Paper presented at the 4th International Symposium on plasma chemistry, Zurich, Switzerland, August 27-Sept. 1st (1979), ISPC-4, 1, 195-203 (1979). CONF-790867--2

CONF-790867--2

DE84 012339

FLOW AND TEMPERATURE FIELDS IN A FREE DISCHARGE INDUCTIVELY COUPLED PLASMA

Ronald Gagné and Maher I. Boulos
University of Sherbrooke, Department of Chemical Engineering
Sherbrooke, Quebec, J1K 2R1, Canada

Ramon M. Barnes
University of Massachussetts, Department of Chemistry
Amherst, Mass. 01003, U.S.A.

AC02-77EV04320

Keywords: Induction Plasma.

ABSTRACT

Computations were made of the flow and temperature fields in an inductively coupled argon plasma at atmospheric pressure under confined and free discharge conditions. The model takes into account gravity effects and swirl in the sheath gas. Natural convection was found to have a negligible effect on the flow and temperature fields under confined discharge conditions but a significant effect for the free discharge. The back flow in the discharge was substantially reduced in the presence of swirl for swirl velocities over the range 0-50 m/s. Also with a moderate increase in swirl, the conduction heat flux to the wall decreased but increased with the further increase in swirl. From an overall energy balance point of view, conductive heat flux to the wall of the plasma confinement tube was substantially lower for a free plasma discharge compared to that for a confined plasma.

1. INTRODUCTION

A special attention has been given over the last few years to the development of computer models for the calculation of the flow and temperature fields in an inductively coupled r.f. plasma (ICP) under different operating conditions. These varied from relatively simple one-dimensional models such as those of Mensing and Boedeker (1) and Primore-Brown (2), which calculated the radial temperature profiles by an energy balance between the local heat generation and heat losses by conduction and radiation, to the more elaborate two-dimensional models such as those of Miller and Ayen (3), Delettrez (4), Barnes and Schleicher (5) Barnes and Nikdel (6), and Boulos (7,8), which took into account the effect of convective heat transfer on the temperature field.

The present investigation was specifically carried out to:

1. Improve the computational procedure of the model proposed by Boulos (7).
2. Extend this model to include gravity and sheath gas and swirl.
3. Determine the effects of natural convection, swirl, and wall confinement on the flow and temperature fields.

2. MATHEMATICAL MODEL

1. Torch geometry: The torch geometries used in the present calculations are shown in Figure 1. The confined plasma torch in Figure 1-a was composed of a 150-mm long quartz tube, 30 mm I.D. with 1.5 mm wall thickness. The 33-mm long induction coil had a diameter of 42 mm. Its leading edge was placed 15 mm downstream of the torch gas inlet. Three gas streams introduced to the torch are represented by Q_1, Q_2 and Q_3 for the central carrier, intermediate and sheath gas, respectively. The free plasma torch in Figure 1-b had essentially the same dimensions as the confined plasma torch except that the plasma confining tube extended only 15 mm downstream of the coil. Beyond this point the argon plasma immerged as a free jet in ambient argon atmosphere.

2. Governing equations: The flow and temperature fields in the torch were calculated by solving the continuity, momentum and energy equations simultaneously with the electric and magnetic fields equations. The following assumptions were made.

1. Axially symmetric system of coordinates with two-dimensional flow and temperature fields and one-dimensional electric and magnetic fields.

2. Steady state, laminar, compressible flow with negligible viscous dissipation.

3. Local thermodynamic equilibrium.

4. Optically thin plasma with the radiation heat losses treated as a volumetric heat sink.

The equations were essentially the same as those used by Boulos (7) except for the addition of gravity and swirl terms in the momentum transfer equation and an extra equation for the swirl momentum transfer. Details of the equations and the numerical procedure can be found elsewhere (9).

3. RESULTS AND DISCUSSION

Calculations were made for an argon plasma at atmospheric pressure. The operating conditions were as follows.

Oscillator frequency	$f = 3$ MHz
Number of coil turns	$N = 4$
Total discharge power	$P_{t_0} = 3$ kW
Total plasma gas flow rate	$Q_0 = 20$ l/min

Q_0, was devided between the intermediate and sheath gas only, with Q_1=0, Q_2= 2 l/min and Q_3= 18 l/min respectively. The average swirl velocity at the inlet of the torch, $\bar{v}_\Theta$, was varied over the range 0-50 m/s.

I. Confined plasma calculations. The streamlines and temperature contours obtained for a confined plasma oriented vertically downwards in the absence of swirl ($\bar{v}_\Theta$=0) were essentially similar to those obtained earlier by Boulos (7). While present calculations were made including the gravity term in the momentum transfer equations, its effect seems negligible in this case. In order to determine the effect of sheath gas swirl on the flow and temperature fields in the torch, calculations were repeated under the same operating conditions with inlet average swirl velocities of 10, 20 and 30 m/s respectively. Typical results for a swirl of 10 m/s are shown in Figure 2.

In Figure 2-c as the gas enters the torch the swirl velocity component of the sheath gas drops rapidly from a maximum value of 19.8 m/s to less than 12 m/s in about 15 mm. Swirl velocities as high as 19.6 m/s reappear, however, futher downstream around the center of the coil due to the constriction of the flow field by the inwards electromagnetically induced flow. This effect is typical of vortex tube behavior. Further downstream, the swirl velocity decrease monotonously to about 2.4 m/s close to the exit of the torch at z/R_0=9.

In the presence of a swirl of 10 m/s, the circulation eddy in the fire-ball moves outwards closer to the wall of the plasma confining tube (Figure 2-a) and the velocity of the back flow along the centerline of the torch decreases from 12 m/s, to only 7.2 m/s. A similar reduction in the centerline gas velocity is also observed on the downstream end of the coil. With further increase in swirl, the back flow in the discharge drops systematically to less than 3 m/s at an average swirl velocity of 30 m/s. The effect however, seems to be limited to the neighbourhood of the axis of the torch, $0 < r/R_0 < 0.3$.

This observation is particularly important with regard to the feeding of powders in the fire-ball of the plasma. Obviously, the reduction in the back flow velocity due to the presence of swirl would make penetration of the discharge easier for the particles instead of bouncing off as noted by Chase (10) and Boulos (8) in the absence of swirl. The effect of swirl on plasma ignition and total gas consumption has also been described (11).

The temperature contours in the discharge zone in the presence of swirl is given in Figure 2-b. From a comparison of these contours with those in the absence of swirl, a slight increase in the diameter of the discharge at the center of the coil appears. In contrast virtually no effect of the swirl on the temperature contours occurs in the tail flame. While the effect of swirl on the radial temperature profiles seems relatively small, swirl can have a strong effect on the heat flux distribution at the wall. With the increase in swirl, the heat flux to the wall on the upstream side of the coil increases substantially, while it proportionally drops on the downstream side of the coil for $2 < z/R_0 < 6$. Further downstream swirl has no influence on the heat flux to the wall over the swirl velocity range investigated. From an overall energy balance, swirl has only a small effect on the fraction of the total plasma power that is lost to the walls by conduction as noted from Table 1.

2. Free plasma calculations. Typical streamlines, temperature and swirl contours obtained for a free plasma oriented vertically upwards with an average inlet swirl velocity in the sheath gas of 10 m/s are presented in Figure 3. The plasma confining tube has the same diameter as that of the confined plasma but extended only 15 mm beyond the end of the induction coil. At this position the plasma emerged as a free jet in the ambient atmosphere which was assumed to be the same as the plasma gas.

The flow field upstream of the induction coil (Figure 3-a) is similar to that obtained for the confined plasma under the same operating conditions. The recirculation eddy gives rise to a back flow of 4.7 m/s. The inward electromagnetically induced flow around the center of the coil has a velocity of about 5 m/s, while the centerline axial velocity of the gases on the downstream side of the coil was about 14.5 m/s. Beyond the confinement region, $z/R_0 > 4.2$, the hot plasma gas streams vertically upwards entraining a substantial amount of ambient gas. As shown in Figure 3-a, the mass flow rate of the entrained gas can be even larger than that of the plasma gas itself. The entrained gas, however, does not mix with the plasma tail flame and does not influence the centerline axial velocity. In contrast, the reduction of the shear stress around the edge of the fire-ball as well as buoyancy effects gives rise to higher axial gas velocities over this region.

The swirl field for a free plasma given in Figure 3-c shows an initial drop in v_Θ from 19.8 to less than 12 m/s in the first 15 mm of the torch. This is followed by a slight increase in swirl as a result of the constriction of the flow. However, before the plasma immerges from the confining tube, its swirl velocity component decays considerably from its initial value. Corresponding to results for the confined plasma, results obtained at different average inlet swirl velocities showed that the back flow velocity in the discharge decrease systematically with the increase of the swirl. However, even with a swirl of 50 m/s, a slight back flow was still detectable in the fire-ball. Similar trends were measured experimentally by Genna et al (11).

It is noticed from Figure 3-b that there is relatively little change in the temperature contours in the coil region. The radial temperature profiles and the heat flux to the wall under confined and free plasma conditions are essentially identical. However, owing to the much shorter plasma confining tube, the integral conductive heat loss of a free discharge is less than that for the confined case. As indicated in Table 1 only 8% of the total plasma power is lost by conduction to the wall for the free discharge, compared to 30% for the confined plasma. The difference appears in the exit gas enthalpy since radiation losses in both cases are hardly affected.

As the gas emerges from the plasma confining tube, it heats up the ambient atmosphere giving rise to its typical laminar flame shape which is strongly influenced by natural convection effects.

4. CONCLUSION

1. Natural convection has a negligible effect on the flow and temperature fields under confined discharge conditions but a significant effect for the free discharge.

2. The back flow velocity on the upstream side of the fire-ball decreases with the increase of sheath gas swirl.

3. Under identical operating conditions, the total conductive heat loss to the walls for a free plasma is much less than that for a confined plasma.

ACKNOWLEDGMENT

This work was supported by the Department of Energy (Office of Basic Energy Sciences) through contract EE-77-S-02-4320. The support of R.G. by the Ministry of Education of the Province of Quebec is gratefully acknowledged.

NOMENCLATURE

f	Oscillator frequency, Hz
L_T	Total length of the plasma confining tube, m
N	Number of coil turns
P_{t_0}	Total plasma power, W
q_c	Percent of the plasma power lost by conduction
q_r	Percent of the plasma power lost by radiation
q_h	Percent of the plasma power remaining in the gas at the exit of the confinement tube
Q_0	Total plasma gas flow rate, l/min
r	Distance in the radial direction, m
R_0	Inside radius of the plasma confining tube, m
T	Temperature, K
v_r	Radial velocity, m/s
V_z	Axial velocity, m/s
v_Θ	Swirl velocity, m/s
z	Distance in the axial direction, m

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Table I. Energy balance

$\bar{v}_\Theta$ m/s	CONFINED PLASMA %q_c	%q_r	%q_h	FREE PLASMA %q_c	%q_r	%q_h
0	30.2	40.4	29.4	8.1	43.6	48.3
10	28.9	42.3	28.8	7.6	45.4	47.0
20	29.1	41.8	29.1	8.1	43.4	48.5
30	29.5	41.4	29.1	8.4	43.6	48.0

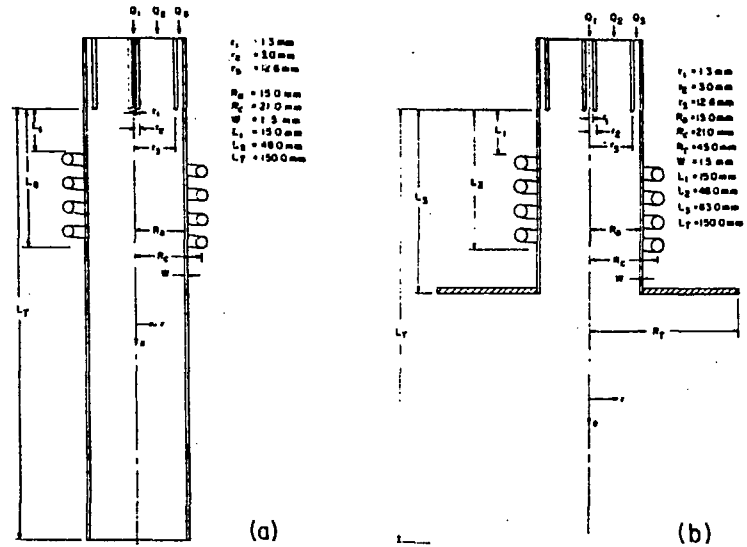

Figure 1: TORCH GEOMETRICS USED FOR THE (a) CONFINED AND (b) FREE PLASMA CALCULATIONS.

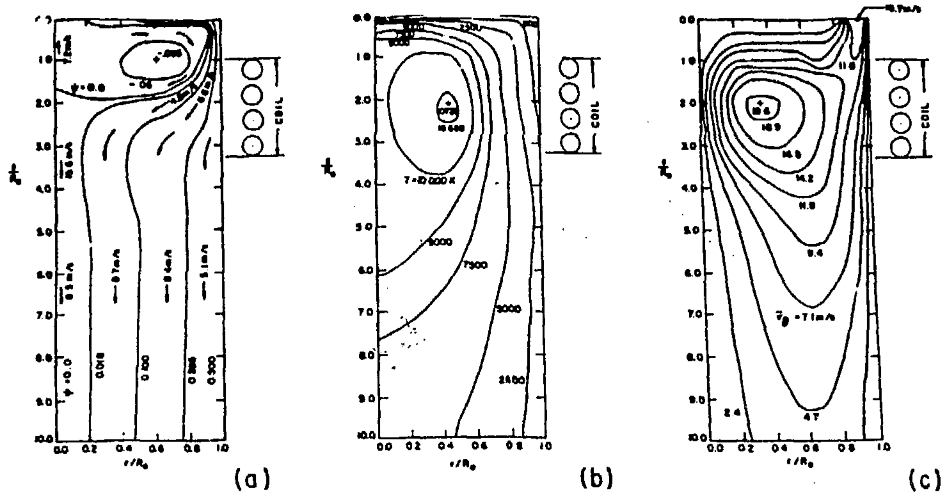

Figure 2: FLOW AND TEMPERATURE FIELDS FOR A CONFINED PLASMA $\overline{v}_{\Theta}$=10 m/s

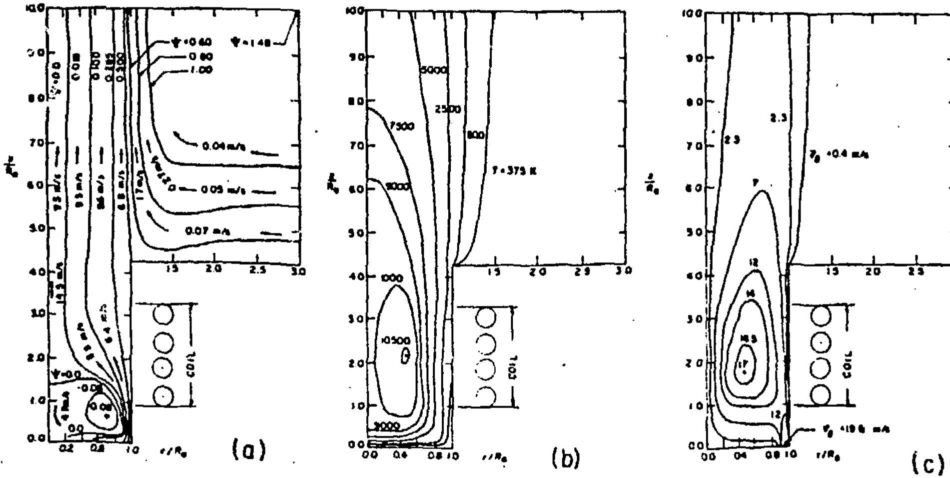

Figure 3: FLOW AND TEMPERATURE FIELDS FOR A FREE PLASMA $\bar{v}_\theta$=10 m/s