Some numerical simulation results of the dynamic temperature distribution in dc plasma torch «Thermoplasma 50-01»

A Saifutdinov¹,², S Fadeev¹, I Fayrushin²
¹ Kazan Federal University, Kazan, Russia
² Saint-Petersburg State University, Saint-Petersburg, Russia

E-mail: as.uav@bk.ru

Abstract. A DC plasma torch “Thermoplasma 50-01” has been modeled and simulated by developing a 2D axisymmetric model of laminar flow and heat transfer coupled to electromagnetic fields. As a result of the numerical solution, the dynamics of the formation of the temperature field and the velocity field in the plasma torch channel and at its exit is presented. The numerical results of the gas temperature and axial velocity result to be quite satisfactory.

1. Introduction

DC arc plasma torches have been known, studied and used for many decades. They used to generate thermal plasma jets in different industrial applications, such as thermal plasma waste treatment, atmospheric or low-pressure plasma spraying, plasma-assisted chemical vapor disposition, plasma preparation of ultra fine-powder, etc [1-5].

At present, new plasma torches are being developed and created all over the world. In particular, modern developments is the «Thermoplasma 50-01» plasma torch, developed in Khristianovich Institute of Theoretical and Applied Mechanics of the Siberian Branch of the RAS [7-10].

One of the important tools for understanding physical processes in plasma torches is numerical modeling. In the last 10-20 years, much research has been undertaken to improve modeling of electric arcs, with the ambitious goal to be able to simulate numerically a working device, like a plasma torch [11, 12].

More recently, in [13] and [14] the complete arc and jet dynamics are simulated with a thermodynamic-equilibrium-based model.

The purpose of this work is numerical simulation of the plasma jet dynamics of the «Thermoplasma 50-01» plasma torch.

2. Description of the Mathematical Model

The continuum assumption is valid and the plasma is considered as a compressible, perfect gas in Local Thermodynamic Equilibrium (LTE), hence characterized by a single temperature $T$ for all its species (atoms, ions, electrons, molecules); the quasi-neutrality condition holds; the plasma is optically thin; Hall currents, gravitational effects, and viscous dissipation are considered negligible.

As the plasma is a conducting fluid, its description requires the solution of the fluid conservation and electromagnetic equations; which, according to the assumptions stated above, are given by:
\[ \frac{\partial \rho}{\partial t} + \nabla(\rho \mathbf{V}) = 0, \]  
\[ \rho \left( \frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} \right) = j \times \mathbf{B} - \nabla \left[ P + \frac{2}{3} \mu (\nabla \cdot \mathbf{V}) \right] + 2 \nabla \cdot (\mu \mathbf{S}), \]  
\[ \rho c_p \left( \frac{\partial T}{\partial t} + \mathbf{V} \cdot \nabla T \right) - \frac{dP}{dt} = \nabla \cdot (\lambda \cdot \nabla T) + j \times \mathbf{E} + \frac{5k_b}{2e} \mathbf{j} \cdot \nabla T - Q_{rad}, \]  
\[ \nabla \cdot (\sigma \nabla \varphi) = 0, \quad \mathbf{E} = -\nabla \varphi, \quad j = \sigma E, \quad \nabla \times \mathbf{A} = -\mu_0 j, \quad \mathbf{B} = \nabla \times \mathbf{A}, \]  
where \( \rho \) is the fluid density; \( t \) is time; \( \mathbf{V} \) velocity; \( j \times \mathbf{B} \) represents the Lorentz force, with \( j \) as the current density and \( \mathbf{B} \) as the magnetic field; \( P \) is pressure; \( \mu \) is the dynamic viscosity; \( c_p \) is the gas specific heat at constant pressure; \( T \) is the temperature; \( j \times \mathbf{E} \) is the Joule heating term, with \( \mathbf{E} \) as the electric field; \( \lambda \) is the thermal conductivity; \( \sigma \) is the electrical conductivity; \( \varphi \) is the electric potential; \( \mathbf{A} \) is the magnetic vector potential; \( \mu_0 \) is the permeability of free space; the term proportional to \( \mathbf{j} \cdot \nabla T \) represents the diffusion of electron enthalpy with \( k_b \) as Boltzmann’s constant and \( e \) as the elementary charge; \( Q_{rad} \) is specific radiation power, depending on temperature.

The computational domain consisted of two parts: a plasma channel inside the plasma torch and a plasma jet at the output of the plasma torch. Table 1 shows the boundary conditions used in the simulation, where \( P_{out} \) represents the outlet pressure equal to 760 Torr, \( h_w \) is the convective heat transfer coefficient at the anode wall equal to 3500 \( W/(m^2 \cdot K) \), \( T_0 \) a reference cooling water temperature of 277 K. \( T_2 = 3600K \), \( T_3 = 500K \) are temperature of cathode and anode. The arc current is current \( I = 200 \) A and air mass flow rate \( m = 1.5 \) g/s.

### Table 1. Boundary conditions.

| Boundary conditions | Inlet | Cathode | Anode | Outlet | Interelectrode insert |
|---------------------|-------|---------|-------|--------|-----------------------|
| \( T = T_0 \) | \( \frac{\partial}{\partial s} \int \rho (\mathbf{v} \cdot n) dA = m \), \( j \cdot \mathbf{n} = 0 \), \( \mathbf{A} \times \mathbf{n} = 0 \); | \( T = T_2 \), \( \mathbf{v} = 0 \), \( j \cdot \mathbf{n} = \frac{I}{\pi R_i^2} \), \( \mathbf{A} \times \mathbf{n} = 0 \); | \( T = T_3 \), \( \mathbf{v} = 0 \), \( \varphi = 0 \), \( \mathbf{A} \times \mathbf{n} = 0 \); | \( \nabla T = 0 \), \( P_{out} = P_0 \), \( j \cdot \mathbf{n} = 0 \), \( \mathbf{A} \times \mathbf{n} = 0 \); | \( -\mathbf{n} \cdot \mathbf{A} \nabla T = h(T_0 - T) \), \( \mathbf{v} = 0 \), \( j \cdot \mathbf{n} = 0 \), \( \mathbf{A} \times \mathbf{n} = 0 \). |

### 3. Numerical simulation and results

In Fig. 1 shows the dynamics of the formation of the temperature field both the plasma torch channel and its output. It is seen that the temperature in the near-cathode region reaches 30000K, and in the near-anode region and at the exit of the plasma torch it is 10000-15000 K. The velocity in the near-cathode region reaches 2500 m/s and in the near-anode region and at the exit of the plasma torch it is 1000 m/s. The plasma jet is set in a time equal to 1.3-1.5 ms.

...
4. Conclusions
A DC plasma torch "Thermoplasma 50-01" has been modeled and simulated by developing a 2D axisymmetric model of laminar flow and heat transfer coupled to electromagnetic fields. In order to solve the partial differential equations of electric currents and magnetic fields, both in the gas than in the anode region, we have contemplated appropriate boundary conditions in the modeling work. Lorentz forces and Joule heating effects have been modeled, coupled to the physical model of the plasma torch and finally computed. The dynamics of the formation of the temperature field and the velocity field in the plasma torch channel and at its outlet is presented.

The numerical results of the gas temperature and axial velocity result to be quite satisfactory. We foresee to develop a more complete reproduction of the thermal and fluid phenomena in a future three dimensional model, which might include the modeling of other issues. In particular, in the future work, it is necessary to consider the effect of gas supply for the anode curtain.

Acknowledgments
The reported study was funded by RFBR, according to the research project No. 16-38-60187 mol_a_dk.

References
[1] Pfender E 1999 Plasma Chem. Plasma Proc. 19 1–31
[2] Murphy A B 1996 J. Phys. D: Appl. Phys. 29 1922–1932
[3] Pan Wenxia, Meng Xian, Chen Xi et al 2006 Plasma Chem. Plasma Process. 26 335–345
[4] Robert C and Tucker Jr 2013 ASM Handbook, Volume 5A: Thermal Spray Technology (ASM International) p 412
[5] Ilyushchenko A F, Shevtsov A I, Okovity V A et al 2011 *The formation of thermal coatings and their modeling* (Minsk: Belarus, Nauka) p 357

[6] Zasypkin I V, Zhukov M F 2006 *Thermal Plasma Torches: Design, Characteristics, Application* (Cambridge International Sciences Publishing, Cambridge) p 720

[7] Kuzmin V I, Mikhailchenko A A, Kovalev O B, Kartaev E V and Rudenskaya N A 2012 *J. of Thermal Spray Technology* **21** 159–168

[8] Kuzmin V, Cartan E, Kornienko E et al. 2014 Plasma spraying of powder coatings with gas dynamic focusing of the dispersed phase. Current problems in engineering = Actual problems in machine building: 1 Materials Intern. Scientific And Practical. Conf., Novosibirsk, March 26, 2014 – Novosibirsk: Publishing House of the NSTU 482–488.

[9] Kuzmin V I, Grigoriev S N, Kovalev O B et al 2013 *Friction and Wear* **34** 221–226

[10] Kuzmin V I, Mikhailchenko A A, Kartaev E V et al 2012 *Journal of Thermal Spray Technology* **21** 159–168

[11] Trelles J, Chazelas C, Vardelle A and Heberlein J 2009 *Journal of Thermal Spray Technology* **18** 728–752

[12] Vardelle A, Moreau C, Themelis N and Chazelas C 2015 *Plasma Chem Plasma Process* **35** 491–509.

[13] Colombo V. and Ghedini E 2005 “Time dependent 3-d simulations of a dc non-transferred arc plasma torch: anode attachment and downstream region effects”, in Proc. ISPC, pp. 169-170

[14] Marchand C, Chazelas C, Mariaux G and Vardelle A 2007 *J. Thermal Spray Tech*. **16** 705–712