NUMERICAL MODELING OF METALLIC BATH HEATING WITH TRANSFERRED ARC

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Abstract: A modeling of metallic bath heating with a transferred arc by considering the flows, electromagnetic and temperature fields both in the arc and the bath is proposed. The model and the main assumptions used are presented with an emphasis on the treatment of the boundary conditions at the plasma-metal interface. Computations are performed for a pilot furnace of 200 kW-2000 A. The computed results are presented and discussed.

1 INTRODUCTION

Electric arcs are widely used in the metallurgical industry and, for a few years, numerous transferred arc plasma torches have been installed for tundish or laddle heating. Although the global behaviour of theses processes is correctly controled, the knowledge and the understanding of the heat transfer between the electric arc and the steel bath are rather limited, that makes their optimization difficult. Because of the complex nature of the plasma, experimental work is difficult and only gives global informations instead of localized informations which may be important for determining the optimum operating conditions in the plasma reactor. But, recent works in modeling [1, 2, 3] demonstrate the interest of using a modeling approach in order to improve and optimize a plasma processing reactor. In the present paper, study is focused on molten metal heating with a transferred arc plasma torch. The interaction between the arc and the metal bath is studied by considering the flow, temperature and electromagnetic fields both in the arc and in the bath. In the following, the mathematical model with the assumptions used are brievely presented. The treatment of the arc-bath interface is particulary developed. After a description of the studied case, some results are shown and discussed.

2 MODEL FORMULATION AND NUMERICAL PROCEDURE

2.1 Geometry

The computing geometry is approximately a 200 kW pilot furnace supplied by Tetronics to EDF's plasma laboratory (Fig. 2.1). It consits of an argon transferred arc between a cathode tip plasma torch and an iron anodic bath under atmospheric pressure. The arc length is 150 mm. The torch body is a water cooled cylinder. A 125 mm radius steel anode is located at the bottom of the furnace. The walls of the furnace are made of high-grade alumina refractory.

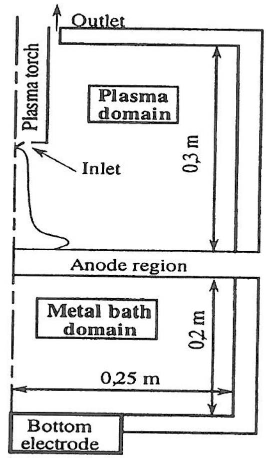

Fig. 2.1 Computing domain

2.2 Basic assumptions

Steady, two-dimensional axisymetrical, plasma and molten metal flows are considered. Local thermodynamic equilibrium (LTE) and global electric neutrality are assumed to prevail in the plasma.

In consequence, the plasma is treated as a continuous fluid using the classical fluids mechanics equations (with Lorentz forces contribution in the momentum equation, Joule and radiative source terms in the energy equation) coupled with the electromagnetic ones [4, 5]. A global radiative dissipation, function of the temperature is introduced, which implies that re-absorption of radiation by the plasma compared with the total radiative loss is unsignificant. The radiative heat transfer in the plasma domain and the iron evaporation are not yet taken into account. Due to the axisymetric geometry, the magnetic field is calculated directely from the current density distribution with the help of the Ampere's theorem. For the bath flow computation, identical equations are solved without, of course, the radiative losses. No interface deformation is considered, the bath surface is fixed as a flat surface.

In such industrial electric arcs, turbulence must be taken into account [6]. This is performed in the present study by means of a two-equations k-epsilon turbulence model. But for instance, due to the large variations of the molecular viscosity, both laminar and turbulent regimes may be present in the same flow. To account for that, a low-Reynolds k-epsilon turbulence model is used [7]. But the possible effect of the turbulence on the electrical conductivity is neglected. The same turbulence model is used in the anodic metal bath in order to treat laminar as well as turbulent cases.

For the arc column and the liquid metal, the transport and thermodynamical properties are functions of the temperature. They are respectively given by [8, 9].

2.3 Modeling

The characteristic times of the flows in the arc and in the bath are very different. So, each domain is computed separately and a coupling is performed by means of the current, heat and momentum transfers at the surface of the iron bath. To handle this problem, several iterations are made as shown in Fig. 2.2 until the surface temperature tends to a steady state. The computations of the arc and metal bath flows are performed using "Melodie", a 2-D axi-symetrical finite-difference/finite-volume code developped at the Laboratoire National d'Hydraulique [10].

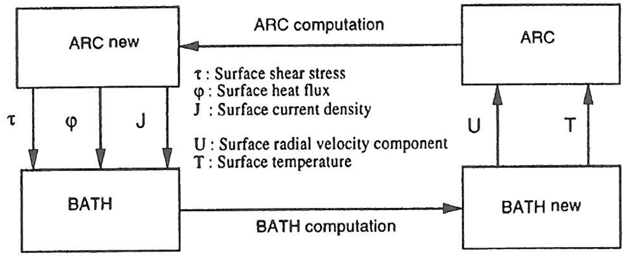

Fig. 2.2 Coupling procedure

2.4 Boundary conditions

Considering turbulent flows, a special treatment of the walls is necessary to account for possible steep gradients in the boundary layer. A global treatment of the boundary layer is then made with the help of wall-functions proposed by Gosman [11, 12].

On the walls, global heat transfer coefficients "h" and external temperatures "T_e" are considered. Those coefficients integrate the wall conductance and the internal convective coefficient. This last one is obtained from the flow computation with the help of the wall-functions. The torch body is water cooled (h = 3000 $W/(m^2.K)$, T_e = 300 K). The refractory walls of the plasma region are water cooled (h = 30 $W/(m^2.K)$, T_e =300 K). The refractory walls of the bath are cooled with high speed forced air (h = 24 $W/(m^2.K)$ for the lateral wall and h = 15 $W/(m^2.K)$ for the bottom wall, T_e =373 K) .

At the gas inlet, a temperature of 300 K and a parabolic velocity profile are imposed. The gas outlet is considered as an open boundary. There is of course no current flowing through those boundaries as well as for the refractory walls.

On the cathode tip, a zero normal derivative of the temperature and a zero electric potential are specified.

For the plasma computation, the anodic metal bath surface temperature is imposed by means of a simplified modeling of anode region based on a balance between conductive flux and Joule effect [10]. The corresponding equation is solved on a one-dimensional subgrid with thermodynamic and transport properties functions of the local temperature (Fig. 2.3). The metal bath surface temperature T_w is obtained from the metal bath computation. A virtual temperature T_v, comparable to the electronic temperature, is used to calculate the electrical conductivity at the boundary in order to allow the flow of current. T_v is deduce from the conservation of the heat flux density through the boundary layer, as shown on fig.

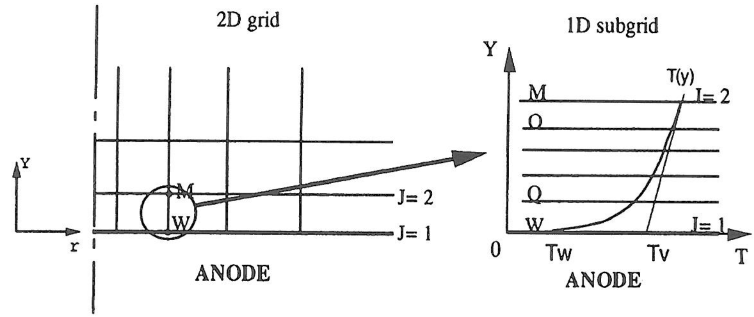

Fig. 2.3 Anodic layer

In the present study, the treatment of the anode region is rather simple but a more sophisticated anodic layer model, capable of accounting for complex phenomena such as metallic vapors and non local thermodynamic equilibrium [13], is going to be integrated.

The radial velocity distribution on the bath surface is imposed and taken equal to the one obtained from the metal bath computation. A uniform electric potential, result of the arc computation through the adjustment of the current intensity is imposed at the plasma-metal interface.

For the metal bath computation, the surface shear stress, the surface heat flux and the surface current density distributions given from the plasma computation are imposed on the bath surface. The Marangoni effect is not considered [3]. The heat transfer in the arc anode region is simply assumed to be convective. The electron heat flux, the radiation heat flux and the heat loss due to the metal evaporation will be considered with the help of the anodic layer model [13] mentioned above.

A uniform current density is imposed on the upper surface of the bottom electrode (anode steel bilette) which is, moreover, supposed to stay at the melting temperature of iron (1809.16 K).

3 RESULTS AND DISCUSSION

The computations were carried out for an arc of 2000 A, 150 mm, 50 Nl Ar/min. The convergence was obtained after four plasma-bath iterations. The computed arc voltage is 90 V (not including electrodes falls), that seems rather realistic. The plasma and metal temperature fields are presented on Fig. 3.1. For the plasma domain, the computed temperature field is in accordance with those usualy found in such argon arcs.

There are two main recirculation zones in the metal bath (see Fig. 3.3) : a Lorentz forces dominated zone where the metal flows towards the bath center in the vicinity of the arc impinging zone and a surface shear force dominated zone where the metal flows towards the wall in the vicinity of the arc impinging zone. The Lorentz forces effect are also significant in the region of the bottom electrode because of the curvature of the lines of electric flux. This feature of the metal flow is in acordance with the results obtained by Gu [1] in a transferred arc heated silicon bath. The characteristic velocity of some cm.s^{-1} seems to be reasonable. The temperature and radial velocity distributions in plasma and metal flow, on both sides of the interface are given in Fig. 3.2. A slight superheating of the metal in the vicinity of the arc impinging can be observed, of course underestimated because the heat flux of the electrons at the anodic bath surface was not taken into account.

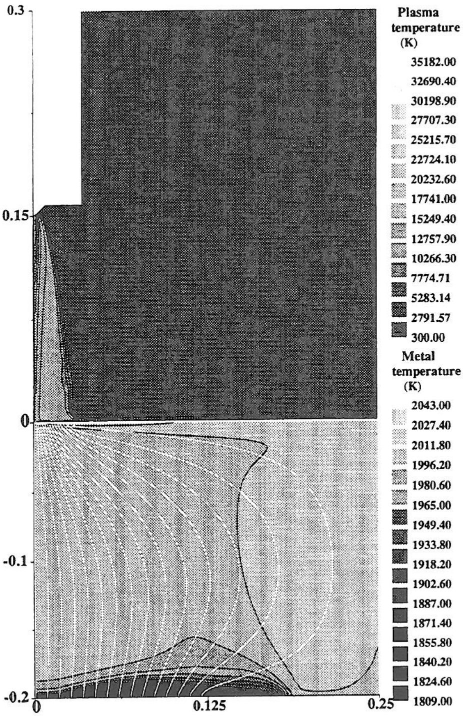

Fig. 3.1 Temperature fields in the plasma and metal with lines of electric flux in the metal bath (in white)

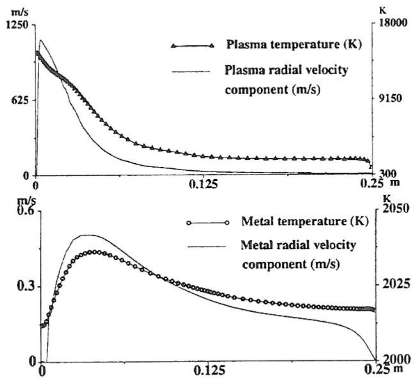

Fig. 3.2 Temperature and radial velocity profiles on both sides of the interface (at y=+1mm and y=-1mm)

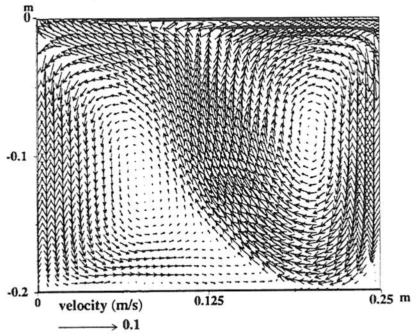

Fig. 3.3 Velocity field in the metal bath

4 CONCLUSION

A 2-D modeling attempt of metal bath heating with a transferred arc has been carried out using Melodie, a finite difference/finite volume code developed at EDF. The model considers flows, temperature and electromagnetic fields both in the arc and in the bath. Each domain is computed separately and coupled by means of momentum, heat and current transfers at the plasma-metal bath interface. Results of the computation give interesting informations about the flow in the metal which is strongly influenced by the electromagnetic forces in the central area of the bath and more less in the vicinity of the bottom eletrode, whereas the rest of the flow is mainly dominated by the driving effect due to the surface shear stress.

The present study can be considered as a preliminary step in the modeling of transferred arc on a metal bath. More complex phenomena are going to be integrated in the model : anode region modeling, metal evaporation and radiative heat transfer, then a comparison with experimental results will be considered.

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