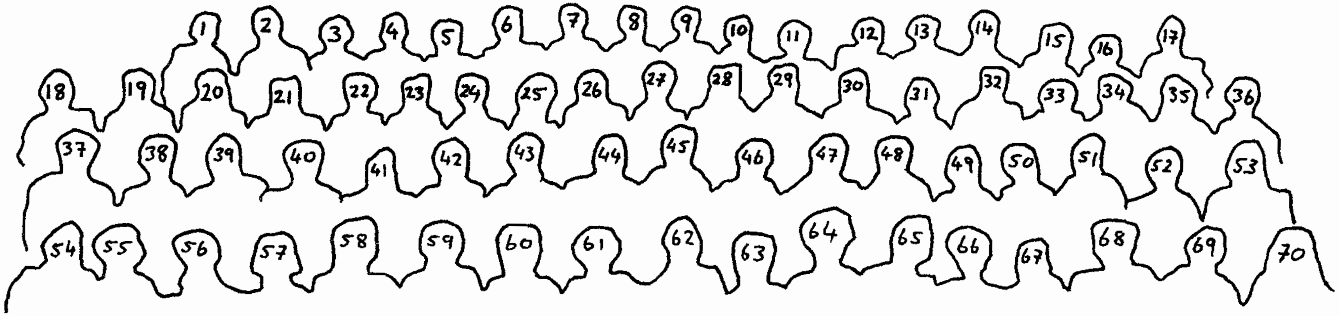

<u>FIRST ROW</u>

1. Neuman
2. Girshick
3. Sevastyanenko
4. Lankas
5. Krejci
6. Sara
7. Dijkhuis
8. Gu
9. Chen
10. Pfender
11. Nutsch
12. Landes
13. Zhao
14. Novikov
15. Begell
16. Moiseev
17. Page

<u>SECOND ROW</u>

18. Ersoy
19. Colyer
20. Mozetic
21. Kostic
22. Konrad
23. Barmenkova
24. Arefi
25. Sember
26. Kopecky
27. Chambon
28. Britz
29. Murphy
30. Proulx
31. Larsen
32. Heberlein
33. Hrabovsky
34. E. Sancaktar
35. O. Sancaktar
36. Malinovsky

<u>THIRD ROW</u>

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38. Cameron
39. Stefanovic
40. Arinç
41. Mrs. Ushio
42. Mr. Ushio
43. Takamura
44. Witalis
45. Bianchi
46. Boufendi
47. Sarette
48. Thomas
49. Elchinger
50. Champeaux
51. Gleizes
52. Delalondre
53. Philippot

<u>FOURTH ROW</u>

54. Mr. Avni
55. Mrs. Avni
56. Çoşkun
57. Ünsal
58. Van Der Mullen
59. Benoy
60. Mostaghimi
61. Gitzhofer
62. Mr. Fauchais
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HEAT and MASS TRANSFER under PLASMA CONDITIONS

Proceedings of the International Symposium on
Heat and Mass Transfer under Plasma Conditions

Edited by

Pierre Fauchais

Begell House
New York • Wallingford (U.K.)

Heat and Mass Transfer under Plasma Conditions

Library of Congress Cataloging-in-Publication Data

International Symposium on Heat and Mass Transfer under Plasma Conditions (1st : 1994 : Çeşme, Turkey)
Heat and mass transfer under plasma conditions : proceedings of International Symposium on Heat and Mass Transfer under Plasma Conditions / edited by Pierre Fauchais.
p. cm.
Includes bibliographical references and index.
ISBN 1-56700-035-5
1. High temperature plasmas--Congresses. 2. Heat--Transmission--Congresses. 3. Mass transfer--Congresses. I. Fauchais, Pierre. II. Title.
QC718.5.H51588 1994
530.4'4--dc20 95-24683
CIP

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Preface

More than 99% of the visible matter in the universe is in the plasma state where it forms the basis of a wide variety of objects and phenomena. This richness of the fourth aggregation state of matter is especially reflected in the wide diversity in plasma transport processes. Transport of particles such as electrons, ions, molecules and radicals and transport of energy, like heat, radiation, ordered and chaotic kinetic energy and internal energy of particles. Transport from one plasma part to the other but also between the plasma and imbedded particulates or between the plasma and the boundary (wall).
In some cases the transport may be described by relatively simple hydrodynamics, in other cases effects of electric and magnetic fields are dominant, while in special situations even a full magneto hydrodynamic treatment taking turbulence on all kind of levels into account, does not lead to a proper understanding of the phenomena.

It is obvious that a fruitful condition is created when experts on the various fields are brought together in order to exchange knowledge as obtained by observational, experimental and theoretical studies. A part from giving scientific satisfaction this will contribute to the insight of plasma engineering problems as well.

This book is the result of the first international symposium on heat and mass transfer under plasma conditions held in Cesme, Turkey July 4-8 1994. The purpose of the symposium was :

- to provide an opportunity for scientists and engineers to present the state-of-the-art,
- to promote exchange of knowledge between experts in the various fields,
- to discuss current problems and research needs.

The program covered novel approaches and recent developments in plasma fundamentals and applications. All speakers were invited. Seventy participants out of twenty countries were present. The presentations were grouped under seven topics each beginning with keynote lectures. The topics discussed were :

1) Plasma Modeling and Characterization (Turbulence, Radiation, EM flow effect).
2) Diagnostic Techniques in Plasma Chemical Applications.
3) Dusty Plasmas and Plasma-Particle Interactions.
4) Plasma-Surface Interactions (Plasma-wall boundary layers, Solid body heating).
5) Non-Equilibrium Effects in Thermal Plasma Systems.
6) Film and Coating Growth (Particulate Nucleation and Rapid Solidification).
7) New branches of Plasma Science and Transport Phenomena.

The organization of this conference would not have been possible without the valuable contribution of Professor Arinç, Chairman of the local organizing committee to whom we are particularly indebted. We would also like to thank all members of the local organizing committee for their efforts and dedication which contributed to the success of this conference. Thanks are due to the Middle East Technical University, Ankara, Turkey and the Scientific and Technical Research Council of Turkey for sponsoring the symposium. We will all cherish the memories of the good time spent together during this week and look forward to meet again at the occasion of the next meeting .

PLASMA MODELING AND CHARACTERIZATION

TURBULENCE MODELLING IN ELECTRIC ARC

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ABSTRACT. This paper describes recent quantitative numerical investigations of turbulence and arc interaction carried out in our laboratories in the frame of industrial applications such as electric arc furnaces and high voltage circuit breakers. The capabilities of k-epsilon models to account for the laminarization process due to large variations of the viscosity is studied in two dimensional axisymetrical stationary simulations of arc flow. A first attempt at modelling the effects of turbulent fluctuations on electrical source terms is also presented. A second order closure model has been used in order to improve the turbulent flux predictions by taking into account the large anisotropy of the turbulent motion. The second part of this paper is devoted to transient and three dimensional electric arcs modelling using direct simulation methodology. Instationary movements of arc due to the self-induced magnetic forces and the influence of fluid flow have been calculated in simple geometry (arcs between plate electrodes). Computations of statistical properties have been performed in order to study the effect of turbulent fluctuations on electric arcs.

1. INTRODUCTION

Numerical investigations of plasma flows has been a growing field of research in the last decade especially in the field of electric arc simulation. But we must notice that many practical characteristics of such flows increase the difficulty in doing numerical predictions, as for instance :

- large variations of the thermodynamic properties (density, specific heat, viscosity...) ;
- presence of both laminar and turbulent regimes in the same flow field ;
- electrical instabilities ;

This paper presents new developments achieved in our laboratories in the field of the numerical modelling of turbulent flows, with a aim of calculating industrial applications of arc such as electric arc furnaces or breakers. First the basic equations used in both two and three dimensional simulations are sketched. Then turbulence modelling and results obtained in two dimensional computations are presented. The last part is devoted to three dimensional transient simulations.

2. BASIC EQUATIONS

Deviations from thermodynamic and ionisation equilibrium due to a high temperature gradient in the fringes of the arc column and near the electrode walls are not taken into account. As a matter of fact, the Local Thermodynamic Equilibrium assumption seems to be acceptable in high pressure high intensity arc columns of industrial configurations studied here. Considering this the following hydrodynamic equations has been solved [1, 2, 16].

Mass balance :

$$\frac{\partial}{\partial t}\rho + \mathrm{div}\,\rho\,\vec{u} = 0$$

where ρ the mass density, and $\vec{u}$ are the local instantaneous velocity.

Momentum balance :

$$\rho \frac{\partial}{\partial t}\vec{u} + \left[\rho \vec{u} . \overrightarrow{grad}\right]\vec{u} = -\overrightarrow{grad} p + div \overleftrightarrow{\tau} + \rho \vec{g} + \vec{j} \wedge \vec{B}$$

where p is the local pressure, g is the gravity acceleration and the last term on the right-hand side of the equation accounts for the electromagnetic forces of Lorentz. τ_{ij} is the momentum diffusion tensor which is written using a dynamic viscosity μ.

Energy balance :

$$\rho \frac{\partial}{\partial t} h + \rho \vec{u}\, \overrightarrow{grad}\, h = \vec{j}.\vec{E} - div \vec{Q} - S_{rad}$$

where h is the enthalpy. The source terms on the right hand side of this equation are Joule heating, thermal diffusion and radiative transfer.

In order to calculate the electromagnetic field, Maxwell's equations have been solved. However, simplified equations may be derived according to the global neutrality assumption and by using the Ohm's law approximation.

Electric charge balance :

$$div\, \vec{j} = 0 \text{ with } \vec{j} = -\sigma\, \overrightarrow{grad}\, V \quad \text{(Ohm's law)}$$

where σ is the electrical conductivity and V the electric potential.
Magnetic field equation :

$$\overrightarrow{curl}\, \vec{B} = \mu_0 \vec{j}$$

In two dimension axisymetrical computations it is solved directly using Ampère's law. In three dimensional simulation, this equation is solved using the magnetic potential vector.

$$\vec{B} = \overrightarrow{curl}\, \vec{A}$$

Finally, the equations set must be completed by a state equation, which allows to compute the local mass density, temperature and transport coefficients (such as the dynamic viscosity and the electrical conductivity) in terms of the pressure and the temperature of the plasma.

3. TURBULENCE MODELLING

The turbulence modelling presented in this part of the paper is based on the numerical predictions of averaged flow properties such as velocity and temperature. In variable density flows, governing equation are generally derived directly from the local instantaneous balance equations of mass, momentum and energy by applying a density-weighted averaging operator (Favre averaging). This averaging process leads to the introduction of further terms in the balance equations, generally diffusive, which account for the transport of mass, momentum and energy by the turbulent motion.

The two equations k-epsilon turbulence model is nowadays extensively used for plasma industrial applications and comparisons with experimental results show that this model allows realistic simulations of mixing of fully turbulent plasmas jets in cold flows [3, 4, 5, 6]. In order to analyse the influence of large density variations, experiments are carried out in our laboratory on the mixing of inert gases with large density differences and experimental results were compared with predictions of a Reynolds stress transport equation model [7]. But turbulence modelling must also account for the transport coefficients dependence on the local temperature as observed in thermal plasma flows. Thus for instance, due to the large variations of the molecular viscosity, both the laminar and turbulent regime may be present in the same flow, when the standard k-ε turbulence model must be used in fully developed turbulent flow regimes.

In the following, the capabilities of different turbulence models to predict electric arc and flow interaction have been studied. Two k-ε (standard and low Reynolds number) and a second order closure based on separate transport equations for turbulent velocity correlations (Reynolds stress) have been tested. A first attempt at modelling the effects of turbulent fluctuations on electrical source terms has been also realised. These studies are initiated in the frame of electric arc furnace modelling where the flow appears in air or in argon. The computations presented here are performed in two dimensional axisymetrical configurations.

3.1 k-epsilon models

Both the standard and low Reynolds k-ε turbulence models are based on the eddy-viscosity assumption. The turbulence velocity correlations appearing in the mean momentum equation writing in a variable density flows is modelled by :

$$\overline{\rho\, u''_i u''_j} = -\mu^t\left[\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right]+\frac{2}{3}\delta_{ij}\left[\bar{\rho}k+\mu^t\frac{\partial U_m}{\partial x_m}\right] \qquad \mu^t = \bar{\rho}C_\mu\frac{k^2}{\varepsilon}$$

where $U_i = \overline{\rho u_i}/\bar{\rho}$ is the Favre-averaging of the i-velocity component and u''_i the corresponding fluctuation. The equations for the turbulent kinetic energy k and its dissipation rate ε writes under the following general forms valid for both models.

Turbulent kinetic energy balance :

$$\bar{\rho}\frac{\partial}{\partial t}k+\bar{\rho}U_j\frac{\partial}{\partial x_j}k = \frac{\partial}{\partial x_j}\left(\bar{\mu}+\frac{\mu^t}{\sigma_k}\right)\frac{\partial}{\partial x_j}k+\mathcal{P}-\bar{\rho}\varepsilon+\Pi_k \qquad \mathcal{P} = -\overline{\rho\, u''_i u''_j}\frac{\partial U_i}{\partial x_j}$$

where $\mathcal{P}$ is the turbulence production rate by the mean velocity gradients.

Turbulence dissipation rate balance :

$$\bar{\rho}\frac{\partial}{\partial t}\varepsilon+\bar{\rho}U_j\frac{\partial}{\partial x_j}\varepsilon = \frac{\partial}{\partial x_j}\left(\bar{\mu}+\frac{\mu^t}{\sigma_\varepsilon}\right)\frac{\partial}{\partial x_j}\varepsilon+\frac{\varepsilon}{k}\left[C_{\varepsilon,1}\mathcal{P}-C_{\varepsilon,2}\bar{\rho}\varepsilon\right]+\Pi_\varepsilon$$

Concerning the mean enthalpy equation the additive diffusion due to velocity-enthalpy correlations term is modelled using a constant turbulent Prandtl assumption (P_r^t).

Finally, the turbulence model contains six empirical constants which are assigned the values given in Table 1.

C_μ	$C_{\varepsilon,1}$	$C_{\varepsilon,2}$	σ_k	σ_ε	P_r^t
0.09	1.44	1.92	1.	1.3	1.

Table 1 : The standard values of the empirical constants
in the high-Reynolds number form of the k-ε turbulence model.

According to Launder and Sharma [8], the form of the standard k-ε model can be enlarged by making the empirical constants functions of the local Reynolds number of turbulence R :

$$C_\mu = 0.09\ \exp\left[-3.4/(1.+R/50.)^2\right] \qquad C_{\varepsilon,2} = 1.92\ \left[1.-0.3\exp(-R^2)\right] \qquad R = \bar{\rho}k^2/\left[\bar{\mu}\varepsilon\right]$$

And in order to provide predictions of the turbulence within the viscous layer adjacent to the wall, further empirical terms Π_k and Π_ε are added in the k-ε transport equations :

$$\Pi_k = -2\bar{\mu}\left[\frac{\partial\sqrt{k}}{\partial x_i}\frac{\partial\sqrt{k}}{\partial x_i}\right] \qquad \Pi_\varepsilon = 2\bar{\mu}\frac{\mu^t}{\bar{\rho}}\left[\frac{\partial^2 U_j}{\partial x_i^2}\frac{\partial^2 U_j}{\partial x_i^2}\right]$$

In the frame of k-epsilon models, a first modelling of turbulent fluctuations in the electrical source terms has been developed using a presumed probability density function (PDF) formalism and assuming that the instantaneous electromagnetic fields are equal to their mean values. The electric field is supposed to have slight fluctuations in comparison with the current density ones, which are driven by the temperature variations through the electrical conductivity dependence. We must notice also that the local instantaneous variations of Lorentz forces are not taken into account in this model. A PDF built with the mean temperature and the variance of the temperature fluctuations is used to model the mean value of the electrical conductivity which affects directly the non-linear source terms of enthalpy and momentum equations.

$$\overline{\vec{j}.\vec{E}} = \overline{\sigma}\,\vec{E}^2 \qquad\qquad \overline{\sigma} = \int \sigma(T)\ \mathrm{pdf}(\,T,\overline{\theta'^2}\,)\,dT$$

A additive transport equation for the variance of the temperature fluctuations is then solved :

$$\overline{\rho}\frac{\partial}{\partial t}\overline{\theta'^2} + \overline{\rho}\,U_j\frac{\partial}{\partial x_j}\overline{\theta'^2} = \frac{\partial}{\partial x_j}\left(\overline{\lambda} + \frac{\mu^t}{\sigma_k}\right)\frac{\partial}{\partial x_j}\overline{\theta'^2} + \overline{\sigma\theta'}\,\vec{E}.\vec{E} \qquad \overline{\sigma\theta'} = \int (T-\overline{T})\ \sigma(T)\ \mathrm{pdf}(\,T,\overline{\theta'^2}\,)\,dT$$

Two PDF, a gaussian and a beta function (like in classical combustion modelling) were tested. But, unfortunately in the case studied (10000 A in air at 1 atmosphere, 20 cm long), the results show with both PDF, a very small deviation of the mean value of the electrical conductivity compared to the conductivity calculated in function of the mean temperature.

a) b)

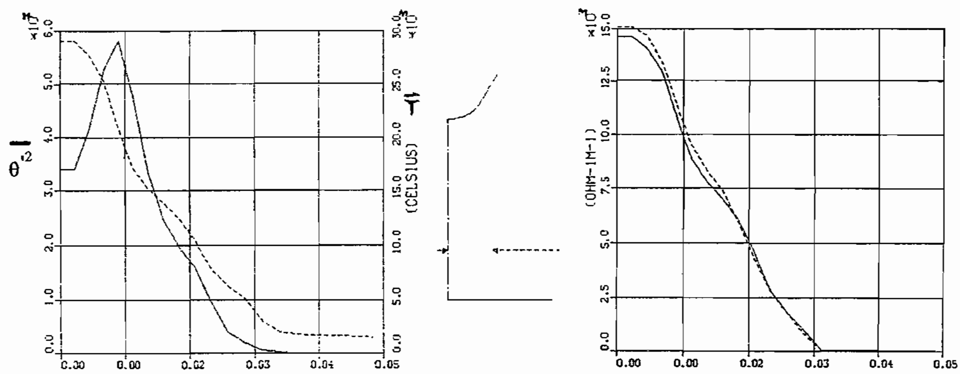


Figure 1 : Radial profiles at 5 cm above the anode of :

a) $\overline{\theta'^2}$ (solid line) and $\overline{T}$ b) $\overline{\sigma}$ (solid line) and $\sigma(\overline{T})$

Electric arc in air at 1 bar, 10000 A, 20 cm long

3.2 Second order closure models (Rij-epsilon model)

A strong limitation of the k-epsilon modelling approach is the eddy viscosity assumption needed for the computations of the turbulent shear stresses. This assumption is questionable when the flow is strongly accelerated and when it impacts against a wall. The second order closure model is based on transport equations for turbulent velocity correlations (Reynolds stress) [9, 10].

$$R_{ij} = \frac{1}{\overline{\rho}}\overline{\rho\, u''_i\, u''_j}$$

$$\overline{\rho}\frac{\partial}{\partial t}R_{ij} + \overline{\rho}\ U_k\frac{\partial}{\partial x_k}R_{ij} = \frac{\partial}{\partial x_k}\left(\overline{\mu} + C_S\,\overline{\rho}\,\frac{k}{\varepsilon}R_{kl}\right)\frac{\partial}{\partial x_l}R_{ij} + \phi_{ij} + \mathcal{P}_{ij} \quad - \overline{\rho}\,\frac{2}{3}\,\varepsilon\,\delta_{ij}$$

The different terms on the right hand side of these equations are diffusion term, pressure-strain correlations, production tensor, and dissipation. The pressure-strain correlations term, which does not appears in k equation, redistributes energy between the various components of Reynolds stress tensor, and corresponds to a return to isotropy. This term is modelled as a sum of a slow and a fast contribution. The fast term $\phi_{ij,2}$ is related to the mean velocity gradient and Reynolds stress while the slow $\phi_{ij,1}$ one is only related to velocity correlations.

$$\phi_{ij,1} = -C_1 \bar{\rho}\frac{\varepsilon}{k}\left(R_{ij} - \frac{2}{3} k\, \delta_{ij} \right) \qquad \phi_{ij,2} = -C_2 \left(\mathcal{P}_{ij} - \frac{1}{3}\mathcal{P}_{mm}\, \delta_{ij} \right)$$

The production tensor is an exact term :

$$\mathcal{P}_{ij} = -\bar{\rho}\left(R_{ik}\frac{\partial U_j}{\partial x_k} + R_{jk}\frac{\partial U_i}{\partial x_k} \right)$$

The dissipation rate equation is written :

$$\bar{\rho}\frac{\partial}{\partial t}\varepsilon + \bar{\rho} U_j \frac{\partial}{\partial x_j}\varepsilon = \frac{\partial}{\partial x_i}\left(\bar{\mu} + C_\varepsilon \bar{\rho}\frac{k}{\varepsilon} R_{ij} \right)\frac{\partial}{\partial x_j}\varepsilon + \frac{\varepsilon}{k}\left[C_{\varepsilon,1}\frac{1}{2}\mathcal{P}_{mm} - C_{\varepsilon,2}\,\bar{\rho}\,\varepsilon \right]$$

C_S	C_1	C_2	C_ε
0.22	1.8	0.6	0.18

Table 2 : The standard values of the empirical constants of the Reynolds stress turbulence model.

3.3 Results

Computations, using both k-ε turbulence and Reynolds stress models, were performed for air and argon free burning arcs under atmospheric pressure. The arc length is 20 centimetres long and the total current intensity is 5000 A. This configuration is closed to arcs found in electric arc furnace used for steel-making. Boundary conditions for the mean velocity, the turbulent kinetic energy and the dissipation rate at the solid boundaries are obtained using a classical wall function method [11].

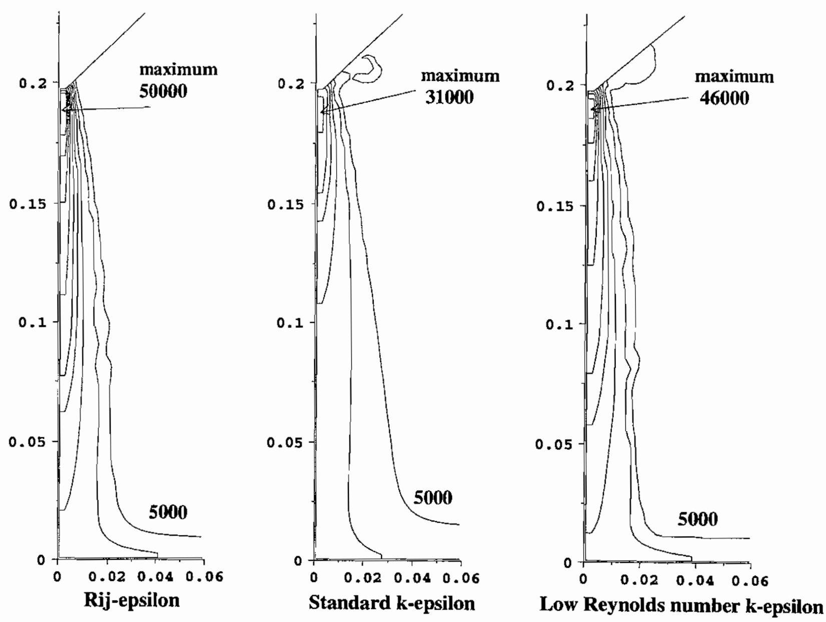


Figure 2: Mean temperature in Celsius predicted by the 3 turbulence models
(isotherms with a step of 5000 Celsius)
A 5000 A, 20cm long arc, in air at 1 bar

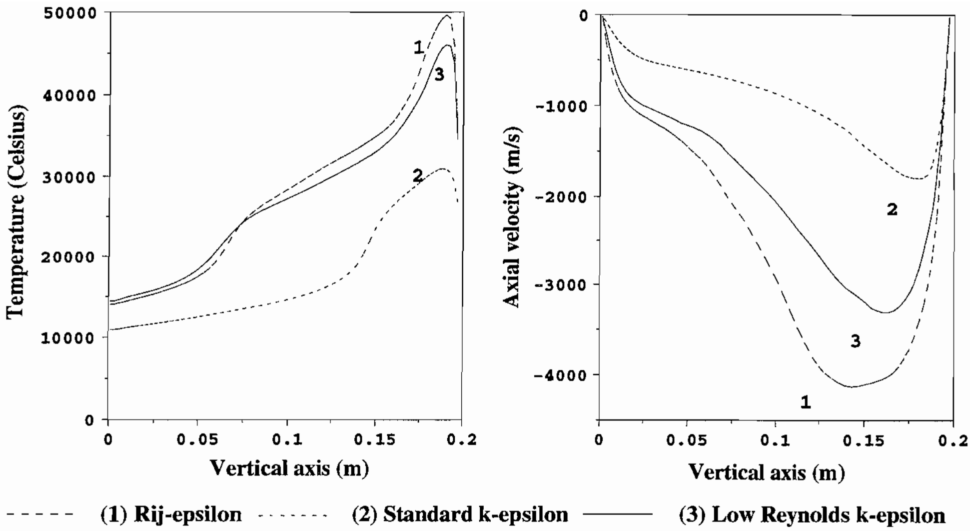


Figure 3: Mean temperature and mean velocity on the axis
A 5000 A, 20cm long arc, in air at 1 bar

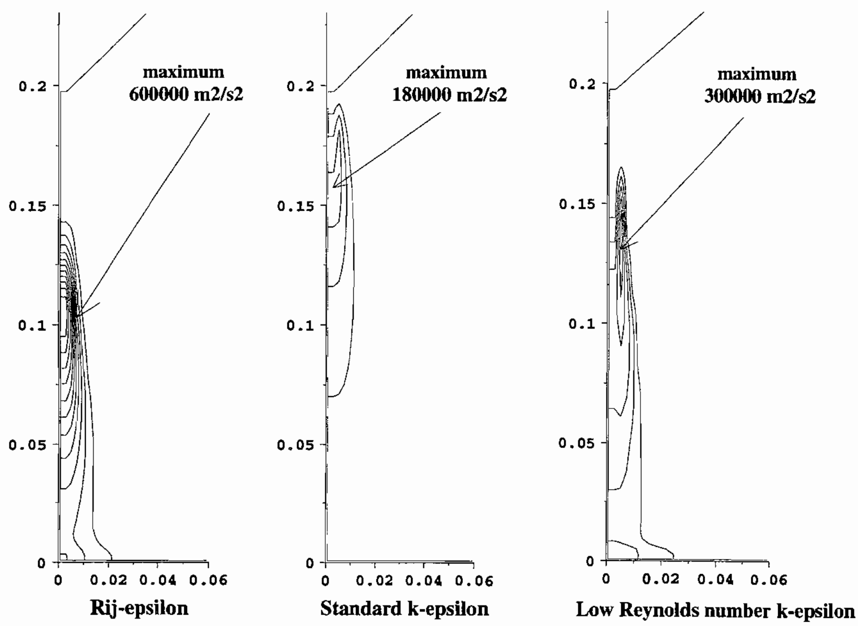
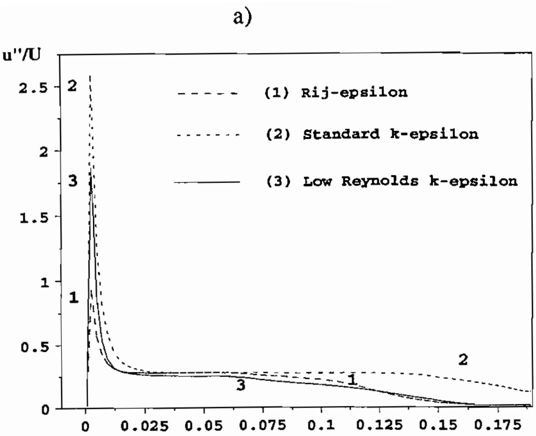
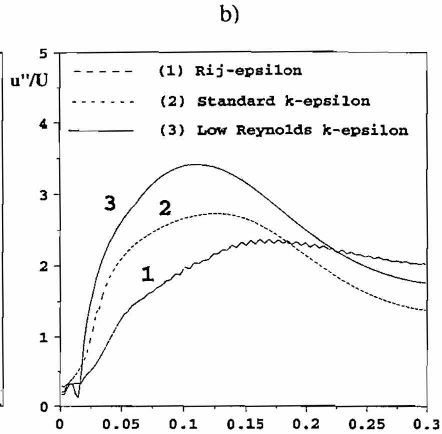


Figure 4: Turbulence energy in m^2/s^2 predicted by the 3 turbulence models
(iso-lines with a step of 50000 m^2/s^2)

The turbulence rate, along the axis and along the radius at about mid-distance from the electrodes are plotted on figures 5. Figures 6 present the axial profile of eddy viscosity, molecular viscosity and diffusivity for the Low Reynolds k-epsilon. The various components of Reynolds stress are sketched on figure 7.





a) along the arc axis b) along the radius at mid-distance from the electrodes (z= 0.11 m)

Figure 5 : Turbulence rate in air (5000 A, 20 cm)

This results show the increase along the vertical axis of the eddy viscosity and turbulence rate predicted by both k-ε models with a maximum in front of the anode. Major discrepancies between the two models correspond to the estimation of these results just downstream the cathode which has an important consequence on the temperature field. The maximum value of the temperature but also the shape of the temperature iso-lines are very different. In this special configuration, the effect of mixing seems to be much more important with the standard k-epsilon model. But in a different cathode configuration, with a total current intensity of 10000 A, the temperature was found to be higher with the standard k-epsilon (the arc was also 20 cm long) [12]. In this configuration, the effect of constriction by the Lorentz forces is found to be very important.

We can notice that, seeing for example figure 5.b, both models predict the lowest turbulence rate in the core of the arc and the highest in the fringes. The results show also that near the cathode, the transport of energy is less affected by the turbulent motion than the transport of momentum. This results are found under the assumption of a constant turbulent Prandtl number which is doubtful in such high temperature flows. This assumption will be avoided in next development by introducing a transport equation for the turbulent heat flux.

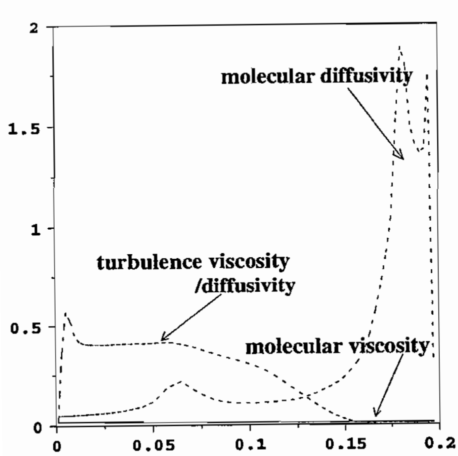


Figure 6 : Viscosities and diffusivities on the arc axis (Low Reynolds model)

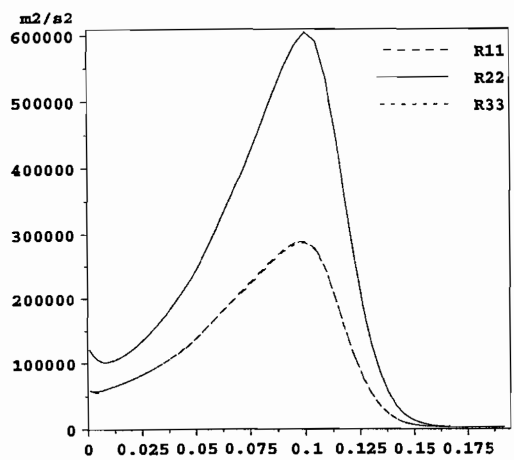


Figure 7 : Reynolds stress tensor components on the arc axis (Rij-epsilon)

Nevertheless, these results showed that the flow is quite turbulent. The comparison with previous results obtained in argon for a completely different arc configuration (300 A, 2.3 cm long) where low Reynolds number model predictions were fully laminar [2], demonstrates the capability of low Reynolds model to take into account the laminarization process. We must notice that in those previous simulations the standard k-epsilon gave higher value of the maximum temperature than the low Reynolds one, at the opposite of the present computations.

Concerning the Rij-epsilon model, the computations presented here have to be related to the standard k-epsilon model results with the aim of comparing two high Reynolds turbulence model. For both models, the turbulent rate along the arc axis is maximum in front of the anode where the plasma jet impinges, but is less important in the case of the Reynolds stress model. In the acceleration region just downstream the cathode, the turbulence rate is also lower than in k-epsilon. This could be probably explain by the effect of production term, exact in Reynolds stress model but modelled in k-epsilon. In the case of impinging jet and acceleration zone the production modelled in k-epsilon is generally overestimated [13].

Calculations performed in argon for the same industrial configuration are also presented. We notice first that the temperatures are lower than in air. The various turbulence models predictions are more closer in the case of argon, but are more or less in accordance with air ones.

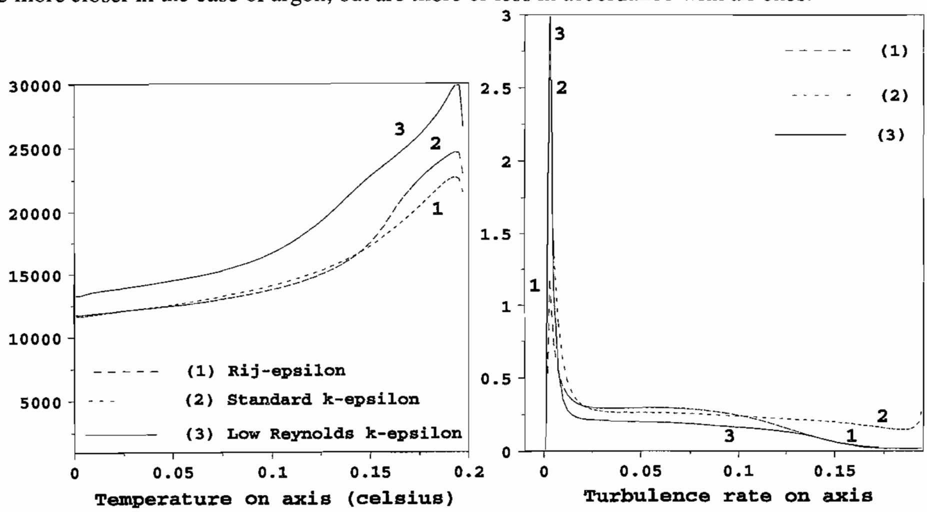


Figure 8 : Mean temperature and turbulence rate on the arc axis (5000 A arc in argon)

4. THREE DIMENSIONNAL TRANSIENT SIMULATION

Considering the poor knowledge about electric arc and flows interaction and especially about turbulence in arcs, and given that movement of arc is transient and three dimensional, the direct simulation methodology is useful to electric arcs modelling. Instationary movements of arc due to the self-induced magnetic forces and the influence of fluid flow have been calculated in simple geometry (arcs between plate electrodes). These studies are initiated in the frame of high voltage circuit breakers modelling where the flow appears in SF_6.

In numerical simulations of electric arcs, the attention has usually been paid to the case of two-dimensional axi-symmetric flows. Unfortunately, a real arc flow is far from perfect axi-symmetric and the interesting case of interaction between an arc and a transversal cannot be studied by such simulations. In that work, which can be considered as a first step in development of tools for three-dimensional transient simulations of electric arcs, the attention was paid to the short time behaviour of electric arcs in interaction with an external flow. Informations are given about the instationary structure of the arc in interaction with a flow driven by a homogeneous pressure gradient. However, some statistics are made and the statistical behaviour of the arcs is also discussed.

4.1 Large Eddy Simulation

In the Direct Simulation formalism, the transport equations for the momentum and energy can be used if all scales in the flow are resolved. If so is not the case, a filtered version of the equations must be considered and the effect of unresolved eddies, so called subgrid scales, on the motion of the resolved part of the flow has to be modelled. This is the Large Eddy Simulation formalism. Since the filtered equations are similar to the above equations except the extra terms that should be modelled, here only the extra terms are presented and a repetition of the equations is avoided. The model used in this work is a modified version of that according to Smagorinsky [14] which takes into account the anisotropy of the computational mesh [15, 16]. The model is moreover formulated for a flow with variable density. If the flux of momentum, due to the motion on subgrid scales, is noted by τ^s_{ij}, the extra term appearing in the left hand side of the transport equation for the momentum is modelled by :

$$\frac{\partial \tau^s_{ij}}{\partial x_j} = - \frac{\partial}{\partial x_j} \mu^t_{jm} \widetilde{d_{im}} \qquad \widetilde{d_{ij}} = \frac{\partial \widetilde{u_i}}{\partial x_j} + \frac{\partial \widetilde{u_j}}{\partial x_i}$$

$$\mu^t_{ij} = - \frac{\widetilde{\rho}}{\sqrt{2}} C_s^2 L_{ij} \sqrt{\widetilde{d_{nm}}\,\widetilde{d_{nm}}} \qquad L_{ij} = \left(\Delta x_1 \Delta x_2 \Delta x_3\right)^{2/9} \left(\Delta x_{[i]}\right)^{4/3} \delta_{[ij]} \qquad C_S = 0.3$$

The above model assumes that there is a similarity between the effects of small eddies on large ones and that of molecular diffusion. In the above formulae $\tilde{u}$ and $\widetilde{\rho}$ are the i-component of the resolved velocity and the resolved density fields, respectively, and $\widetilde{d_{ij}}$ denotes the strain of the resolved velocity field. Δx_1 Δx_2 and Δx_3 denote the resolutions in x_1, x_2 and x_3, respectively, and C_S is the only parameter in the model. Note that in L_{ij} summation with respect to the indices in brackets must be suppressed.

In the similar manner, the energy can be transported by subgrid eddies and their effect on the transport of energy must be modelled. In the present work, a model similar to the one above has been used. The coefficient of subgrid diffusion is found based on the calculated subgrid viscosity and making use of a subgrid Prandtl number Pr^s. The model is formulated as subgrid transport of enthalpy, i.e. if Q^s_j is the subgrid flux of energy, the extra term appearing in the left hand side of the equation of transport of energy will be modelled by :

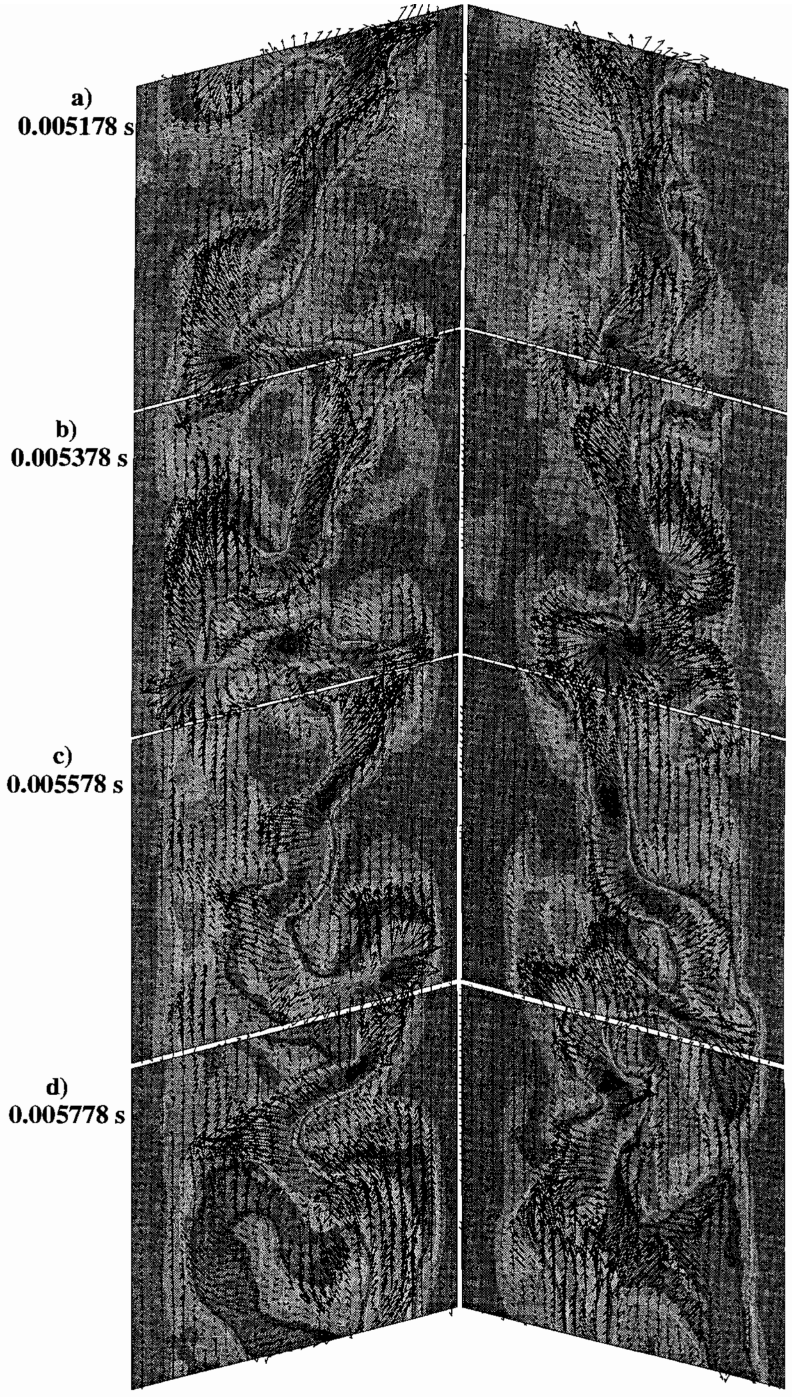
$$\frac{\partial Q^s_j}{\partial x_j} = - \frac{\partial}{\partial x_j} \left[\frac{\mu^t_{jl}}{Pr^s} \frac{\partial \widetilde{h}}{\partial x_l} \right] \qquad Pr^s = 0.25$$

4.2 Application to 3D transient simulation of electric arc.

Results from simulation of a 1000A electric arc in SF_6 are reported. The background pressure is 5 bars. The arc is assumed to burn in a periodic box with the coordinate system denoted by (x_1, x_2, x_3). The computational box is 5 cm x 5 cm x 5 cm which has been discretized using 48 points in x_1 direction, of the arc and 64 points in each of the two other directions, x_2 and x_3. The current passes from one x_2x_3 plane to the other, i.e. the x_1 coordinate coincides with the mean axis of the arc. The flow is driven by a homogeneous pressure gradient of 1 bar/m in the same direction as that of the electrical current.

Figure 9 illustrates an instantaneous picture of the arc and it's surrounding flow. In experimental observations, usually the most visible parts of the plasma are those with the highest temperature. In accordance with that, figure 9 is generated by projection of the value of the field variables at the hottest points on the vertical planes. The colouring is based on the enthalpy distribution, the arrows show the velocity field.

According to figure 9, the center of the arc, where the gas is hot and the molecular viscosity and diffusivity are not negligible, is not quiescent but on the contrary is likely to be the source of an irregular motion which in interaction with the flow generates a turbulent like flow pattern.

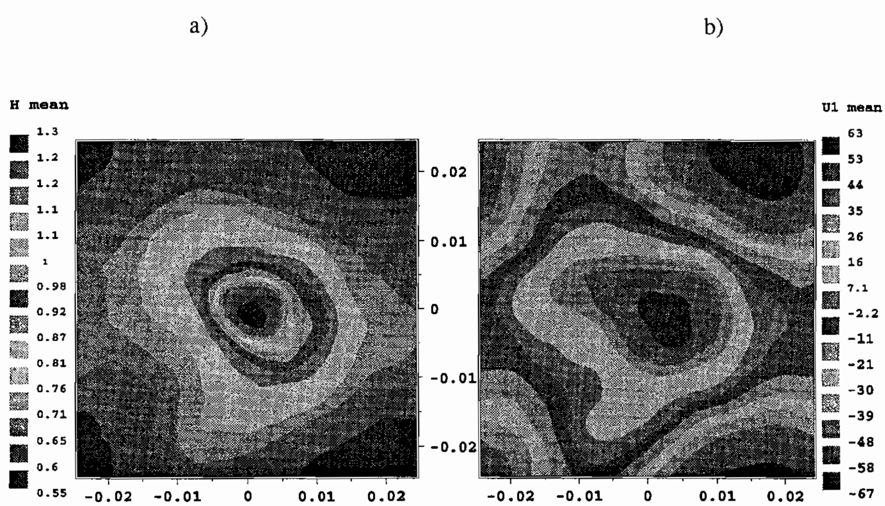


Figures 9 : Three dimensional motion of an arc in SF_6. The total current is 1000 A, and the arc is influenced by a constant pressure gradient (1 bar/m) in the vertical direction.

In figures 9.a-9.d the instantaneous picture of the arc is presented at four different instants of time with a time difference of 2 10^{-4} s. It is worth noting that despite the short time scale, sufficient changes in the shape of the arc can be observed. Specially the attention must be paid to 9.b and 9.c which show the moment before and after the formation of a loop, short circuit of the arc and finally radiative loss of energy in the part of plasma where the Joule effect disappears. It is worth noting that such changes cause a fast displacement of the source of energy, the Joule dissipation, and perturb the balance of energy.

The statistical behaviour of the arc is studied by means of averaged fields and second order moments. The averaging process was chosen to be that according to Favre. In addition to averaging in time, it was found to be necessary to even integrate the variables in at least one homogeneous spatial direction. The first method was to integrate in x_1 direction in addition to in time. But as the position of the arc is not fixed in the space and moves freely, a long time average of any quantity results in a constant value in the computational box. Another noteworthy point is that the maximum value of the mean enthalpy is lower than what is required for SF_6 to be conductive. This effect is due to that the axis of the arc is not very well defined when the arc has a complex topology and is making loops such as those observed in figures 9.a-9.d. In order to make a correction for that, the position of the axis of the arc, at each x_2x_3 plane, has been defined as the weighted average of the positions of the conductive parts of the gas. The weighting function has been chosen such that the hot points are weighted more than the cold ones. For simplicity, in what follows, the quantities obtained by the second method is called 'arc-averaged' quantities.

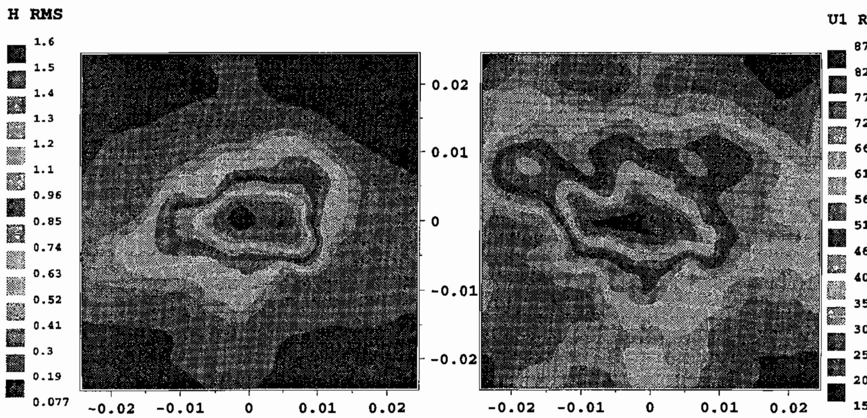
Figures 10.a and 10.b present the arc-averaged enthalpy field and the mean velocity distribution around the axis of the arc. A comparison between enthalpy field and current density distributions indicate that the current density field is very well correlated with the enthalpy field and decreases fast with the distance from the axis of the arc.



Figures 10 : arc-averaged a) enthalpy field (10^{-7} J/kg) b) velocity (m/s)

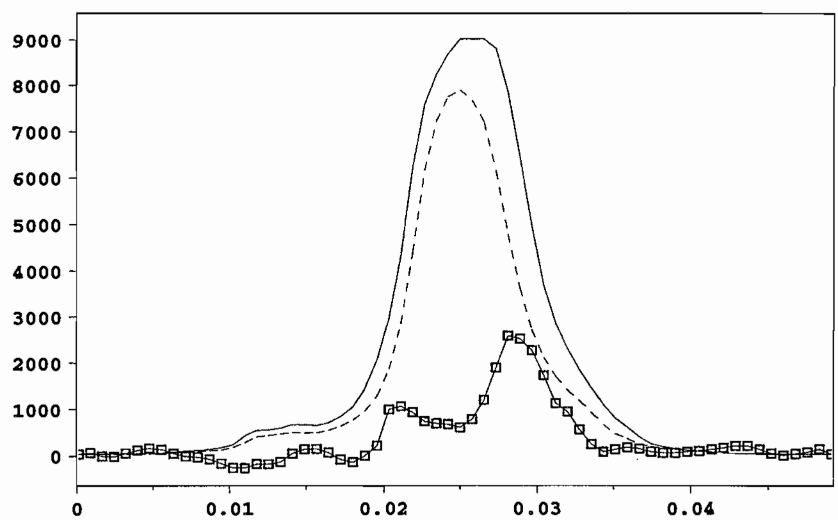
Fluctuating parts of the arc-averaged enthalpy and streamwise velocity are presented in figures 11.a-11.b, respectively. According to that figure the fluctuations are strongest on the axis of the arc. A fact which would not be expected if the fluctuations were generated by shear layers near the edge of the arc. A closer look to figure 9 suggests that, unlike the case of turbulent diffusion of a source of energy, the core of the arc is very active and is generating disturbances due to electrical source terms.

a) b)



Figures 11 : arc-averaged fluctuations a) enthalpy field b) streamwise velocity (m/s)

Figure 12 compares the mean Joule term with the mean radiative loss of energy and the divergence of the turbulent flux of energy. The two first terms are of the same order of magnitude. But the part of energy which is not dissipated by radiation is transported out by turbulent fluctuations.



Figures 12 : Balance of energy
(*solid line* : Joule effect, *dashed line* : radiative loss, *squares* : turbulent transport)

These results show that the flow, which is found to have a turbulent like pattern, is strongly driven by source terms, i.e. the Joule heating, the Lorentz forces and also the radiative loss of energy which is particularly important in SF_6. The axi-symmetrical geometry of the arc does not seem to be stable but it tends to oscillate in space and time. An important remark is that the core of the arc is not standing still but there is strong activity both in form of temperature and velocity fluctuations. The fluctuations inside the core of the arc do not seem to be generated at it's edge. As a consequence turbulent arc models must be constructed with respect to the physics of the arc, especially the electrical source terms, Lorentz forces and the Joule effect, which also have a non-linear behaviour must be included in the model. A noteworthy fact is that the above mentioned terms are important in the core of the arc where the shearing effects are negligible and the molecular diffusivity and viscosity are important.

Another characteristic behaviour of the arc-flow interaction is that there are events of completely different time scales. The velocity inside the arc is at least one or two orders of magnitude larger than that outside in the cold gas. The changes of the geometry of the arc occur on a much shorter time scale and finally events such as reconnection of the arc plasma and fast changes in the current path happen at even shorter time scale.

Simulations such as those reported here permit a detailed investigation of the structure of electric arcs in interaction with the flow. For applications like high voltage circuit breakers, knowledge about the fine structure of electric arcs with a short time scale is needed in addition to long time, mean characteristics of the flow. That is due to the fact that the long time scale is responsible for changes in the fluid flow while interruption of the electrical current appears on a short time scale. The results discussed above give information about the dynamics of arcs on a time scale relatively short compared to that of the flow. Although attempts have been done in order to study the statistical structure of the arc, unfortunately, it must be noted that, due to the topological complex structure of the arcs, the statistics presented here must be interpreted with special attention. The latter point, the statistical structure of electric arcs, is still to be studied in more detail. Moreover, a systematic parameter study is required for an accurate modelling of electric arcs and their interaction with the flow of the gas.

5. CONCLUSION

This paper presents modelling attempts related to high pressure arc plasma with the aim of investigating turbulence and electric arc interaction. First, two dimensional stationary electric arcs computations results including a turbulence model have been performed in the frame of industrial applications such as electric arc furnaces. Two-equation turbulence models (k-epsilon models) and a second order closure model based on separate transport equations for turbulent velocity correlations (Reynolds stress) have been tested. The laminarization process due to large variations of the viscosity seems to be predicted by the low Reynolds k-epsilon model. Calculations performed with the Reynolds stress model lead to a lower turbulence rate than k-epsilon in acceleration zone just downstream the cathode and in the impinging jet zone near the anode. The interpretation of the computations obtained with these classical turbulence models is very difficult because, unfortunately today, experimental validations are not possible because of the lack of measurements in industrial arc configurations especially for turbulence. That is why Large Eddy Simulation methodology is useful for electric arc modelling and knowledge.

In order to provide a set of data to be used for modelling the effect of turbulent fluctuations on electric arcs, transient and three dimensional Large Eddy Simulation of electric arcs have been developed with the aim of high voltage circuit breakers simulations. The movement of the arc takes place in a very short characteristic time and seems to be mainly driven by the Lorentz forces. The fluctuating motion is very high in the core of the arc where the flow is usually supposed to be laminar. Such fluctuations seem to be generated by Lorentz forces and not by shear layer like in classical turbulence.

Considering those results, it seems to be interesting to continue in the same way, the two different simulations approaches presented here, in order to improve electric arc fluctuations modelling.

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