ELECTRODE EROSION IN SUBMERGED ARC FURNACES

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ABSTRACT

The role of the electric arc in the consumption of electrodes in submerged arc furnaces has long been debated. The hostile environment in the furnace does not make direct measurement feasible, so simulation has been used to evaluate the arcs contribution to the erosion. Magnetofluiddynamic (MFD) electric arc simulations and a cathode / anode sub-model developed in order to provide boundary condition to the arc model have been used for this purpose. The cathode / anode sub-model provides current distributions and cathode / anode fall voltages for the arc and temperature distribution for the electrode surface, which is paramount to the erosion rate which in turn is calculated from the Clausius Clapeyron equation and the Hertz Knudsen formula for the vapour transport. In the case of high-current industrial AC arcs, arc currents are typically ~100 kA, phase voltages ~100 V and total furnace power ~10 – 60 MW. The results show that although enormous amounts of material is evaporated, much of it recondenses on the surface. Furthermore the results show that the arc erosion increases strongly with the arc current. If a single arc is present its contribution to erosion is close to the actual total erosion in the furnace. Results from this analysis indicate that there are possibly more than one arc present in the crater, in which case less than 40% of the total erosion would be due to the arc, the rest is chemical erosion.

1. INTRODUCTION

Submerged-Arc Furnaces for industrial production of ferroalloys are not a friendly environment for observations and direct measurements. The industry reports a certain amount of electrode consumption, due to both arc erosion and chemical corrosion. The significance of each factor has however not been known, and is difficult to observe on the furnace. Chemical corrosion is dependent on the operation, and high electrode consumption is obviously related to visible flow of SiO gas along the electrode shaft. The arc erosion is probably more constant but is difficult to evaluate experimentally for high current industrial arcs. Simulation models for industrial AC arcs have been developed and published previously by the authors [6]. It is clear that the arc behaviour at the electrode is all important when estimating the role of arc erosion in the total electrode consumption. The arc behaviour is very sensitive to the boundary conditions at cathode and anode, and therefore considerable work has been put into the development of cathode sub-models specifically suited for high-current AC arcs, but different approximations are valid there than for low-current arcs. The main part of the work presented in this paper was published in Steel Research International in June 2006 [12]. The results are based on a model treats anode and cathode in essentially the same way, as the enormous energy impact from the arc ensures that both surfaces emit and receive an abundance of electrons. It does not require the energy balance in the ionization layer to be fulfilled as there is an abundance of energy from the electric arc that enters this layer. The cathode fall voltage is assumed constant over the cathode surface and determined by the requirement that the total current from the electrode should be equal to the imposed arc current. The energy impact from the arc in the form of radiation and particle flux is taken as a boundary condition for the Fourier equation for heat conduction which is solved for the electrode body. The arc itself is simulated by a complete magneto fluid dynamic model which solves the Navier stokes equations for transfer of momentum and energy, as well

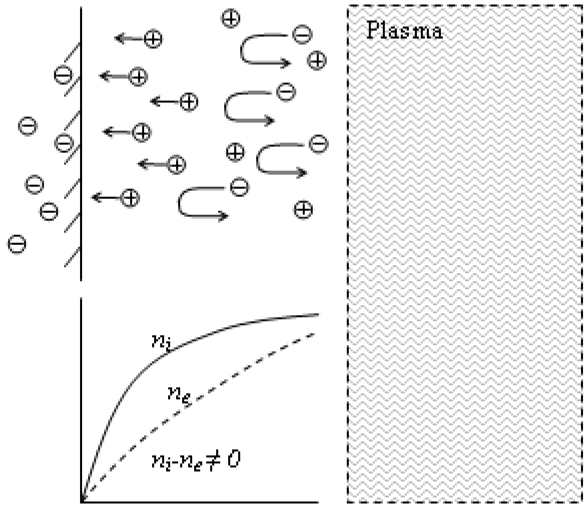

Figure 1: Schematic drawing of a space charge sheath

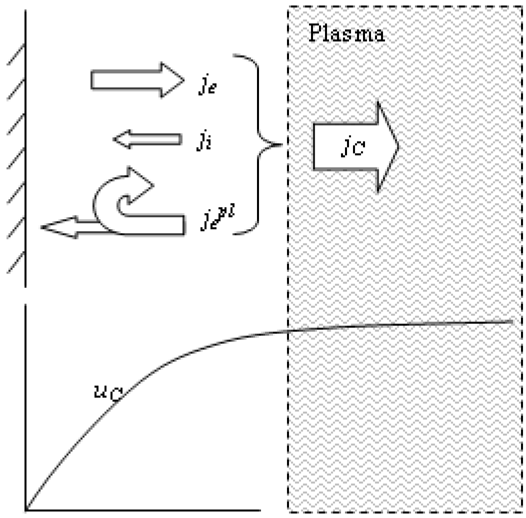

Figure 2: Current components in the cathode model

as an equation for the magnetic field. This MFD model provides the temperature at the electrode surface which determines the equilibrium pressure of carbon that sublimates from the surface. The sublimated carbon is then either transported away, or condenses on other parts of the electrode surface. Results from this model predict an arc attachment of a larger diameter than the arc itself, in addition to a negative anode fall voltage. It also implies that electrode erosion is highly dependent on the arc current, the number of arcs burning in parallel and the geometry of the surface. An electrode model that solves for the current distribution within the electrode and studies the resulting mechanical tensions in the electrode was developed in parallel to this work and is published by Palsson et al. in a different paper at this conference [10]. There an upper limit to the time an arc may burn at a certain location, depending on the current it carries, is established.

2. GENERAL CATHODE SPOT THEORY

If there initially is a wide body of plasma at local thermodynamic equilibrium (LTE) and suddenly a part of it is surrounded by an isolating wall, the wall will initially be bombarded and charged up by fast moving plasma electrons. The negatively charged wall will then repel approaching plasma electrons and attract ions, thus forming a *space charge sheath* that shields the plasma gas from the effect of the negatively charged wall. Approaching plasma electrons will not notice the wall before they enter the space charge sheath, but as they penetrate the ion layer the shielding effect is reduced and they are slowed down by the electric field. For an isolating wall the potential drop in the sheath is exactly high enough to ensure zero total current. When a net current is applied upon a plasma contained between two walls, it is natural to assume that the potential fall is adjusted such that the there is a net charge exchange between the plasma and the wall consistent with the applied current. The thickness of this space charge sheath is approximately $25\lambda_D$ which is close to 1 μm and orders of magnitude smaller than the thermal boundary layer, which in the case of an industrial arc is close to 500 μm as derived in [1].

The AC cathode/anode sub-model (CASM) to be described is based on the following assumptions: The cathode current density j is composed of three components: Thermionically emitted electrons j_e, ions from the plasma that reach the cathode surface j_i, and finally plasma electrons that pass through the potential barrier and reach the surface j_{epl} The models are to a certain extent based on ideas appearing in Neumann's theory [2] and Benilov's model [3][5] for low-current DC arc cathodes.

When a body is sufficiently hot, a fraction of its electrons have kinetic energy high enough for them to overcome the energy barrier called the work function ϕ which traps them in the body. The thermionic emission current density is given by Richardson-Dushman's equation:

$$j_e(T_C) = 1.2 \cdot 10^6 T_C{}^2 f \exp\left(\frac{e(\varphi + \Delta\varphi)}{k_B T_C}\right) \tag{1}$$

where T_C denotes the cathode surface temperature, e is the electronic charge, ϕ the thermionic work function, k_B is Boltzmann's constant and $\Delta\phi$ is the Shottky correction. The factor f in the Richardson Dushman equation is a scaling factor accounting for the fact that a thermionically emitted current with the theoretic value of $f = 1$ has never been observed. According to Pfender et al.'s [4] estimate, $f = 0.5$, which is used in this work. The hot plasma gas contributes with electrons that diffuse over the cathode fall potential u_C and enter the cathode. *The counter-diffusing plasma electron current* is given by:

$$j_{epl} = \frac{1}{4} e n_{e0} c_e e^{-eu_c / k_B T_c}$$
$$c_e = \sqrt{\frac{8 k_B T_e}{m_e \pi}} \tag{3}$$

where n_{e0} is the electron density at the edge of the space charge sheath, and c_e is the mean electron velocity in each direction. Benilov et al. [5] reported a solution for the plasma sheath equation that leads to the following expression for the current density of plasma ions towards the surface:

$$j_i = n_{i\infty} \frac{0.8}{2+\alpha} \sqrt{\frac{k_B (T_C + T_e)}{M_i}}$$
$$\alpha = \sqrt{\frac{k_B T_h}{m_i D_{ia\infty} k_r n_{i\infty}^2}} \tag{4}$$

where $D_{ia\infty}$ is the ion-atom diffusion coefficient k_r is the ion-electron recombination rate coefficient and T_h the heavy particle temperature, all evaluated at the edge of the ionization layer. In conventional cathode models it is assumed that the energy balance for the ionization of atoms by emitted electrons is fulfilled in the ionization layer all over the cathode spot. This is the limit of the self-sustained cathode spot which does not receive energy from the arc. That approximation is valid for low-current arcs. From that energy balance shown in Equation 5, the radially dependent cathode fall voltage $u_C(r)$ can be determined:

$$j_e\left(u_C + 2\frac{k_B T_C}{e} - 3.2\frac{k_B T_e}{e}\right) = j_i\left(U_i + 2\frac{k_B T_i}{e} + 3.2\frac{k_B T_e}{e} - 2\frac{k_B T_C}{e}\right)$$
$$+ j_{epl}\left(u_C + 2\frac{k_B T_e}{e} - 3.2\frac{k_B T_e}{e}\right) \tag{5}$$

Here j_e and j_i represent the electron and ion current densities in the near cathode layer and U_i is the ionization potential. The thermionically emitted electrons are accelerated over the space charge sheath potential fall u_C. The thermionic electrons are emitted with their two-dimensional enthalpy in equilibrium with the cathode body, but need to be heated up to the plasma temperature to be in thermodynamic equilibrium. The energy supplied by the thermionic electrons is used to ionize atoms, and bring the electrons excited from the atoms to equilibrium with the arc plasma. The counter-diffusing electrons must overcome the space charge potential, and carry a two-dimensional enthalpy to the cathode.

The cathode spot of a high current arc is however dominated by the arc so the limit of a self sustained cathode spot unaffected by the energy flux from the arc expressed in Equation 5 is not valid. *The diffuse spot cathode/anode sub-model (CASM)* described and used in this work is based on the observation that in a relatively short high-current industrial arc, the energy supply from the arc is so overwhelming that it is not possible to divide the cathode and the arc into two separate energy domains that do not exchange energy. It cannot be required that thermionic electrons accelerated through the cathode fall supply all energy required to sustain the arc spot as the radiation from the arc and the abundance of much more energetic plasma electrons strongly contributes to the ionization of neutral atoms and equilibration of colder electrons. This means that instead of *two separate energy balances*, Equation 5 on the one side, and the *MFD* transport equations for the arc on the other, an energy balance for the whole system must be solved *within the MFD model.* In the *CASM* only the energy balance for the electrode itself is be considered. The heat flux into the cathode / anode body must be tapped from the arc by a boundary condition for the arc model. In this new model cathode and anode are considered to be formally identical, and the total current balance

$$I(t) = 2\pi \int_0^{r_{\max}} j_e(r,t) r dr + 2\pi \int_0^{r_{\max}} j_{isat}(r,t) r dr - 2\pi \int_0^{r_{\max}} j_{epl}(r,t) r dr \tag{6}$$

is fulfilled at any time for both cathode and anode. This means that the cathode as well as the anode thermionically emit electrons consistently with their temperatures, and that they are both bombarded with plasma electrons and ions dependent on the temperature of the plasma next to the electrode. The difference between cathode and anode is only that the net current is negative in the cathode half-period and positive in the anodic half-period. The cathode/anode fall voltage, here termed u_C for consistency, is determined by solving Equation 6 for the given current at each timestep. This means that the potential fall is adjusted such that the there is a net charge exchange between the plasma and the wall consistent with the applied current. Radiation fluxes and plasma temperatures are obtained from arc simulations. An iterative procedure is used to couple the MFD arc model and cathode/anode model. In the simulations it is assumed that the cathode/anode body is a good current conductor as compared to plasma. It is also assumed in this model that u_C is constant over the surface.

An extension to AC is accomplished by imposing a periodically varying arc current. The non-steady two-dimensional axi-symmetric Fourier equation is solved for the electrode body using the heat flux in Equation 7 as a boundary condition, to obtain a periodically varying cathode surface temperature $T_c(r,t)$. The computational domain is assumed large compared to the cathode spot radius (0.1 m) in the radial direction and to the thermal penetration depth of 50 Hz temperature oscillations (1 mm) in the axial direction. As a boundary condition we need an expression for the heat flux:

$$\dot{q}_c = j_i\left(u_c + 2\frac{k_B T_i}{e} - 2\frac{k_B T_C}{e} + U_i - \phi\right) - j_e\left(2\frac{k_B T_C}{e} + \phi\right) + j_{epl}\left(2\frac{k_B T_e}{e} + \phi\right) + \dot{q}_{sub} + \dot{s}_{rad} \tag{7}$$

Radiation from the arc is taken into account, and sublimation is calculated according to the Clausius-Clapeyron equation for the equilibrium vapour pressure of carbon as a function of temperature given in Equation 8, and the Hertz-Knudsen equation for the maximum evaporation rate from the surface in Equation 9 which provides the mass flux in kg/m^2s.

$$p_{eq} = C_1 e^{-\frac{H_{vap}}{RT}} \tag{8}$$

$$G_0 = \sqrt{\frac{m}{2\pi k_B T}} \left(p_{eq} - p^*\right) \tag{9}$$

For carbon H_{vap} = 716.68 kJ/mol, and $C_1 = 2.29*10^9$ bar provides the equilibrium pressure in bars. The complication in using the Hertz-Knudsen is determining p^*. If the surface temperature is below the sublimation point defined by the ambient total pressure p_a, the value of p^* will be somewhere between p_{eq} and the partial pressure p_0 of the cathode material (carbon) in the bulk. Where in that interval the value lies, depends on the dominating mass transfer resistance in the system. An equilibrium will be established between the sublimation rate and the removal of sublimated atoms. In the case of *diffusion control*, the mass transfer will be slow, and p^* will assume a value close to p_{eq}. If *evaporation kinetics*, expressed by (9), is the rate controlling mechanism, the value of p^* be closer to p_0.

The second case is when the surface temperature rises above the sublimation temperature at p_a. Then p^* will assume a value close to p_a. A jet of carbon vapor away from the surface is formed, and the mass transfer is limited by the fluidmechanic resistance to that jet flow expressed by the pressure drop $p^* - p_a$. In this work the transport equations for carbon in the electric arc region have not been solved, and therefore some simplifying assumptions were made. Primarily Equation 9 was written in the following form:

$$G_0 = C_2 \sqrt{\frac{m}{2\pi k_B T}} \left(p_{eq} - p^*\right) \tag{9*}$$

where the factor C_2 in the Hertz-Knudsen equation is between 0 and 1. C_2 is a measure of the mass transfer resistance from the surface. Alternatively, this resistance could be expressed by a mass transfer coefficient which will depend on the local flow velocity. The value of p^* was taken as the ambient pressure p_a (1 bar) in the areas where the surface temperature exceeds the sublimation point, and also in areas where the gas flow comes directly from that area. For that purpose the gas flow obtained by arc simulations was analyzed in order to determine in what area the gas at the surface is brought directly from the hottest part of the cathode spot. It is assumed that where a sublimation jet is present (surface temperature above the sublimation temperature), $C_2 = 1$. In the area of over-saturated gas, $C_2 = 0.1$, and elsewhere $p^* = 0$, as there the gas temperature is below the plasma temperature and all vapor atoms have reacted and formed molecules. The choice of the factor C_2 = 0.1 is derived from an estimated average value of the mass transfer coefficient. A sensitivity analysis in the following section shows that the results are not overly sensitive to the choice of this value, the variation in erosion of 30%, as shown in Figure 4 for a 51kA arc, is not more than may be expected from other error factors. the order of magnitude stands unaltered and the validity of qualitative results is not compromised.

The electromagnetic equations are not solved for the electrode body and therefore Ohmic heating in the electrode is disregarded in this model. Results shown in [10] demonstrate that it is not at all insignificant. In fact, Ohmic heating limits the amount of time the arc can burn at each location to seconds, dependent of the current magnitude. For the cathode spot behavior while the arc is at a certain location, the Ohmic heating within the electrode is however insignificant.

The abundance of energy provided by the electric arc is such that the energy balance in Equation 5 is not fulfilled, separated from the arc. But as the heat flux by particle impact in Equation 7 includes heat transport due to ambipolar diffusion and heat flux due to the current, the boundary condition for heat transport in the plasma must be included as a source (or sink) term in the MFD arc model. This source term, which is included in the cells next to the cathode/anode surface, has the form:

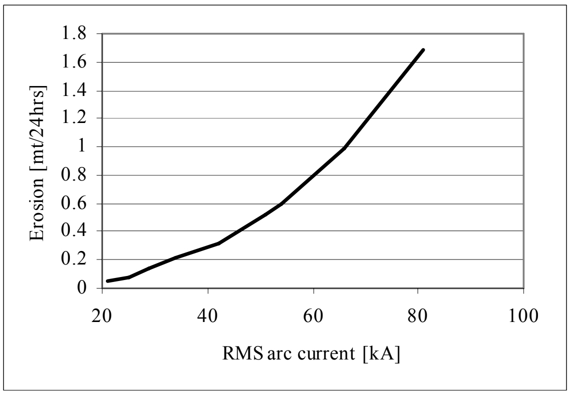

Figure 3: Electrode erosion in metric tons pr. 24 hours as a function RMS arc current

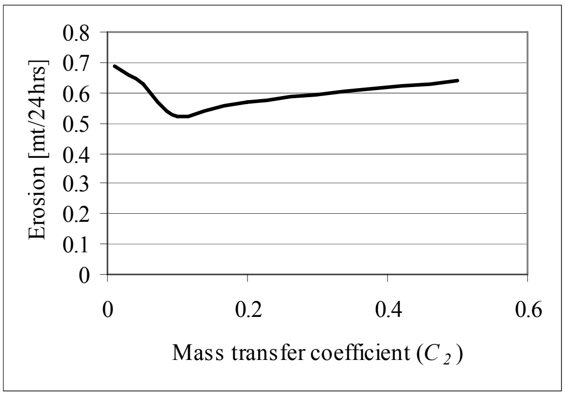

Figure 4: Electrode erosion for different selections of the mass transfer rate coefficient C_2. The results are obtained for a 51kA arc

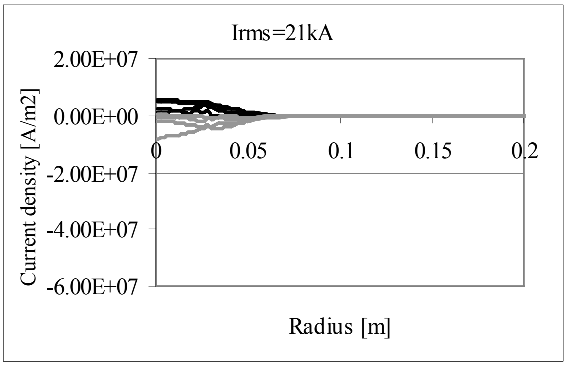

Figure 5: Current density as a function of distance from the symmetry axis for an arc carrying a RMS current of 21kA . Black lines for the anodic half-period and grey for the cathodic half-period

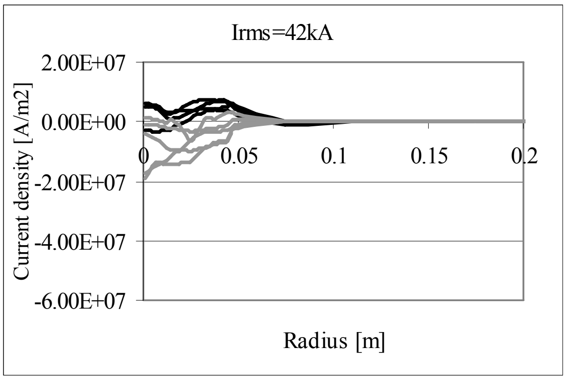

Figure 6: Current density as a function of distance from the symmetry axis for an arc carrying a RMS current of 42kA . Black lines for the anodic half-period and grey for the cathodic half-period

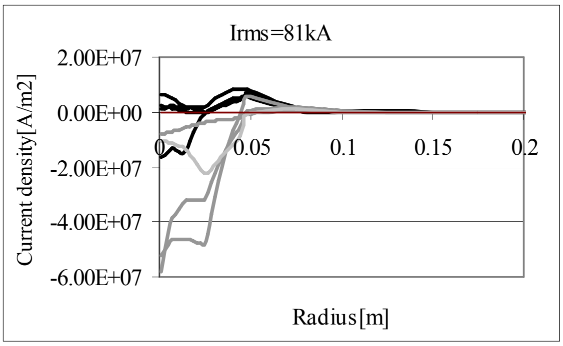

Figure 7: Current density as a function of distance from the symmetry axis for an arc carrying a RMS current of 81kA. Black lines for the anodic half-period and grey for the cathodic half period

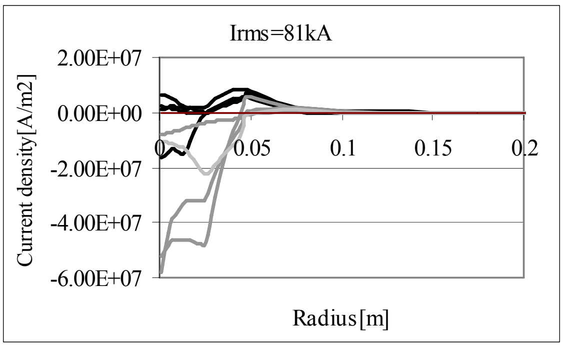

Figure 8: Current / voltage characteristics for AC arcs as calculated by an MFD arc model, previously published in [7]

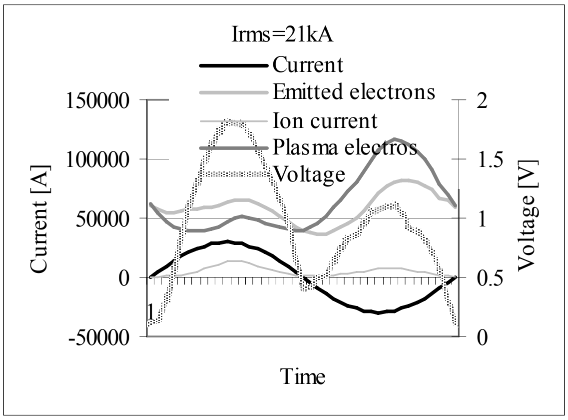

Figure 9: Current, current components and voltage development over a period for a 21kA arc

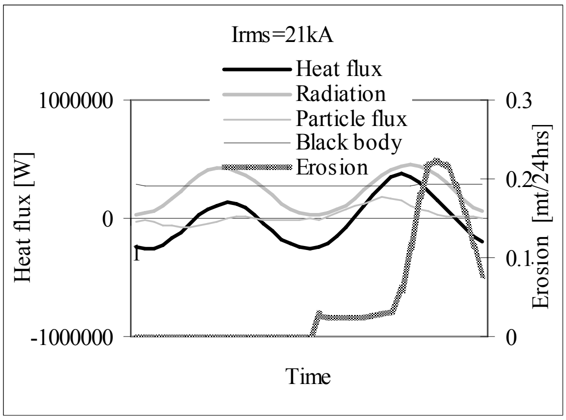

Figure 10: Heat flux from different sources and erosion over a period for a 21kA arc

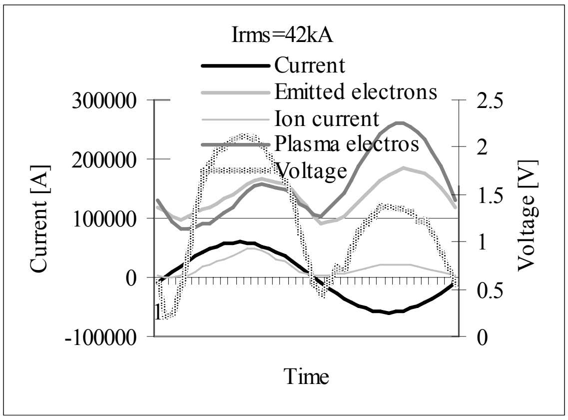

Figure 11: Current, current components and voltage development over a period for a 42kA arc

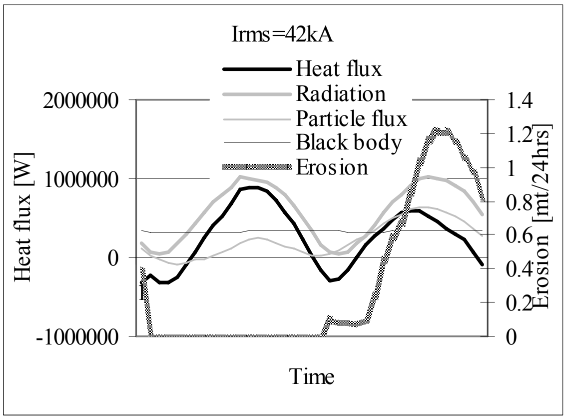

Figure 12: Heat flux from different sources and erosion over a period for a 42kA arc

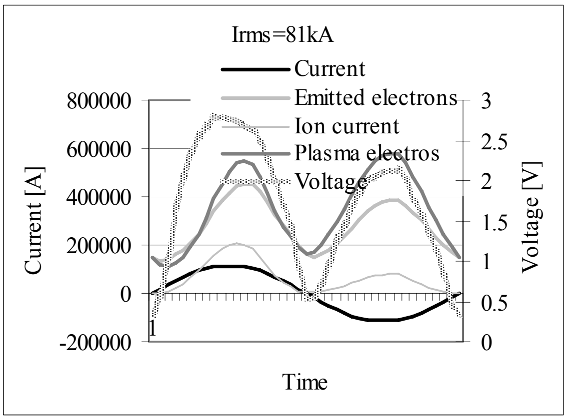

Figure 13: Current, current components and voltage development over a period for a 81kA arc

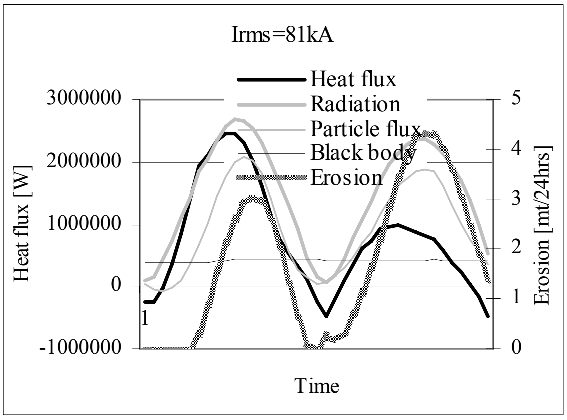

Figure 14: Heat flux from different sources and erosion over a period for a 81kA arc

$$\dot{q}_{bound} = -j_i\left(2\frac{k_B T_i}{e} - 2\frac{k_B T_C}{e} + U_i\right) + j_e\left(u_C + 2\frac{k_B T_C}{e}\right) - j_{epl}\left(u_C + 2\frac{k_B T_e}{e}\right) \quad (9)$$

Notice that the thermionic work function ϕ terms do not appear in this equation have as ϕ is exclusively a material property, which determines the energy of an electron within the material as compared to a free electron. The electric arc is not directly influenced by the work function except by ϕ's effect on the current density of emitted electrons. *The same equations apply at **the anode**.*

3. SIMULATION RESULTS

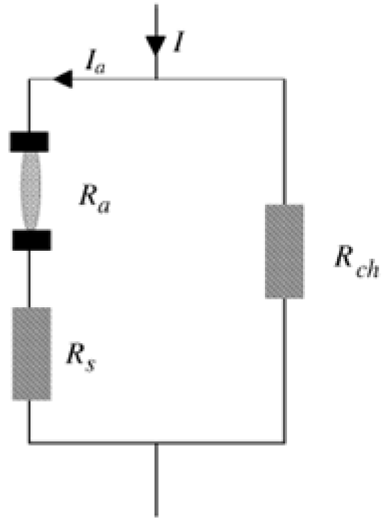

Figure 15: A schematic drawing of a configuration with conducting charge resistance in parallel to the arc [13]

Energy flux from the arc is by radiation and the kinetic energy of particles, and cooling is by black body radiation, electrode material evaporation and heat transport into the electrode body. It has been shown that heat transfer into the electrode is comparatively very small (order of magnitude 20 kw), due to the relatively low heat conductivity of the carbon material and the limited temperature gradients [10]. Heat generation within the electrode body due to Ohmic heating is, however, a considerable contributor, and that heat can only be removed by heat conduction. The temperature within the electrode body cannot, however, rise much above the sublimation point for carbon. Therefore the length of time when a stationary arc may burn at a certain location is limited, and much shorter for high-current arcs than for lower-current arcs. Simulation results shown in Figure 3 also indicate that the electrode erosion increases more than linearly with increased current. The erosion from an 80kA arc is 1.7 tons/24hrs, while splitting that arc into two parallel arcs of 40kA will result in an arc erosion of 0.64 tons/24hrs divided between the two arcs. For an industrial furnace a typical electrode consumption on an electrode carrying a typical current of 120kA may be close to 1.5 tons/24hrs [11]. Measurement on a Ferrosilicon furnace indicate that 20-40% of the phase current bypass the arc and pass through the charge in the lower regions of the burden where the carbon materials have formed well conducting and sintered SiC [13]. This configuration is shown schematically in figure 15.

Assuming an arc current fraction of 2/3, (with the other 1/3 passing through the charge materials), simulations for a single arc indicate an arc erosion rate of 1.7 mt/24hrs per electrode while *two* parallel arcs would lead to a total erosion of 0.64 mt/24hrs between them. As chemical erosion is by most furnace operators thought to be the dominating contributor, and the erosion varies greatly with furnace operation, raw materials and segregation patterns, these observations correspond better to a multiple arc configuration. Simulation on high-current AC arcs indicate a rising current/voltage characteristic for arcs carrying more than 7 kA, which means that splitting a high-current arc in two or more will decrease the voltage required. Figure 8 demonstrates this for MFD simulations using the boundary conditions presented in [7]. Any physical system strives towards reducing its resistance and according to Kaufmann´s stability criterion for DC arcs [14], a rising current / voltage characteristic leads to a stable formation of more than one arc. If Kaufmann´s stability criterion is applicable to AC-arc as well as DC arcs, two or more arcs burning in parallel is a likely configuration.

A sensitivity analysis for the selection of the mass transfer rate coefficient C_2 defined in the previous section shows that the erosion has a minimum close to the value selected. Reducing the mass transfer rate will reduce the carbon vapour recondensation in the system, and increasing it will increase the sublimation at surface temperatures below the sublimation point of 4090 K. The results from this analysis indicate that the sensitivity of the total erosion to the selection of this parameter is of the order of 30%, and within the limits of the expected errors of other uncertainty factors. Figure 4 shows the results from such analysis for a 51kA arc.

Figures 5, 6 and 7 show the current density distribution as a function of distance from the symmetry axis at even time intervals. It is seen for the 21 kA arc, the current distribution in the cathode half-period is quite smooth and the density always positive. For the 42 kA arc a drop in the centre is seen for the current density and for the 81kA arc, the central current density is actually negative in the cathode half period. This is due to the high energetic plasma electrons that penetrate the voltage barrier.

Figures 9, 11 and 13 show the total current and current component development as well as the voltage barrier for RMS arc currents of 21, 42 and 81 kA, respectively. It can be seen that the total current is the sum of the three current components of different directions, that each is larger than the total current. The size of the current components as compared to the total current gets more exaggerated as the total current is higher. As previously reported, the cathode and anode fall voltages are of the same sign, and will almost cancel out as contributors to the total arc voltage. Figures 10,12 and 14 show the heat flux to the surface and the contributions of radiation, black body radiation as well as heat transfer by particle impact. The contribution of sublimation and condensation are included in the particle impact heat transfer. The erosion rate in the units of metric tons pr. 24 hours is included in these figures that are for 21, 42 and 81 kA arc current, respectively. The erosion takes place primarily in the anodic half-period. For the lower current levels there is seemingly no erosion in the cathode half-period. This is probably not a precise result, but a consequence of the simplifying assumptions. However, the tendency is clear, the anode half-period causes much more wear than the cathodic.

4. DISCUSSION AND CONCLUSIONS

An attempt has been made to evaluate the role of arc erosion in the electrode consumption in industrial submerged-arc furnaces for production of silicon and ferrosilicon. It has always been a matter of discussion how much erosion is caused by the electric arc itself and how much is due to chemical reactions with raw materials and gas that leaves the crater. Simulation models that describe both the electric arc and the arc attachment to the electrode, are used in this endeavour. The diffuse spot cathode/anode model CASM deviates in important aspects from cathode models previously reported in the literature. Most existing models have been made for low-current DC arcs, where the cathode spot must be energetically self-sustained, and no energy is extracted from the arc itself. The novel model used in this work represents the other limit: The cathode/anode spot is dominated by energy impact from the arc, and must be included in the energy balance for the arc itself. An improvement in the model would include coupling the MFD arc model and the cathode/anode sub-model and solve both models simultaneously. The transport equation for the vaporized electrode material should then be solved within the MFD model.

Although the CASM has not yet been fully integrated into the MFD arc model, the tentative iterative results indicate a much lower cathode current density than previously assumed and a much smaller cathode fall voltage, which indeed has the same sign in the anodic half-period. This means that when considering the total arc-cathode-anode system, the voltages for the cathode and anode almost cancel out! A *negative* anode fall voltage has previously been suggested by Pfender, but the standard assumption is that cathode and anode fall voltages add up. The relatively low current density gives rise to a cathode spot, wider than the part of the arc attached to it. Such wide cathode spots have been observed and discussed on some occasions.

The erosion rate depends highly on the arc current: doubling the arc current more than quadruples the erosion rate. This supports that it is not unlikely that there is more than one arc burning in the craters of submerged-arc furnaces, a hypothesis which primarily was based on Kaufmanns stability criterion [14] and the rising current voltage characteristic displayed by the arc. Other observations that support this opinion are the rising current/voltage characteristics for high-current AC arcs, and the Ohmic heat generation within the electrode body close to the arc attachment reported by Palsson et al.[10]. For a Soderberg electrode in an industrial furnace producing FeSi75, that carries a current of 120kA, a *single arc* in the crater the model results would imply that arc erosion would count for electrode erosion comparable to the total electrode consumption for a stable well operated furnace. Only 40% would be attributed to arc erosion if *two arcs* do the job. Furnace operators know that segregation in the furnace, changes in raw material and SiO blowing along the electrode can lead to large changes in the electrode erosion, and probably find the latter figure easier to believe. Interpreting the results, one should also keep in mind that uncertainty in parameter determination may lead to an error of approximately 30%.

REFERENCES

[1] G. A. Sævarsdottir, "High current AC-Arcs in Silicon and Ferrosilicon Furnaces", Ph.D. Thesis, Tapir, 2002:56
[2] Neumann W.,"The mechanism of the thermoemitting arc cathode", Akademi-Verlag, Berlin, 1987.
[3] Benilov M.S. " The ion flux fom a thermal plasma to a surface", J.Phys. D: Applied Phys. 28, 1995, pp.286-294.
[4] E.Pfender, M.Boulos, P.Fauchais, "Methods and Principles of Plasma Generation", Plasma Technology in Metallurgical Processes, pp. 27-47, ISS-1987
[5] M.S.Benilov, G.V.Naidis, "Ionization layer at the edge of a fully ionized plasma", Physical Review E, Vol 57, No 2, Feb 1998.
[6] Liebenham M A, Lichtenberg A J, "Principles of plasma discharges and materials processing",1994, John Wiley and Sons NY.
[7] G.A.Sævarsdottir, J.A.Bakken, V.G.Sevastyanenko, Liping Gu, "Arc Simulation Model for Three-Phase Electro-Metallurgical Furnaces", INFACON 9, June2001, Quebec City, Canada. In proceedings pp.253-263.
[8] R.Bötticher, W.Bötticher, "Numerical modelling of arc attachment to cathodes of high-intensity discharge lamps", J.Phys D: Appl. Phys. 33(2000) pp. 367-374.
[9] Ahmed Kaddani, Said Zahrai, Oliver Simon, "Kinetic model for the space charge zone in the cathode region of electric arcs", ABB Technical report SECRC/KB/TR-95/244E, Vesterås, Sweden, 1995.
[10] H. Palsson, G.A. Saevarsdottir, M. T. Jonsson and J. A. Bakken, ´Thermal effect on carbon based electrodes close to a high current electric arc.', INFACON 11, February 2007, New Dehli, India. In Proceedings.
[11] Th. Magnusson, Icelandic Alloys, personal communications January 2004.
[12] G. A. Saevarsdottir, H. Palsson, M. T. Jonsson, J. A. Bakken, "Electrode erosion due to high current electric arcs in silicon and ferrosilicon furnaces.", Steel Research International, Scandinavian Journal of Metallurgy, Issue 6, 2006.
[13] G. A. Saevarsdottir, "*High current AC-Arcs in Silicon and Ferrosilicon Furnaces*", Ph.D thesis, IME-rapport 2002:36, NTNU.