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Numerical Modeling of an Electric Arc and Computation of Rate of Cooling For Particles in Transferred Arc System

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Abstract: *A model has been designed to analyze the arc-anode interaction and fluid flow in a transferred arc based system. Computational domain consists of an aluminium anode and a transferred arc plasma torch situated in cylindrical chamber, which is cooled by water. This model symmetry about its axis and it is considered as axis symmetric model. CFD commercial code FLUENT is used to model the plasma flow, solid anode and computation of vapour flow in plasma gas. Argon gas is used to form plasma. Different rates of current are used during computations and fluid flow is constant. Rate of cooling for particles for different current is measured. For 125 Amp current & 5 lpm gas flow rate, cooling rate of particle is computed to be 41,340 K/Sec.*
Keywords*: Anode-arc interaction, cooling of particles, electric arc, plasma flow, transferred arc system.*

I. INTRODUCTION

In transferred arc systems, interaction between arc and anode is important because heat transfer from arc to anode governs the rate and profile of vaporization. The nucleation and growth of the particles then depends on how the vapour flows in the plasma gas. Current has important effect on the flow of gases near the anode and their effect on the vapour flow need to be understood. Thus in our study, we have focused on computing and analysing the arc-anode interaction and the flow of plasma gas under the effect of various forces. For our study, we have chosen a system, which is used for producing vapour flow in plasma gas.

The system employs a transferred arc torch and an aluminium block as anode. The torch and anode are located in a cylindrical chamber, which is cooled by water. This configuration provides symmetry about its axis and two dimensional axis symmetric models has been employed.

The aim of this study is two folds, simulation of the arc in the system and understanding the electrical and thermal interaction between the arc and the anode. We have then applied this understanding to analyze the flow of vapour speared from the anode into the plasma gas. We model the following for our study: the plasma column, the anode, the energy transfers between the plasma column and anode taking into account the current-carrying path both in the plasma and anode block. Calculations are carried out using the commercial software FLUENT version 6.3.26, with user defined function added to take in the effects specific to thermal plasmas.

The computations are done for different flow rates of plasma forming gas. Effect of heat and current between plasma and anode is calculated. Effect of temperature and velocity is analyzed. Rate of cooling of particles are also reckoned.

II. ASSUMPTIONS

We have carried out our simulations under the following assumptions:
The arc is axially symmetric, which means that the hydrodynamic equations could be written in two-dimensional cylindrical coordinates (r, z).
The plasma column is assumed to be in LTE.
The plasma is a Newtonian fluid.
The flow is assumed to in steady state.
Properties of the plasma gas depend on the local temperature.
The anode surface is supposed to be spatially and temporally not deformable.
Effect of the evaporation from the anode surface and the presence of metal vapour in the plasma are neglected.
Flow in the molten metal is not modelled and thus we have not modelled the welding pool effects (magnetic pressure, Marangoni effect, arc pressure, etc.).
The effects of gravity are neglected. As explained by Lowke [1] in his paper, the gravity term is negligible when the current is higher than 30 A due to the magnitude of the weight compared with the axial gradient of the pressure.

III. GOVERNING EQUATIONS

In this section, we present the mathematical model for a two dimensional system. System consists of a transferred arc torch, an aluminum anode located at an axis symmetric position in a cylindrical chamber. Location of outlet makes the overall process non axis symmetric but in a large chamber, effect of this non symmetry on the near arc processes is neglected. Thus, system is modeled as a two dimensional axis symmetric. As the plasma can be approximated to a fluid, the Navier-Stokes equations are used to describe the plasma column. Apart from the Navier-Stokes equations, which solves current conservation equation, has been added.
The conservation equations for various quantities such as energy, mass, momentum, current, turbulent kinetic energy and its dissipation rate etc. can be written in the generalized form suggested by Patankar [2]:

$$\vec{\nabla}.(\rho\vec{v}\phi) = \vec{\nabla}.(\Gamma_\phi\vec{\nabla}\phi) + S_\phi \tag{1}$$

where, Φ represents the scalar quantity for which the conservation equation is to be solved, ρ is the fluid mass density, *v*the velocity vector, Γ_φ the diffusion coefficient for the scalar, $S_\Phi$the source term.

Table 1 Conservation equations in the generalized form of Patankar

Conservation Equations	**Φ**	□$_{\Phi}$	**S_Φ**	
Mass	1	0	0	(2)
Axial momentum	u	μ	$-\frac{\partial P}{\partial z} + 2\frac{\partial}{\partial z}\left(\mu\frac{\partial u}{\partial z}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left[\mu r\left(\frac{\partial u}{\partial r} + \frac{\partial v}{\partial z}\right)\right] - \frac{2}{3}\frac{\partial}{\partial z}\left[\mu\left(\frac{\partial u}{\partial z} + \frac{1}{r}\frac{\partial}{\partial r}(rv)\right)\right] + j_r . B_\theta$	(3)
Radial momentum	V	μ	$-\frac{\partial P}{\partial r} + \frac{2}{r}\frac{\partial}{\partial r}\left(\mu r\frac{\partial u}{\partial r}\right) + \frac{\partial}{\partial z}\left[\mu\left(\frac{\partial v}{\partial z} + \frac{\partial u}{\partial r}\right)\right] - \frac{2}{3}\frac{1}{r}\frac{\partial}{\partial r}\left[\mu r\left(\frac{\partial u}{\partial z} + \frac{1}{r}\frac{\partial}{\partial r}(rv)\right)\right] - \mu\frac{2v}{r^2} - j_z . B_\theta$	□
Energy	T	κ	$\frac{j_r^2 + j_z^2}{\sigma} - U + \frac{5}{2}\frac{K_B}{e}\left(j_z\frac{\partial T}{\partial z} + j_r\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left[\left(\rho D - {}^{\kappa}/_{C_p}\right)h_i\frac{\partial X_i}{\partial z}\right] + \frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\rho D - \frac{\kappa}{C_p}\right)h_i\frac{\partial X_i}{\partial r}\right]$	□
Current	V	σ	0	□
Mass fraction	X_i	ρD	0	□

The various quantities for which the conservation equations are solved for a two dimensional axis symmetric system are presented in Table 1. Φ is replaced by T, the temperature, *u*, *v*, and the axial & radial components ofthe velocity or V, the electric potential V while solving for energy, momentum and current conservation equations respectively. It assumes the value of 1 when we solve for the mass conservation equation. $\Gamma_{\Phi,}$ the diffusion coefficient and S, the source term for each conservation equation is also given in the Table 1. In equations (2) - (7), μ, κ, C_P and σ are, respectively, the viscosity, the thermal conductivity, the specific heat and the electrical conductivity of the gas.The thermodynamic and transport properties depend on the local temperature.

P represents the pressure. The source term, S, in the energy equation represents Joule's effect, the radiation losses (U) and the electronic enthalpic flux. The losses by radiation can be written as $4\pi\varepsilon_N$, where ε_N is the net emission coefficient taken, in our case, for a 3 mm radius. $j_z$and $j_r$are the axial and radial current density components, and $B_\theta$is the azimuthal magnetic induction. Argon is used as the plasma gas for all our study. For argon, the transportcoefficients come from data generated by Thiagrajan using the computer code developed by Murphy. The emission coefficients for argon were taken from [3].
Current density $j_z$and j_r are obtained by solving the electric potential distribution equations (8) and (9).

$$j_z = -\sigma\frac{\partial V}{\partial z} \tag{8}$$

$$j_r = -\sigma\frac{\partial V}{\partial r} \tag{9}$$

The magnetic field in the theta direction is calculated using vector potential approach [5]. Here $A_r$and A_z are the radial and axial component of vector potential.

$$B_\theta = \frac{\mu_0}{r}\int_0^R j_z(r)\, rdr \tag{10}$$

System description, Computational domain and Boundary conditions

To analyze the fluid flow behavior in a transferred arc we have chosen a geometry, which has been used for producing metal vapour flow in the system. Schematics of cross section of the chamber are shown in the Figure 1. The chamber is of 450 mm height and 225 mm radius. Though in the actual system [4, 5] the gas outlet of the chamber makes it non axis symmetric but as the outlet is located far from the axis, its effect on the near axis processes is assumed to be negligible and the system is modeled as two dimensional axis-symmetric. The important dimensions of the system are given in Table2.
The boundary conditions are listed in Table 4. Due to axis symmetry only one half of system shown in Figure 1 is used as computational domain.

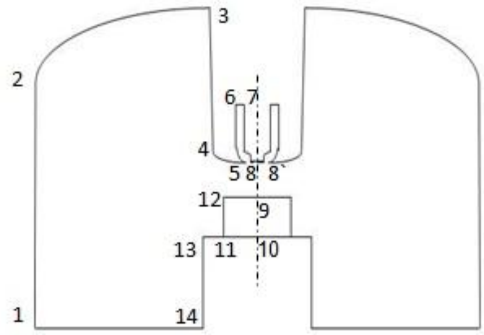

Fig. 1 Schematic of system

Table2 System Dimensions

Boundary	Dimension (mm)	Description	Boundary	Dimension (mm)	Description
1 – 2	320	Chamber wall	**13 – 11**	20	Insulating wall
1 – 14	175	Chamber wall	**11 – 10**	30	Anode base wall
8-8`	4	Cathode tip	**11 – 12**	30	Anode side wall
3-3`	20	Outlet	**8 – 9**	52	Symmetry axis
6 – 7	4.5	Inlet	**5 - 8`**	1	Tourch nozzle
13 – 14	70	Chamber wall			

All the external boundaries except the anode base are taken as water cooled boundaries. The water cooled boundaries are defined as convection heat transfer boundaries with the value of heat transfer coefficient h is taken to be 4000 w/m^{2}K. The anode base is taken as fixed temperature boundary.

Table3 Boundary conditions

Boundary	u	V	T	V	Boundary	u	V	T	V
3’- 4 - 5 – 6	u = 0	v = 0	h = 4000	$\frac{\partial V}{\partial r}$	**10 – 11**	u = 0	v = 0	T=500	V=0
6 – 7	Mass flow rate	Mass flow rate	h = 4000	$\frac{\partial V}{\partial r}$	**9 – 12**	u = 0	v = 0	Eq.(15)	Eq.(16)
7 - 8’	u = 0	v = 0	h = 4000	$\frac{\partial V}{\partial r}$	**11 – 13**	u = 0	v = 0	h = 4000	$\frac{\partial V}{\partial r}$
8’ – 8	u = 0	v = 0	h = 4000	Eq.(18)	**13 – 14**	u = 0	v = 0	h = 4000	$\frac{\partial V}{\partial r}$
8 – 10	$\frac{\partial u}{\partial r}$	v = 0	$\frac{\partial T}{\partial r}$ =0	$\frac{\partial V}{\partial r}$ =0	**3 - 3’**	Pressure outlet	Pressure outlet	h = 4000	$\frac{\partial V}{\partial r}$

Current density profile at the cathode tip is taken to be linear as suggested by [5] and given by the equation (11). $r_{spot}$is the radius of the arc spot at cathode, I is the total arc current and r is the distance from the axis.

$$j(r) = \frac{3I}{\Pi r_{Spot}^2}\left(1 - \frac{r}{r_{Spot}}\right) \quad (11)$$

The computation domain was meshed using quadrilateral elments. The mesh consist of 5345 cells and 5594 nodes. Total arc flow was 5 lpm and the rate of current was varied from 125 A to 200 A.

IV. RESULTS

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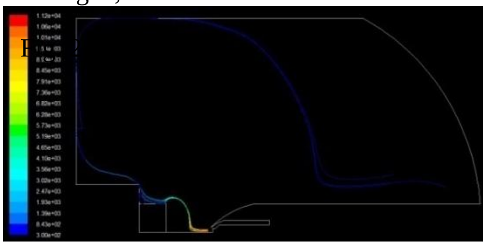
Simulations have been done by varying current between 100 Amp to 200 Amp and the flow rate of plasma gas is constant 5lpm. These values are chosen keeping in mind the range of values generally used in systems described in previous section. We have presented cooling rates of different particles. Implications of these data to the evaporation and subsequent vapor flow are then discussed.

Pathlines are used to visualize the flow of mass less particles in the problem domain. The particles are released from one or more surfaces that we have created with the tools in the Surface menu. A line or rake surface is most commonly used.

The Transform Surface panel allows us to create a new data surface by rotating and/or translating an existing surface, and/or by specifying a constant normal distance from it. Transform Surface contains a list of existing surfaces from which you can select the surface to be transformed. The selected surface will remain unchanged; the transformation will create a new surface.



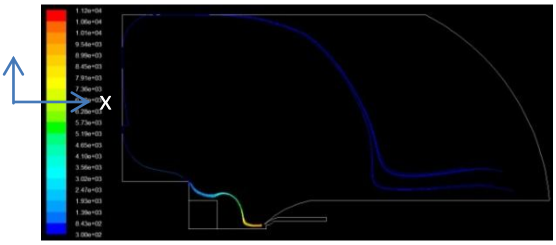


Fig. 2 Temperature Pathlines of transform 37&Fig. 3 Temperature Pathlines of transform 35

Here, first we separated cathode in to 8 different cathode segments. After that we transformed those cathodes to 5 mm in negative x-direction. Transformed 37 are transformed of cathode 0 and cathode 1. Similarly, transformed 38, 39 and 40 are transformed of cathode 2 & 3, transformed of 4 & 5 and transformed of cathode of 6 & 7.

For 125 A & 5 lpm case, Temperature vs. Time graph for particle 1 of Transform 37, which is most outer particle of the all particles, is shown in Figure2 and similarly, Temperature vs. Time graph for particle 4 of Transform 35, which is last particle to go out of inside stream, is shown in Figure3.

Transform 35 has 8 particles and all 8 particles are travel inside the chamber as shown in Figure 3.Cooling rate for Transform 37 Particle 1 (most outer particle) = 32.71e03 K/Sec.Cooling rate for Transform 35 Particle 4 (first outer particle) = 49.97e03 K/Sec.

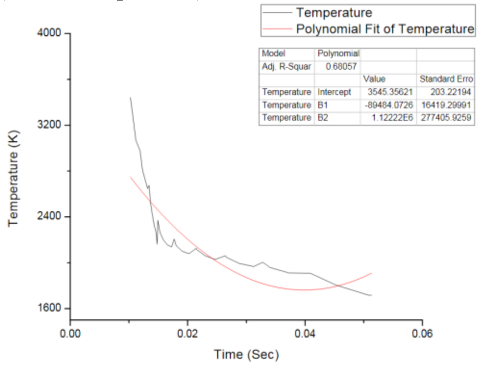


Fig. 4 Temperature vs. Time graph of particle 1 of transform 37

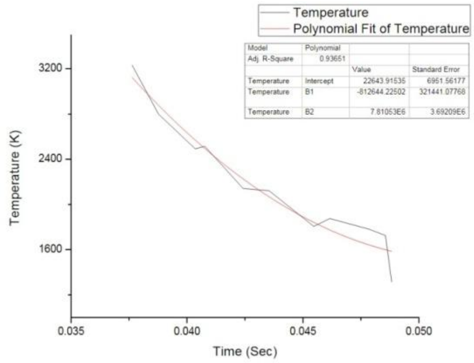


Fig. 5Temperature vs. Time graph of particle 4 of transform 35

Table4 shows the cooling rates of particles for different cases. Here, we can observe that when the gas flow rate is increased, average cooling rate of particle is increased. Similarly, when the current is increased, average cooling rate of particle is also increased.

Table4 Cooling rates for the particles for different cases

Sr. No	Case	Data for Particle	Cooling Rate (K/sec)	Avg. CoolingRate
1	125 A 5 lpm	Transform 37 Particle 1	32.71e03	41.34e03 K/Sec
		Transform 35 Particle 4	49.97e03	
2	150 A 5 lpm	Transform 37 Particle 1	22.55e03	54.76e03 K/Sec
		Transform 35 Particle 2	86.37e03	
3	175 A 5 lpm	Transform 37 Particle 1	17.78e03	67.66e03 K/Sec

		Transform 35 Particle 2	117.55e03	
4	200 A 5 lpm	Transform 37 Particle 1	12.03e03	87.45e03 K/Sec
		Transform 35 Particle 2	162.88e03	

Equation (12) is used to find the cooling rate of the particle. Differentiate equation (12) with respect to time, so that we can find the slope for the curve and this is the rate of cooling for that particle. We can find the values of B_1 and B_2 from Table5 for respective particle. T = temperature and t = time.

$T = B_1*t + B_2*t^2 + C$

Cooling rate of particle $dT/dt = B_1 + 2*B_2*t$

Table 5Various details to find cooling rates of particles for different cases

Sr. No	Case	Data for Particle	B_1	B_2	C	Time at 2000 K
1	125 A 5 lpm	Transform 35 Particle 4	-8.1e05	7.8e06	2.3e04	0.02366
		Transform 37 Particle 1	-8.9e04	1.1e06	3.5e03	0.02602
2	150 A 5 lpm	Transform 35 Particle 2	4.1e05	-1.6e07	9.6e02	0.01622
		Transform 37 Particle 1	-7.5e04	9.3e05	3.4e03	0.0339
3	175 A 5 lpm	Transform 37 Particle 1	-1.6e05	6.9e05	3.3e03	0.03762
		Transform 35 Particle 2	-3.5e05	7.0e06	5.9e03	0.01676
4	200 A 5 lpm	Transform 35 Particle 2	-1.9e05	9.2e05	4.8e03	0.01610
		Transform 37 Particle 1	-5.9e04	6.6e05	3.2e03	0.03826

V. CONCLUSION

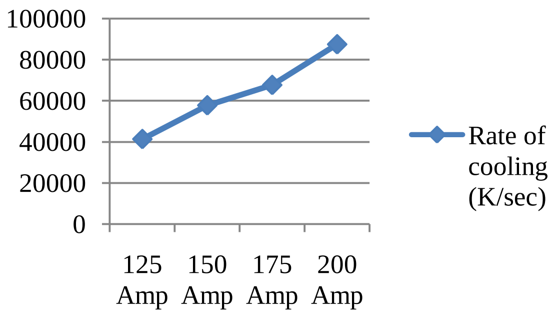


Fig. 6 Rate of change of cooling rate for different particles

Rate of cooling of vapour is computed 41,340 K/Sec for 125 A current and 5lpm gas flow rate and it is increasing with the increase rate of current.

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