Three-dimensional effects in the modelling of ICPTs

Part I: Fluid dynamics and electromagnetics

D. Bernardi, V. Colombo, E. Ghedini, and A. Mentrelli

Dipartimento di Ingegneria delle Costruzioni Meccaniche, Nucleari, Aeronautiche e di Metallurgia (D.I.E.M.) and C.I.R.A.M., Università degli Studi di Bologna, Via Saragozza 8, 40123 Bologna, Italy

Received 22 May 2003
Published online 5 August 2003 – © EDP Sciences, Società Italiana di Fisica, Springer-Verlag 2003

Abstract. In this paper, we numerically investigate the 3-D effects of different flow operating conditions and of complete or simplified treatments of the electromagnetic field on the characteristics of Ar and Ar/N₂ discharges in inductively coupled plasma torches working at atmospheric pressure. Simulations are performed by means of the commercial code FLUENT® suitably customized to solve the electromagnetic field equations in the frame of an extended grid model. Steady state continuity, momentum and energy equations are solved for optically thin plasmas under the assumption of LTE and laminar flow. Results of parameterization on the net amount of power dissipated in the discharge, frequency of the RF generator, flow rate distribution of inlet gases and swirl velocity are presented, showing the impact of these parameters on the fluid dynamic and electromagnetic behaviour of the plasma.

PACS. 52.75.Hn Plasma torches – 52.65.-y Plasma simulation – 52.80.Pi High-frequency and RF discharges

1 Introduction

Modelling is a useful tool to investigate the characteristics of inductively coupled plasma torches, since an accurate characterization of the plasma discharge by means of typical diagnostic methods is very difficult to perform, especially for what concerns the flow field. Numerical modelling of this kind of devices involves the coupled solution of the fluid dynamic, energy and electromagnetic field equations for the plasma. The authors have recently developed a fully 3-D model [1–4] in the framework of the FLUENT® code to remove the axisymmetry assumption, which is the fundamental hypothesis of all the previous 2-D models [5–8], with the aim of predicting the non-axisymmetric effects induced by the actual shape of the induction coil. Apart from the increase in computational effort and in the number of governing scalar equations, the 3-D extension of the previous 2-D models implies that also the scalar potential must be taken into account, due to the presence of a space-varying electrical conductivity in the plasma discharge [9]. In this paper, we show the impact on the solution of using either a simplified or a complete electromagnetic model, taking into account or neglecting the scalar potential. Moreover, a parameterization on the net amount of power dissipated in the discharge and on the working frequency of the RF generator is performed.

Investigations on the plasma fluid dynamics are carried out for different distributions of inlet gas flow rates and swirl velocity magnitude and direction, in order to highlight the effects of such parameters on the 3-D behaviour of the discharge. Finally, a comparison of results obtained using pure argon and Ar/N₂ mixture as plasma gas is performed.

In the second part of this work [3], the attention will be focused on the impact of different coil shapes and torch geometries on the characteristics of pure argon discharges. Simulation results will be presented for conventional helicoidal, planar and double-stage coil configurations and for a torch with elliptical cross-section. Moreover, the effects of reducing the post-coil length on plasma temperature and velocity distributions will be shown for the same torch geometry considered in this paper.

2 Torch geometry and mathematical model

Torch geometry (referring to Tekna Plasma Systems Inc., PL-50 model) and common operating conditions employed in the following simulations are shown in Figure 1. Corresponding dimensions are summarized in Table 1. The complete electromagnetic field approach includes the 3-D governing equations for the vector potential,
The simplified electromagnetic model for an argon operated torch with net power dissipated in the discharge \( P = 25 \) kW and without inlet gas swirl velocity are shown in Figure 2, in order to introduce a reference case to which compare the other results. In particular, Figures 2a and 2c show a strong non axisymmetry of the discharge and a maximum of the plasma temperature located near the quartz confinement tube. The effects of using the complete electromagnetic model are shown in Figure 3, for the same operating conditions of the previous case. Plasma temperature differences between the two cases are negligible, while the tangential velocity obtained using the complete model reduces its magnitude with respect to that calculated with the simplified one. Real and imaginary components of the electric charge density distribution that arises because of the plasma conductivity gradient is shown in Figure 4. Electric charges are mainly located in the regions where the maximum values of the gas temperature gradient occur. Corresponding scalar potential fields, whose source is the charge density, are shown in Figure 5. Temperature fields obtained introducing a swirl velocity component \( v_{s} = \pm 20 \) m/s in the sheath gas, are presented in Figure 6, showing that the presence of such component induces a better confinement of the plasma discharge with respect to the previous cases, and that the maximum temperature zone is far from the quartz tube, avoiding the risk of its melting. Figure 6 puts also into evidence that a change in the swirl direction of the sheath gas leads to much different results in the temperature fields at the torch exit and in the upstream region of the discharge, as a consequence of the complex 3-D fluid dynamic phenomena that occur in the torch. As an alternative to the previous case, a swirl component \( v_{wp} = \pm 20 \) m/s is applied to the plasma gas; corresponding results are reported in Figure 7, showing a lower efficiency in the discharge confinement with respect to the case with swirl velocity component in the sheath gas. Reducing the power dissipated in the discharge to a value of 15 kW, with a swirl component in the sheath gas \( v_{wp} = +10 \) m/s, leads to the results of Figures 8 and 9, corresponding, respectively, to the cases with and without carrier gas. The effects of an increase in the RF generator frequency from

**3 Selected results**

Where not specified, the results presented here refer to two perpendicular planes passing through the axis of the torch, whose relative position is evidenced by coil view. In the following, \( P \) denotes the net amount of power dissipated in the discharge, \( f \) is the frequency of the RF generator, while \( Q_{1}, Q_{2}, Q_{3} \) are the carrier, plasma and sheath gas flow rates, respectively. For each case, detailed operating conditions are summarized in the corresponding figure caption. Plasma temperature and velocity fields calculated within the framework of the simplified electromagnetic model for an argon operated torch with net power dissipated in the discharge \( P = 25 \) kW and without inlet gas swirl velocity are shown in Figure 2, in order to introduce a reference case to which compare the other results. In particular, Figures 2a and 2c show a strong non axisymmetry of the discharge and a maximum of the plasma temperature located near the quartz confinement tube. The effects of using the complete electromagnetic model are shown in Figure 3, for the same operating conditions of the previous case. Plasma temperature differences between the two cases are negligible, while the tangential velocity obtained using the complete model reduces its magnitude with respect to that calculated with the simplified one. Real and imaginary components of the electric charge density distribution that arises because of the plasma conductivity gradient is shown in Figure 4. Electric charges are mainly located in the regions where the maximum values of the gas temperature gradient occur. Corresponding scalar potential fields, whose source is the charge density, are shown in Figure 5. Temperature fields obtained introducing a swirl velocity component \( v_{s} = \pm 20 \) m/s in the sheath gas, are presented in Figure 6, showing that the presence of such component induces a better confinement of the plasma discharge with respect to the previous cases, and that the maximum temperature zone is far from the quartz tube, avoiding the risk of its melting. Figure 6 puts also into evidence that a change in the swirl direction of the sheath gas leads to much different results in the temperature fields at the torch exit and in the upstream region of the discharge, as a consequence of the complex 3-D fluid dynamic phenomena that occur in the torch. As an alternative to the previous case, a swirl component \( v_{wp} = \pm 20 \) m/s is applied to the plasma gas; corresponding results are reported in Figure 7, showing a lower efficiency in the discharge confinement with respect to the case with swirl velocity component in the sheath gas. Reducing the power dissipated in the discharge to a value of 15 kW, with a swirl component in the sheath gas \( v_{wp} = +10 \) m/s, leads to the results of Figures 8 and 9, corresponding, respectively, to the cases with and without carrier gas. The effects of an increase in the RF generator frequency from

**3 Selected results**

Where not specified, the results presented here refer to two perpendicular planes passing through the axis of the torch, whose relative position is evidenced by coil view. In the following, \( P \) denotes the net amount of power dissipated in the discharge, \( f \) is the frequency of the RF generator, while \( Q_{1}, Q_{2}, Q_{3} \) are the carrier, plasma and sheath gas flow rates, respectively. For each case, detailed operating conditions are summarized in the corresponding figure caption. Plasma temperature and velocity fields calculated within the framework of the simplified electromagnetic model for an argon operated torch with net power dissipated in the discharge \( P = 25 \) kW and without inlet gas swirl velocity are shown in Figure 2, in order to introduce a reference case to which compare the other results. In particular, Figures 2a and 2c show a strong non axisymmetry of the discharge and a maximum of the plasma temperature located near the quartz confinement tube. The effects of using the complete electromagnetic model are shown in Figure 3, for the same operating conditions of the previous case. Plasma temperature differences between the two cases are negligible, while the tangential velocity obtained using the complete model reduces its magnitude with respect to that calculated with the simplified one. Real and imaginary components of the electric charge density distribution that arises because of the plasma conductivity gradient is shown in Figure 4. Electric charges are mainly located in the regions where the maximum values of the gas temperature gradient occur. Corresponding scalar potential fields, whose source is the charge density, are shown in Figure 5. Temperature fields obtained introducing a swirl velocity component \( v_{s} = \pm 20 \) m/s in the sheath gas, are presented in Figure 6, showing that the presence of such component induces a better confinement of the plasma discharge with respect to the previous cases, and that the maximum temperature zone is far from the quartz tube, avoiding the risk of its melting. Figure 6 puts also into evidence that a change in the swirl direction of the sheath gas leads to much different results in the temperature fields at the torch exit and in the upstream region of the discharge, as a consequence of the complex 3-D fluid dynamic phenomena that occur in the torch. As an alternative to the previous case, a swirl component \( v_{wp} = \pm 20 \) m/s is applied to the plasma gas; corresponding results are reported in Figure 7, showing a lower efficiency in the discharge confinement with respect to the case with swirl velocity component in the sheath gas. Reducing the power dissipated in the discharge to a value of 15 kW, with a swirl component in the sheath gas \( v_{wp} = +10 \) m/s, leads to the results of Figures 8 and 9, corresponding, respectively, to the cases with and without carrier gas. The effects of an increase in the RF generator frequency from

**3 Selected results**

Where not specified, the results presented here refer to two perpendicular planes passing through the axis of the torch, whose relative position is evidenced by coil view. In the following, \( P \) denotes the net amount of power dissipated in the discharge, \( f \) is the frequency of the RF generator, while \( Q_{1}, Q_{2}, Q_{3} \) are the carrier, plasma and sheath gas flow rates, respectively. For each case, detailed operating conditions are summarized in the corresponding figure caption. Plasma temperature and velocity fields calculated within the framework of the simplified electromagnetic model for an argon operated torch with net power dissipated in the discharge \( P = 25 \) kW and without inlet gas swirl velocity are shown in Figure 2, in order to introduce a reference case to which compare the other results. In particular, Figures 2a and 2c show a strong non axisymmetry of the discharge and a maximum of the plasma temperature located near the quartz confinement tube. The effects of using the complete electromagnetic model are shown in Figure 3, for the same operating conditions of the previous case. Plasma temperature differences between the two cases are negligible, while the tangential velocity obtained using the complete model reduces its magnitude with respect to that calculated with the simplified one. Real and imaginary components of the electric charge density distribution that arises because of the plasma conductivity gradient is shown in Figure 4. Electric charges are mainly located in the regions where the maximum values of the gas temperature gradient occur. Corresponding scalar potential fields, whose source is the charge density, are shown in Figure 5. Temperature fields obtained introducing a swirl velocity component \( v_{s} = \pm 20 \) m/s in the sheath gas, are presented in Figure 6, showing that the presence of such component induces a better confinement of the plasma discharge with respect to the previous cases, and that the maximum temperature zone is far from the quartz tube, avoiding the risk of its melting. Figure 6 puts also into evidence that a change in the swirl direction of the sheath gas leads to much different results in the temperature fields at the torch exit and in the upstream region of the discharge, as a consequence of the complex 3-D fluid dynamic phenomena that occur in the torch. As an alternative to the previous case, a swirl component \( v_{wp} = \pm 20 \) m/s is applied to the plasma gas; corresponding results are reported in Figure 7, showing a lower efficiency in the discharge confinement with respect to the case with swirl velocity component in the sheath gas. Reducing the power dissipated in the discharge to a value of 15 kW, with a swirl component in the sheath gas \( v_{wp} = +10 \) m/s, leads to the results of Figures 8 and 9, corresponding, respectively, to the cases with and without carrier gas. The effects of an increase in the RF generator frequency from