Three dimensional computational fluid dynamic simulation of a segmented Non-transferred Arc Plasma Torch

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Abstract

Three dimensional computational fluid dynamic (CFD) simulation of a segmented non transferred arc plasma torch is done for the purpose of computing heat load to various torch components and obtaining the temperature and velocity profile at the exit of the torch. The region inside the torch was simulated along with simulation of water flow channels. To obtain the current flow and resulting joule heating, electric potential equation is solved inside the torch region. Simulation runs for several values of arc current and plasma gas flow rate are done and results are compared.

Keywords: *Arc plasma torch, computational fluid dynamic simulation (CFD)*

1. Introduction

DC plasma torches have been used to create high temperature chemically active zone for carrying desired chemical reactions in a controlled manner. In many such cases non transferred plasma arc torch is attached to a reaction chamber. The plasma gas heated by an electric arc comes out of the torch at a high velocity and expands into the reaction chamber creating a wider high temperature zone appropriate for carrying the desired material processes. Computational fluid dynamic (CFD) analysis of such systems is useful for designing the plasma torch as well as the process chambers.

The computational fluid dynamic analysis of inside the torch is important for two reasons. The first reason is the design of the torch itself. High thermal load on torch components significantly affects the life of a plasma torch. In designing a compact plasma torch with longer operational life, computation of heat load on various components is a critical issue for estimating the optimum cooling requirement. The second reason is that the conditions at torch exit serve as the inlet conditions for a reaction chamber that is attached to the torch. Generally a radial profile of temperature and axial velocity is assumed at reaction chamber inlet. However, their variation with gas flow rate and torch power is difficult to estimate correctly. Computations inside the torch can be used to obtain accurate values of the data at the torch exit.

Inside the reaction chamber knowledge of temperature, velocity and species concentration profile of the gas is of most importance. The temperature and species concentration profile determine the rate of chemical reaction and velocity profile is important for estimating the residence time inside the chemically active zone.

For these reasons there have been several efforts to model and compute the fluid dynamics inside and outside the torch. Both two dimensional and three dimensional models have been developed. The two dimensional model [1,2] have assumed the anode arc attachment in the form of a ring. In reality the arc attaches at the anode in form of a constricted spot thus exhibiting three-dimensional behavior both inside the torch and at the nozzle exit. Thus, assumption of ring attachment by two dimensional models is not a valid one for analysis a realistic plasma torch and three dimensional models are required. Li et al [3] have developed a steady model for Ar plasma and determined the arc attachment position. Baudary et al [4] have developed an unsteady model for Ar-H_2 plasma and studied the arc behavior and voltage fluctuation in restrike mode. In a plasma torch the source of energy is high current flowing in plasma arc and because of extremely high temperature in plasma core, radiation heat transfer and the heat transfer by plasma gas convection are the most important mechanisms responsible for heat transfer inside the plasma torch. Apart from that, the flow is highly turbulent because complex geometry and large temperature gradients. Thus, inside the torch, we need to solve governing equations for energy, radiation, turbulent flow and MHD.

In this work we present a detailed computational fluid dynamic and magneto hydrodynamic analysis of three dimensional simulations carried in a non-transferred arc segmented torch.

2. Numerical model

The plasma is assumed in local thermal equilibrium (LTE). Compressible effects of the gas are not considered. As the convective flow is large, buoyancy effects due to gravitation are not important and neglected. The plasma gas is argon and its thermal and electrical properties of argon depend on the local temperature only. Non LTE in vicinity of cathode and anode arising because of difference in mobility of various charged particles is not considered.

Under these assumptions the governing equations for the steady state flow are,

$$\nabla.\rho V = 0 \tag{1}$$

$$\nabla.\rho VV = -\nabla p + \nabla.(\mu_{eff}(\nabla V + \nabla V^{T})) + J\ X\ B \tag{2}$$

$$\nabla.(V(\rho H + p)) = \nabla.(k_{eff}\nabla T) + J.E + S_R \tag{3}$$

Equations (1), (2) and (3) are conservation equations for mass, momentum and energy respectively. Here ρ, V, p, J, B, H and E represent gas density, flow velocity vector, gas pressure, electric current density, magnetic field, energy and electric field respectively. H in the energy equation is defined as

$$H = h - \frac{p}{\rho} + \frac{V^2}{2} \tag{4}$$

μ_{eff} and k_{eff} are viscosity and thermal conductivity respectively and includes both laminar and turbulent components. Standard k-ε model is employed for turbulence. Turbulent viscosity, μ_t and thermal conductivity, k_t are given by

$$k_t = \frac{\mu_t C_p}{\Pr_t} \quad ; \quad \mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{5}$$

Pr_t is turbulent PRANDTL number and C_μ is a constant. k is turbulent kinetic energy and ε is its dissipation rate. k and ε are obtained by following equations.

$$\nabla.\rho kV = \nabla.((\mu + \frac{\mu_t}{\sigma_k}).\nabla k) + G_k + G_b - \rho\varepsilon \tag{6}$$

$$\nabla.\rho\varepsilon V = \nabla.((\mu + \frac{\mu_t}{\sigma_\varepsilon}).\nabla\varepsilon) + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{7}$$

G_k and G_b are kinetic source term for production of turbulent kinetic energy and turbulent production due to natural convection. $C_{1\varepsilon}$, $C_{2\varepsilon}$, σ_k *and* σ_ε are constants with following values : $C_{1\varepsilon}$=.09, $C_{2\varepsilon}$=1.44, σ_k=1.0 σ_ε=1.3

For a medium in which radiation absorption, emission and scattering is present, radiation transport can solved using following equation

$$\frac{dI(\vec{r},\vec{s})}{ds} + (a + \sigma_s)I(\vec{r},\vec{s}) = an^2\frac{\sigma T^4}{\pi} + \frac{\sigma_s T^4}{4\pi}\int_0^{4\pi} I(\vec{r},\vec{s}')\phi(\vec{s},\vec{s}')d\Omega' \tag{8}$$

Here vector r, s and s' are position, direction and scattering direction vector. I, s, a, n, σ_s, σ, φ and Ω' are radiation intensity, path length, absorption coefficient, refractive index, scattering coefficient, Stefan-Boltzman constant, phase function and solid angle respectively.

The momentum conservation equation has a $J\times B$ source term arising due to Lorentz forces. Similar Energy equation term has joule heating term $J.E$ as a source term. To obtain these source term the following electromagnetic equations are solved in the segmented torch domain.

$$\nabla.(\sigma_e \nabla\phi) = 0 \tag{9}$$

$$J = -\sigma_e \nabla.\phi \tag{10}$$

$$\nabla^2 A = -\mu_0 J \tag{11}$$

$$B = \nabla\ X\ A \tag{12}$$

Here σ_e and A are electrical conductivity and vector potential respectively. The thermodynamic and electrical properties such as electrical and thermal conductivity of the gas are taken from [5].

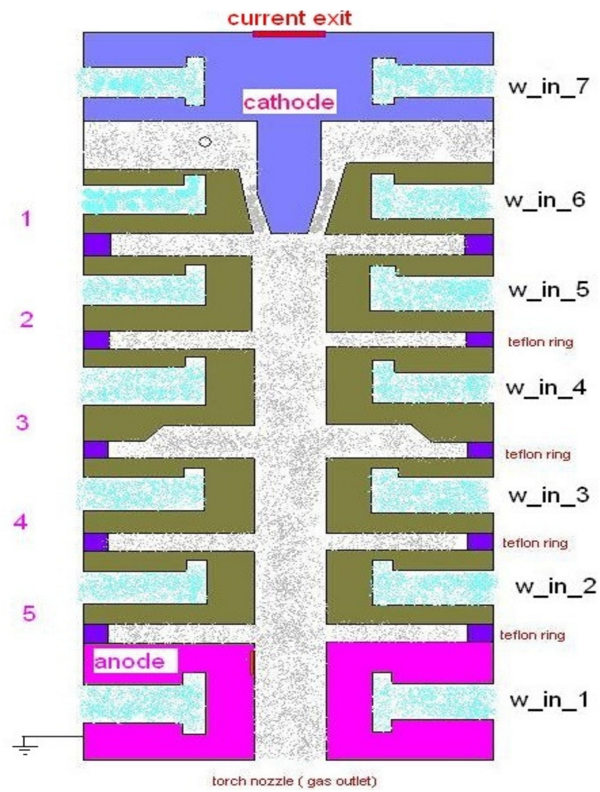

Figure 1 : Schematic of segmented torch interior

3. System description and computational domain

The schematic diagram of complete computational domain is shown in figure 1. The segmented torch is cylindrical in shape. The argon gas enters through gas inlet located near the torch cathode, gets heated inside the torch, exits through torch outlet. Segmented torch consists of a cathode, five floating anodes (numbered 1 to 5) and a grounded anode. All the electrodes are insulated from each other with the help of teflon rings in between them. The cathode is electrically connected to a current controlled power supply at the current exit spot shown in the diagram. The current exit spot is taken 8 mm in diameter. Arc connects at the anode to a fixed 2mm diameter circular spot. The pure argon gas enters into the torch at a specified flow rate through tangential inlet near cathode and as it flows it is heated due to joule energy produced by electric arc. The argon gas exits through the torch nozzle. All the electrodes are water cooled. Water enters through inlets (numbered w_in_1 to w_in_7) and exits thorough outlet located diametrically opposite to respective inlets. All external surfaces are exposed to atmosphere.

4. Experimental and Boundary conditions

The torch and chamber operates at atmospheric pressure. All the external surfaces of segmented torch are assumed to be exposed to atmosphere. All the inner surfaces are treated as coupled boundaries for all solution variables except electrical potential. All electrodes are made of copper. The standard values of electrical and thermal properties of copper, teflon and water are used. These properties are assumed to be temperature independent. The boundary conditions used for segmented torch are listed in table-1.

5. Results and discussions

The simulation run was done for two cases. For case 1 we used 280 Ampere current and 26 liters per minute of argon gas flow rate. For case 2 current is kept the same and argon gas flow rate was reduced two 20 liters per minute.

Figure 2 shows the variation of current density on X-Y plane which symmetrically cut across the circular anode spot. The region near the cathode tip shows the highest current density and also the highest variation in current density. Because of the geometrical affect, the gas velocity is smaller in this region. This results in increase of temperature in this region. This also can be seen in figure 3 which shows the temperature profile in the torch on the X-Y plane.

We can see a zone of higher temperature and temperature variation near cathode region. As electrical conductivity of argon gas follows the trend of temperature variation, current density profiles can be explained. After some distance downstream from the cathode tip, gradients of velocity and temperature die down. As we can see from figure 3, temperature almost remains constant along the axis of the torch. This trend is maintained till very near to anode spot beyond which temperature starts dropping because joule heating stops in this region. Current density follows this trend except near anode spot where there is some rise in current density. This rise is not primarily because of higher electrical conductivity as there is no corresponding rise in temperature. The boundary condition at anode forces the current to flow only to anode spot and in order to conserve the current, current density increases here. As we can see current flows through a well defined arc but radiation and convection causes the temperature diffuses in zones between the electrodes. Due to arc attachment to one side of the torch, temperature rise is also more in that direction. This asymmetry is prominent as we go closer to anode. Table 2 shows the rise in temperature of cooling water for each of the seven cooling channels.

Table-1: Boundary conditions for segmented torch

	Temperature	Velocity	Pressure	Electrical potential
Outer boundaries of floating anodes, Teflon ring and cathode	300	-	-	$\frac{\partial \phi}{\partial n} = 0$
Outer boundary grounded anode	300	-	-	0
Teflon ring-gas interface	Coupled surface	-	-	$\frac{\partial \phi}{\partial n} = 0$
Teflon ring- copper interface	Coupled surface	-	-	Coupled surface
Electrodes-Gas interface	Coupled surface	-	-	$\frac{\partial \phi}{\partial n} = 0$
Gas inlet	300	Mass flow rate	-	$\frac{\partial \phi}{\partial n} = 0$
Gas outlet	-	-	atm	$\frac{\partial \phi}{\partial n} = 0$
Anode spot	Coupled surface	-	-	Coupled surface
Current inlet	300	-	-	Given current density

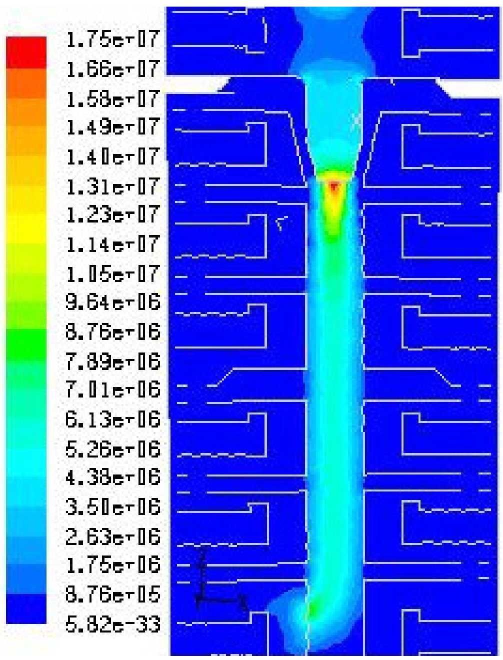

Figure 2 current density J (ampere/m^2) in X-Y plane

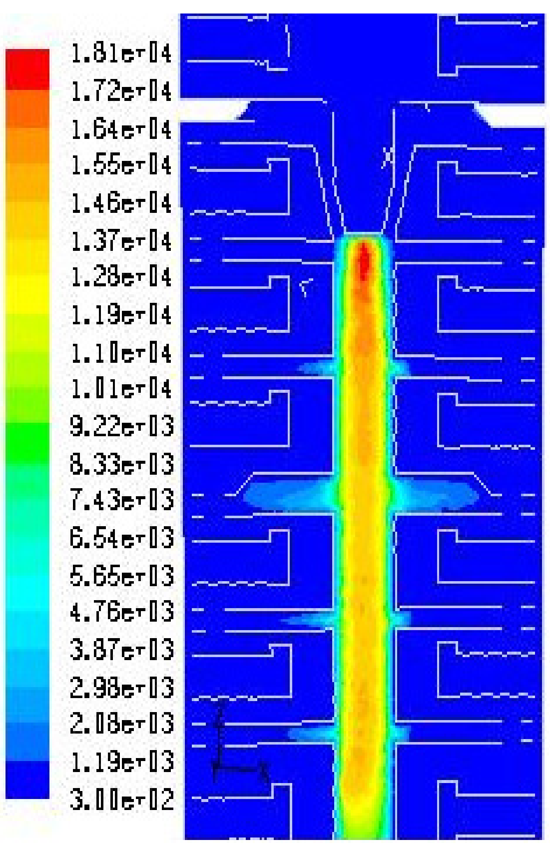

Figure 3 Temperature profile in X-Y plane

Table 2 showing rise in water temperature of the seven water cooling channels

Channel No.	Win -1	Win -2	Win -3	Win -4	Win -5	Win -6	Win -7
Temperature rise(K)	5.8	2.3	2	1.5	.5	.5	.8

As we can see from the table-1, the difference between inlet and outlet water temperature is maximum for the lowest channel which corresponds to the anode. There is a sharp decrease in temperature difference between channel 1 and channel 2. After this the temperature difference decreases slowly and than there is marginal rise for channel 7 which corresponds to cathode. We looked at the relative importance to of radiative and convective heat transfer processes in heat transfer to the torch from the gas. We found that contribution of radiative heat transfer is less than 20% and thus convective heat transfer is the major process. Thus most of the heat is carried along with the gas and causes higher heat transfer to

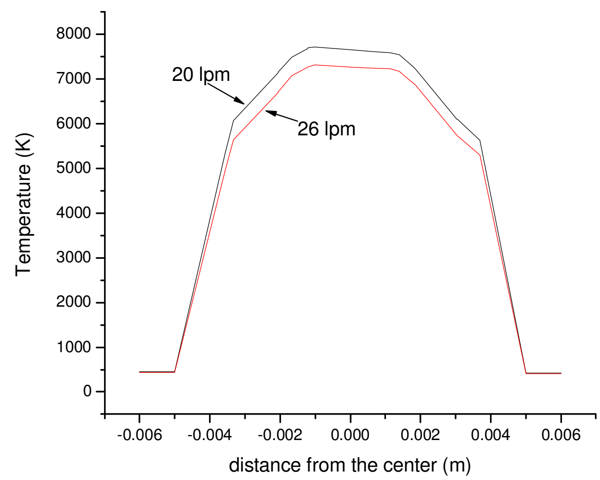

Figure 4 Temperature profile at exit nozzle as a function of distance from the center

lower electrodes. As a large current flows through the cathode and there is a high current density zone near it, there is slight increase in the temperature rise of the cathode water cooling channel. The anode cooling channel shows the maximum rise in temperature of cooling water. On anode not only the part of heat generated in upper region of torch is deposited due gas convection, there is a very high current density zone present in this region. Thus a large amount of heat is deposited to anode causing temperature of its cooling water to be the maximum. Fig. 4 and 5 shows temperature and velocity profiles at the exit nozzle as a function of radial distance from the nozzle center. These are profiles on X-Y plane which symmetrically cut across the circular anode spot. The temperature profiles at the nozzle exit is almost symmetric as compared to velocity profiles, suggesting that temperature diffuses faster. The exit velocity is higher at the

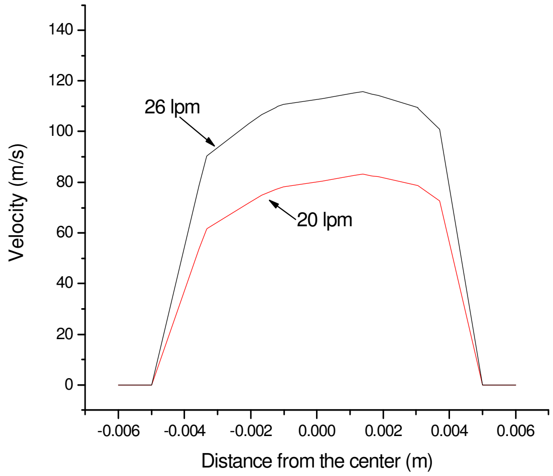

Figure 5 Velocity profile at exit nozzle as a function of distance from the center

opposite side where the anode spot is located. The high temperature zone near the anode spot creates a high pressure zone and pushes the gas away. As the anode spot is slightly upstream of the nozzle, velocity at the opposite end is increased.

6. Conclusion:

A detailed CFD analysis of a water cooled segmented torch system consisting of five floating electrodes apart from a cathode and an anode has been done. MHD, radiation and turbulence processes were included in the model. For 280 ampere current the computed voltage difference between cathode and anode was around 88 volts. The analysis of heat transfer to various electrodes shows that heat is transferred primarily because of gas convection and radiation plays a secondary role. The maximum heat is transferred to the anode which is the lower most electrodes. The asymmetry caused by the location of anode arc spot clearly results in the asymmetry of parameters at the torch nozzle exit. We have shown that three dimensional analysis of the torch is important to obtain accurate data both inside and outside the torch.

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