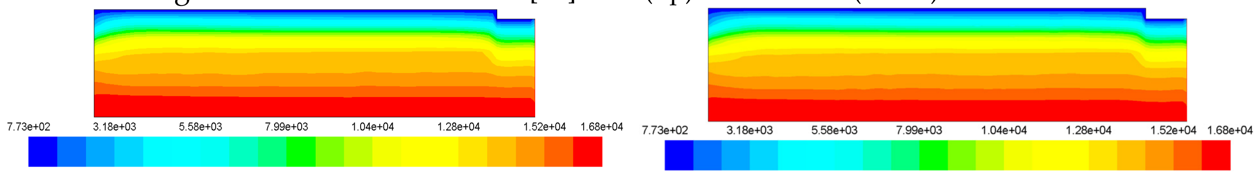

Figure 5. Temperature distribution [K] with (up) and without (down) Lorentz force.

5. CONCLUSIONS

From a comparison of velocity, pressure and temperature (Figure 3 - Figure 5) follows that Lorentz force at assumed flow regime has no significant influence on a quantitative and qualitative distribution of parameters characterizing basic thermodynamic and hydrodynamic conditions inside the plasmatron chamber. Only in the case of a static pressure Lorentz force deforms a shape of isobars, which has the shape of parallel vertical lines without an influence of Lorentz force. Neglecting of Lorentz force and associated neglecting of calculation of magnetic induction represents useful simplification of the CFD model.

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