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Fluid dynamic modelling of electric arcs for industrial applications

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Abstract : This paper presents recent developments on fluid dynamic computations performed at *Electricité de France* in the frame of industrial applications of arcs, like steel making electric arc furnaces, metal bath heating by a transferred arc plasma torch installed for tundish or ladle heating, and also high voltage circuit breakers in SF_6. The simulations have been carried out using our numerical tools, *Mélodie*, *ESTET* and *N3S* codes. The attention has been paid on modelling of radiative transfer, using partial characteristics for SF_6 and discrete transfer for air or argon .

Introduction

This paper presents recent developments on fluid dynamic computations performed at *Electricité de France* in the frame of industrial applications of electric arcs. At the *Laboratoire National d'Hydraulique*, simulations of electric arcs flows at atmospheric pressure have been carried out at the beginning for plasmas torches and then for steel making electric arc furnaces modelling. Recently, our numerical tools were adapted in order to model metal bath heating by a transferred arc plasma torch, and also to simulate high voltage circuit breakers in SF_6. For these works performed in collaboration with others departments of the *EDF Research Division*, different developments have been made to take into account, for example, the interaction of electric arcs with electrodes or the coupling of a arc plasma flow with a liquid metallic bath flow, and to improve the radiative transfer modelling.

2D axisymetrical computations have been performed in *Mélodie*, a finite differences/volumes code, and recently in *N3S*, a finite elements code. 3D simulations including radiative transfer modelling of industrial furnaces have been started in *ESTET*, a finite volumes code. These codes are general fluid dynamic codes developed at *LNH* for complex and reactive flows, adapted for electric arcs flows.

Metallurgical applications

Electric arcs are widely used in the metallurgical industry, in electric arcs furnaces used in steel making industry for example. For a few years, numerous transferred arc plasma torches have been installed for tundish heating. Although the global behaviour of theses processes is correctly controlled, the knowledge and the understanding of the heat transfer between the electric arc and the steel bath are rather limited, that makes their optimisation difficult. Because of the complex nature of the plasma, experimental work only gives global informations instead of local ones which may be important to determine the optimum operating conditions in the plasma reactor ; modelling is then of great interest to improve a plasma process (ref. 1).

The first study is focused on molten metal heated with a transferred arc plasma torch (ref. 2 and 3). The simulations are performed for a 2000 A arc of 15 cm or 25 cm, representing an experimental furnace located at *EDF* laboratory. The sizes of the furnace, containing 300 kg of steel, are 25 cm for radius and 50 cm for height. 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 which are computed separately using *Mélodie* code. The coupling between the plasma and the liquid bath is insured by taking into account a specific modelling of the anodic layer, corresponding to the boundary layer occurring on the bath surface. It is performed by means of a one-dimensional subgrid model at LTE (ref. 4), where temperature and iron mass fraction profiles are calculated in order to ensure electrical and thermal coupling between the arc column and the bath surface. This anodic model gives the heat flux transmitted to the bath, evaluated from the enthalpy balance in the negative space charge zone near the bath surface and accounting for metal evaporation (Fig.1).

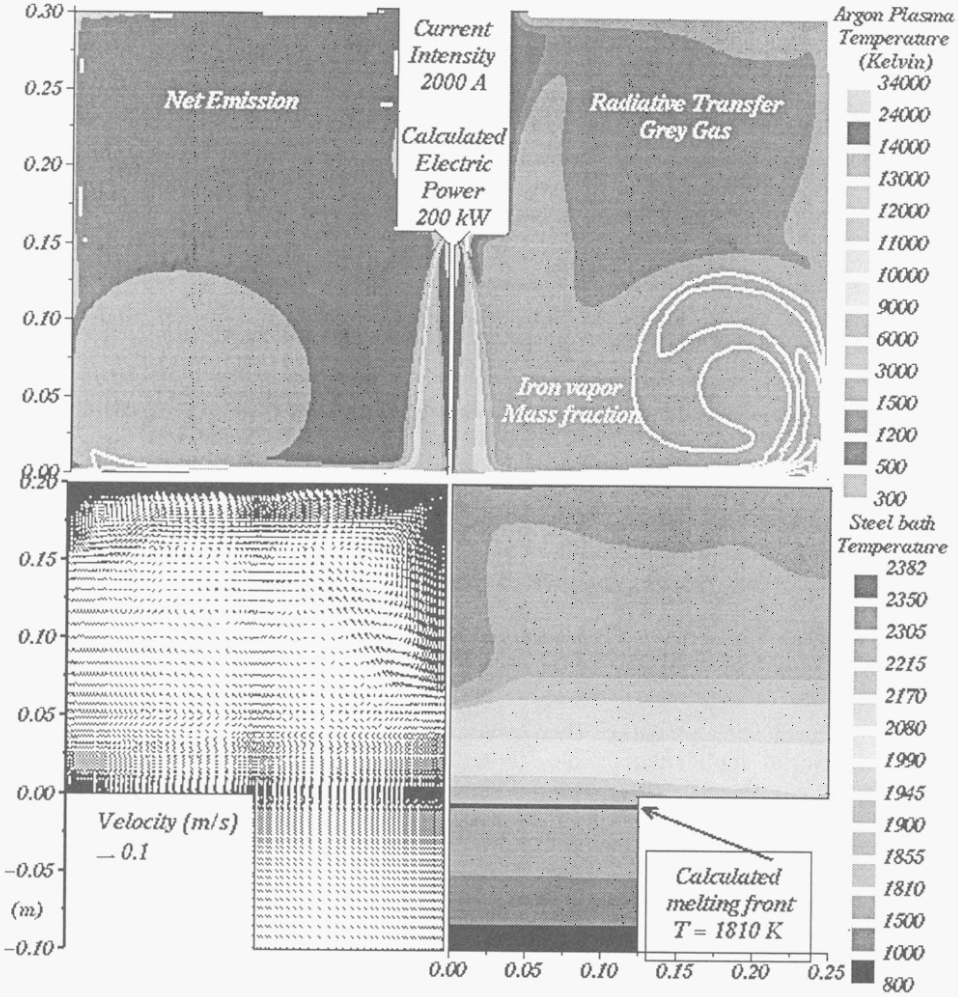

Figure 1 : Steel heating by arc in a furnace: arc and bath computational results.

In the plasma domain, a rather sophisticated simulation of radiation is obtained by using the 3D discrete transfer method of the *ESTET* code (ref. 5), with an assumption of grey gas (see equation (1) to (6)). The comparison with a simplified method (a net emission term function of the local temperature, pressure, and composition of the plasma) shows how the 3D discrete radiative transfer method gives a better modelling of thermal transfer on the walls and also a realistic value of the ambient temperature in the furnace (fig. 1 and 3). The temperature in the arc core is less affected by the radiation modelling because the furnace is mainly filled with argon at atmospheric pressure which is not absorbent.

In the second case, electric arc furnace in air (ref. 7), the absorption phenomena are obtained by the discrete transfer method taking into account the spectral nature of the radiation, and then have a great influence on the temperature result in the core of the arc. This spectral model, based on the assumption that properties of plasma are "grey" on spectral bands $\Delta\lambda$ ($= \lambda_2 - \lambda_1$), uses the radiative transfer equation, as follows :

$$\frac{dL_{x,\Delta\lambda}}{dx} = - K_{\Delta\lambda}\, L_{x,\Delta\lambda} + K_{\Delta\lambda}\, \frac{M^0_{\Delta\lambda}}{\pi} \qquad (1)$$

Equation (1) on the radiation intensity L is solved for each direction x and each spectral band. $M^0{}_{\Delta\lambda}$ (2) corresponds to the blackbody radiation associated to $\Delta\lambda$. If the gas is considered to be "fully" grey (λ_1=0 and λ_2=∞), equation (1) corresponds to the classical grey gas radiative transfer equation. Then $M^0{}_{\Delta\lambda}$ becomes M^0, given by Stefan law (3).

$$M^0_{\Delta\lambda} = \int_{\lambda_2}^{\lambda_1} M^0_\lambda d\lambda \quad (2) \qquad M^0 = \int_0^\infty M^0_\lambda d\lambda = \sigma T^4 \quad (3)$$

The radiative source term appearing in the enthalpy balance equation is calculated by :

$$S_{rad} = \sum_{\Delta\lambda} K_{\Delta\lambda}\alpha_{\Delta\lambda} - 4\sum_{\Delta\lambda} K_{\Delta\lambda} M^0_{\Delta\lambda} \quad \text{with} \quad \alpha_{\Delta\lambda} = \int_{4\pi} L_{x,\Delta\lambda} d\Omega \qquad (4)$$

The radiative properties ($K_{\Delta\lambda}$ and $M^0_{\Delta\lambda}$) of the air plasma are given by a 2 wave lengths intervals model : the first band represents the far UV (λ_1 = 1,2410^{-8} m and λ_2 = 1,18 10^{-7} m), and the second one the nearly other wave lengths (λ_1 = 1,18 10^{-7} and $\lambda_2 = \infty$) (ref. 6).

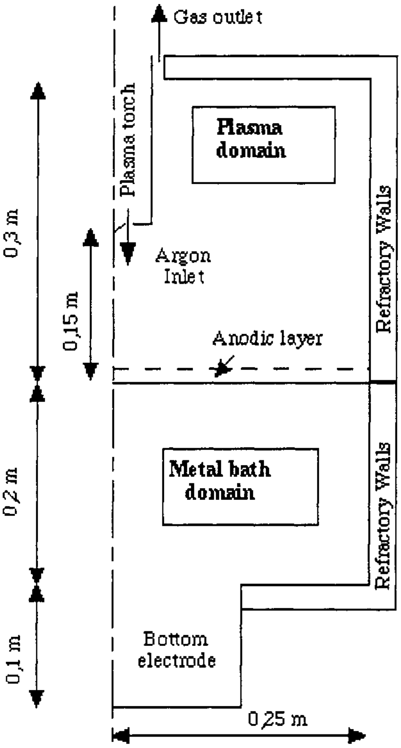

Fig. 2 : Liquid steel heating by an 2000 A arc
Computational domain

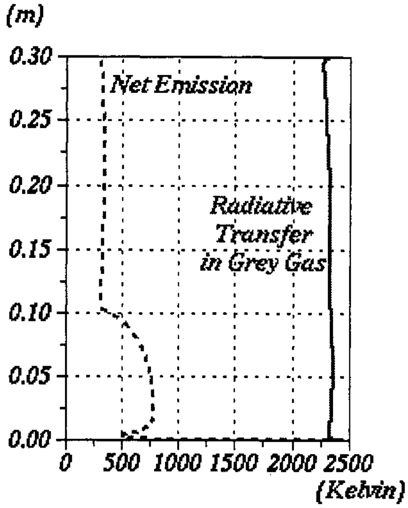

Fig. 3 : Calculated temperature profiles on the vertical refractory wall.

Boundary conditions for intensity on walls is defined from wall emissivity ε and radiative incident flux :

$$L_{\Delta\lambda,wall} = [(1-\varepsilon) Q_{incident} + \varepsilon M^0_{\Delta\lambda}] / \pi \qquad Q_{incident} = \sum_{\Delta\lambda} \int_{2\pi} L_{x,\Delta\lambda} d\Omega \qquad (5)$$

The thermal flux on walls (6) takes into account radiative exchange, and allows to calculate also the wall temperature if the wall exchange coefficient h_{wall} and the external temperature are known (see fig. 3).

$$\phi_{wall} = h_{wall}(T_{wall} - T_{external}) = \varepsilon Q_{incident} - \varepsilon M^0_{\Delta\lambda} + h_f(T_{fluid} - T_{wall}) \qquad (6)$$

The electric furnace simulations take into account the turbulence of the flow by using a low Reynolds number k-epsilon model (ref. 8), and try to predict the energy transfer from the arc to the metallic bath by using a simplified 1D modelling of the plasma boundary layer on the bath. Calculations are performed for 10 kA and 40 kA arcs of 20 or 40 cm long, burning in different gazes. These configurations of steel making furnaces, correspond to the last step of scrap iron melting when the arc is burning on a flat metallic bath. By predicting radiation absorption in the fringes of the arc, the spectral radiative transfer model carries out improvements in the results, in terms of temperature fields and of electrical potential.

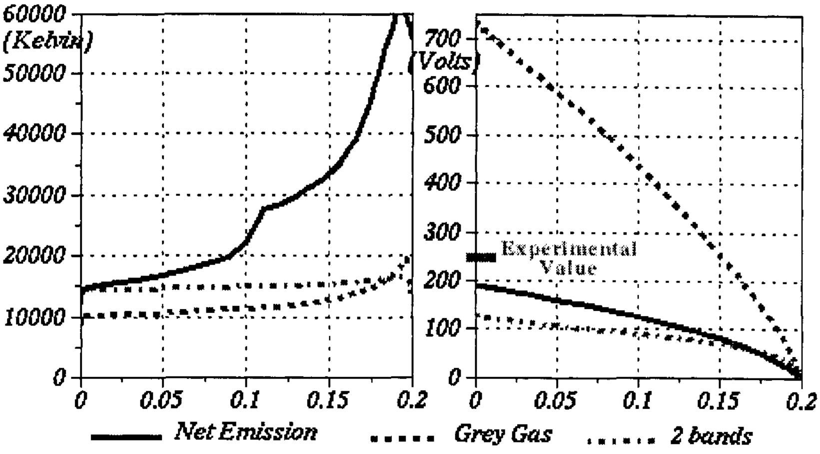

Fig. 4 : Temperature and potential on the arc axis for a 10000 A arc with 3 radiative transfer models.

High voltage breakers modelling

Electric arcs encountered in breakers have specificities that lead to take into account a lot of complex physical phenomena. The filling gas of the studied breakers is SF_6 generally at high pressure (to 8 10^5 Pascal). The electric arc is created between two electrical contacts ; one contact is moving with time in order to be completely open when the current is approaching 0. Our calculations corresponds to half of the current period. In breakers, the problem is to blow the electric arc which appear with the aperture of the contacts. Depending on the configuration of the breakers, an over imposed flow, or a flow induced by the over pressure created inside the breaker by absorption of radiation emitted by the arc zone, can help to the extinction of the arc at current 0. Generally this flow is very important, and can induce shock waves in some configurations. The pressure has large variations in the computational domain : the modelling has to take into account the compressibility of the flow in terms of variation of the plasma properties with local pressure. As it has been said, radiation is of great importance in the process, because of absorption phenomena which can be important in SF_6, and also due to the stiff gradients of temperature and pressure which may occur. So a radiative transfer model, based on the partial characteristics method (ref. 9 and 10), has been implemented. In the simulations presented here, the Local Thermodynamic Equilibrium is always assumed, and interaction with electrodes are roughly simplified.

Two configurations have been computed. The first configuration (fig. 5) corresponds to an experimental set-up simulating a puffer breaker for a 2000 A current : we are in the case of an over imposed flow. The second configuration represents a self blast and rotary arc breaker, for a maximum current of 8100 A. In this geometry, the arc induces, by radiative transfer, the increase of pressure in the expansion volume, and consequently generates, at current 0, an important flow from this volume to the contacts.

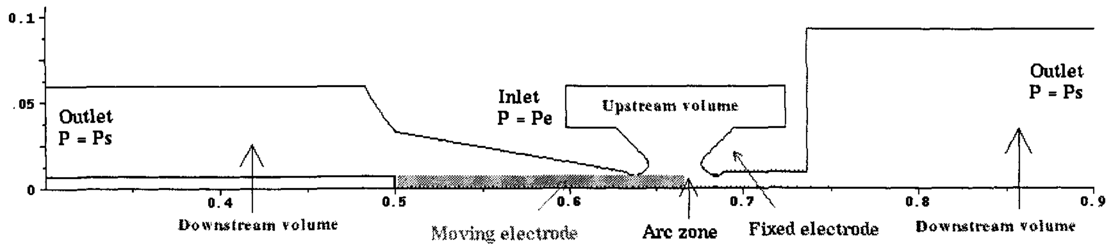

Fig. 5 : Puffer breaker computation domain

Calculations are realised using *Mélodie* or *N3S* codes (fig. 6) in connection with 2 manufacturers (*GEC Alsthom and Schneider Electric*). The computations are 2D and axisymetrical, so simplifications have been made in order to impose the arc to be located on the axis of the geometry : in particular, the current goes between fictitious plane electrodes perpendicular to the axis. The simulations take into account the movement of the contact. Predictions obtained for both breakers seem to be realistic in terms of temperature, electrical potential and Mach number level : in the puffer breaker a shock wave has been found inside the moving contact. The Mach number is also high on the nozzle wall when the contact is fully open (fig. 7).

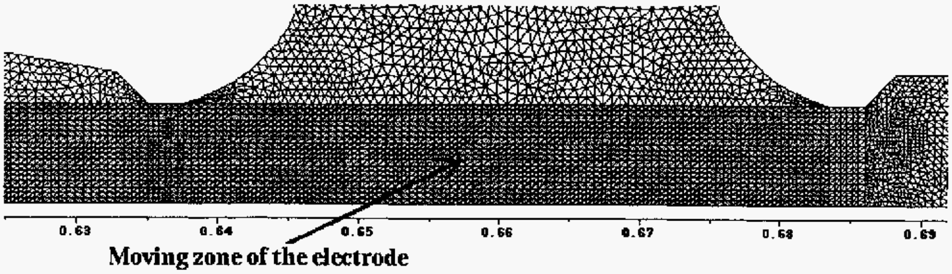

Fig. 6 : Puffer breaker electrode zone meshes for finite elements code

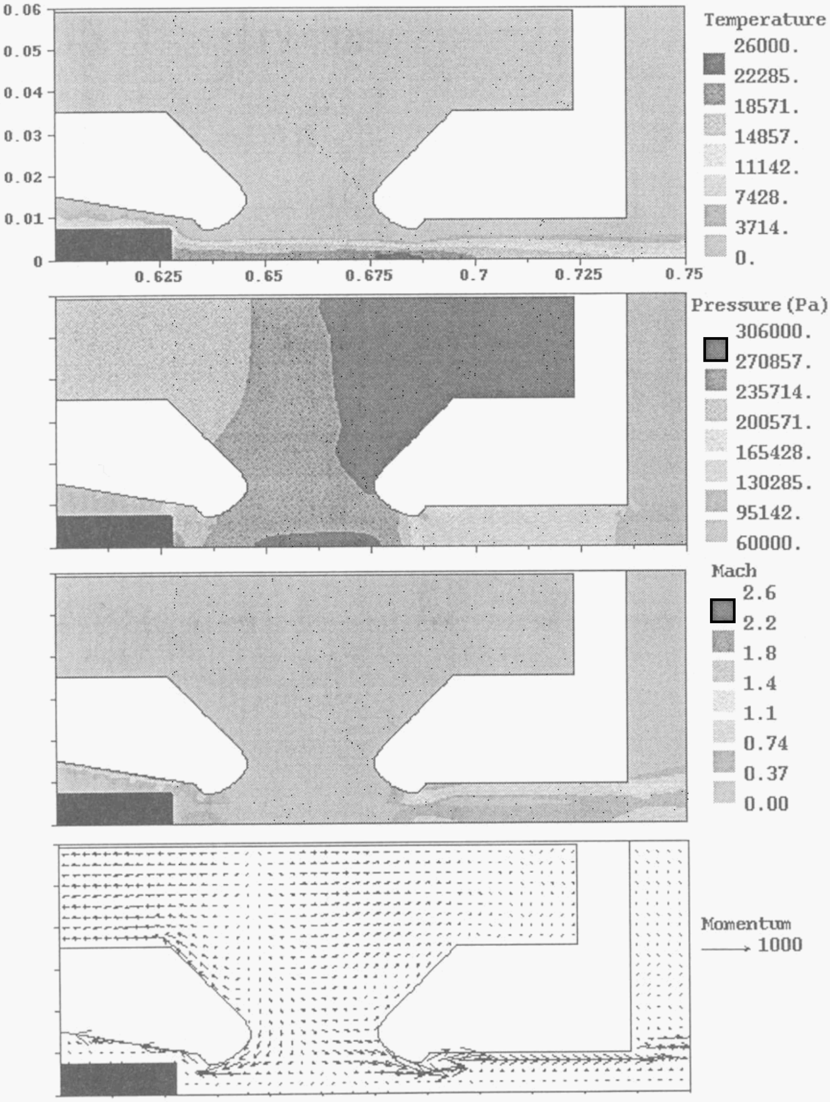

Fig. 7 : Puffer breaker results at the end of electrode opening (constant current = 2000 A).

In the self blast arc, a realistic over pressure seems to be well predicted by using the radiative transfer based on partial characteristics. In order to show the absorption region, the positive radiative source term calculated at different times of the simulation is plotted on fig. 8.

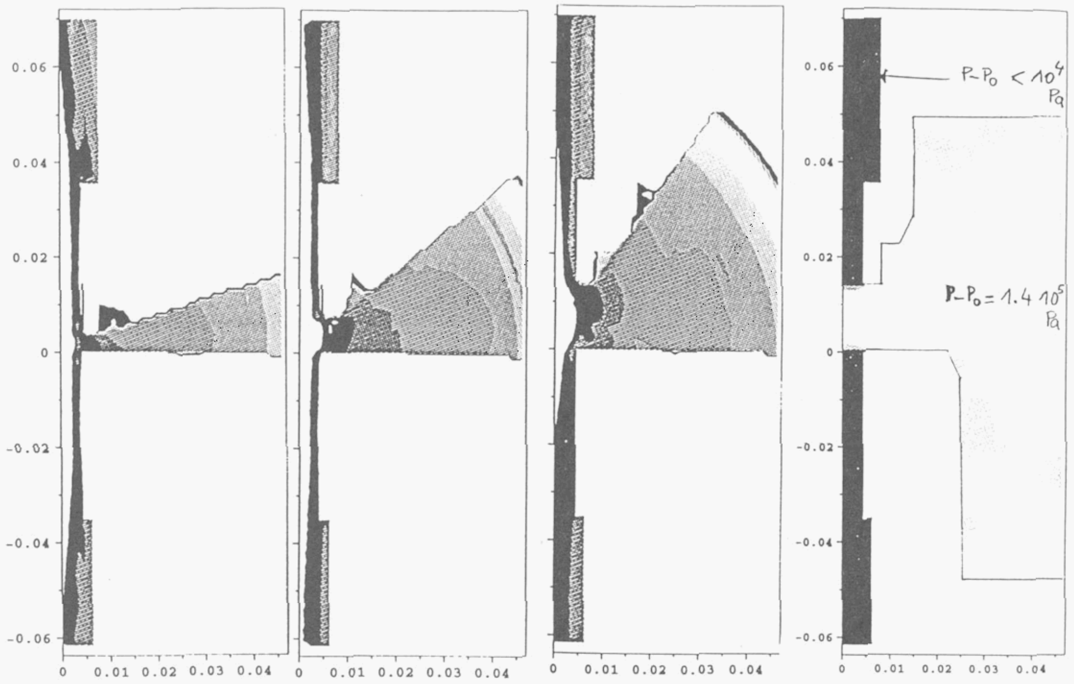

Fig. 8 : Radiative source term at 3 moments of the self blast breaker, and relative pressure at current zero

Conclusion

This paper presents recent developments on fluid dynamic computations performed at *Electricité de France* for steel making electric arc furnaces applications, and high voltage circuit breakers in SF_6. The simulations carried out in *Mélodie, ESTET* and *N3S* codes, takes into account complex physical phenomena : for example, thermal, electric and dynamic coupling of arc and metallic bath flows in the case of metal bath heating by a transferred arc plasma torch installed for tundish or ladle heating, or movement of electrode and flow compressibility in the case of breakers. Furthermore, in all the industrial processes studied here, radiative transfer modelling is found to be of great importance. Partial characteristics for SF_6 or discrete transfer for air or argon seems to give realistic predictions, and reabsorption is obtained using spectral models.

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