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Three-dimensional effects in the modelling of ICPTs

Part II: Induction coil and torch geometry

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Abstract. In this paper, a 3-D numerical study is performed to investigate the effects of the induction coil design and torch geometry on the characteristics of argon 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 are presented for different coil geometries including conventional helicoidal, double-stage and planar configurations. The physical behaviour of a torch with elliptical cross-section is also analyzed. Additionally, the effects on plasma temperature and velocity fields of reducing the post-coil length in a conventional torch are shown.

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

1 Introduction

Mathematical modeling represents a useful tool to predict the characteristics of the discharge in inductively coupled plasma torches (ICPTs), as the detailed diagnostics of these systems is very difficult to carry out, in particular with regard to the flow field and power distribution in the plasma. Although 2-D axisymmetric models [1–4], which have been widely employed in the past, can describe with good approximation the main physical phenomena occurring within ICPTs, 3-D approaches must be used to analyze the asymmetry effects due to the actual shape of the induction coil or to investigate torches with non conventional cross-section. In this frame, a fully 3-D model including both a simplified and a complete treatment of the electromagnetic field has been recently developed by the authors within customized commercial code FLUENT© [5–8]. While in the first part of this work [8] we use such a model to evaluate the effects on the behaviour of a standard conventional torch of different flow and operating conditions, adopting either a simplified or a complete electromagnetic field approach, also on gas mixtures, here the attention is focused on the impact of different coil shapes and torch geometries on the characteristics of pure argon discharges. Simulation results are presented for conventional helicoidal, planar and double-stage coil configurations as well as for a torch with elliptical cross-section. Moreover, the effects of reducing the post-coil length on plasma temperature and velocity distributions are shown for the same torch geometry considered in [8].

2 Modelling approach

All the calculations are performed for optically thin plasmas, under the assumptions of LTE and laminar flow. Plasma temperature and velocity fields are obtained by solving the three-dimensional mass, momentum and energy conservation equations, while the electromagnetic field is calculated by means of the simplified model [8] which neglects the scalar potential due to the electric charge density distribution in the plasma. Since this assumption does not have a great impact on the solution, as shown in [6,8], it is adopted here for the sake of simplicity. The coupled set of governing equations is solved in the frame of the FLUENT©-based UDS approach [4] using vanishing boundary conditions and a grid extending also outside the torch region for the treatment of the electromagnetic field, as done in [8].

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.

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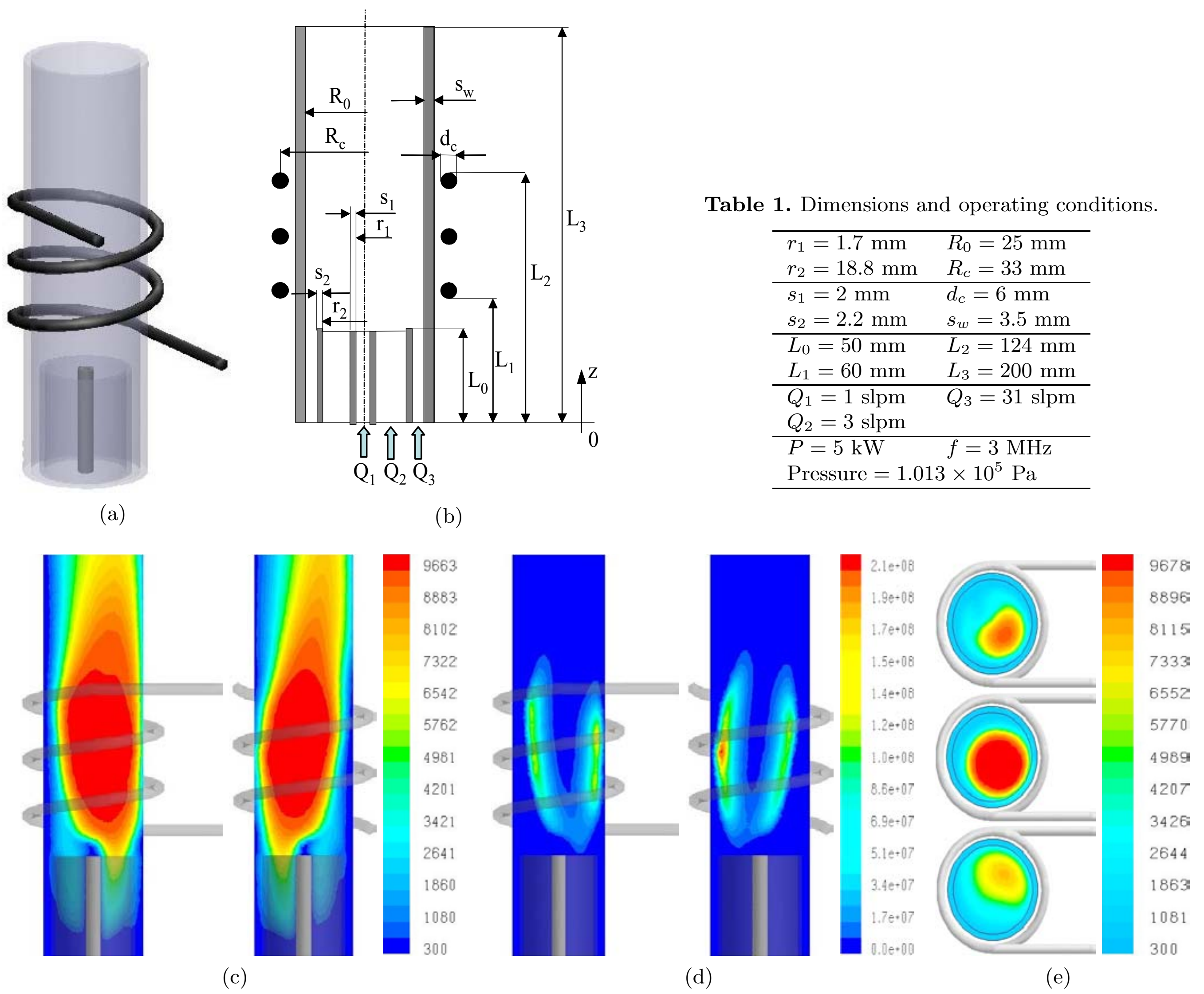
Table 1. Dimensions and operating conditions.

$r_1 = 1.7$ mm	$R_0 = 25$ mm
$r_2 = 18.8$ mm	$R_c = 33$ mm
$s_1 = 2$ mm	$d_c = 6$ mm
$s_2 = 2.2$ mm	$s_w = 3.5$ mm
$L_0 = 50$ mm	$L_2 = 124$ mm
$L_1 = 60$ mm	$L_3 = 200$ mm
$Q_1 = 1$ slpm	$Q_3 = 31$ slpm
$Q_2 = 3$ slpm	
$P = 5$ kW	$f = 3$ MHz
Pressure $= 1.013 \times 10^5$ Pa	

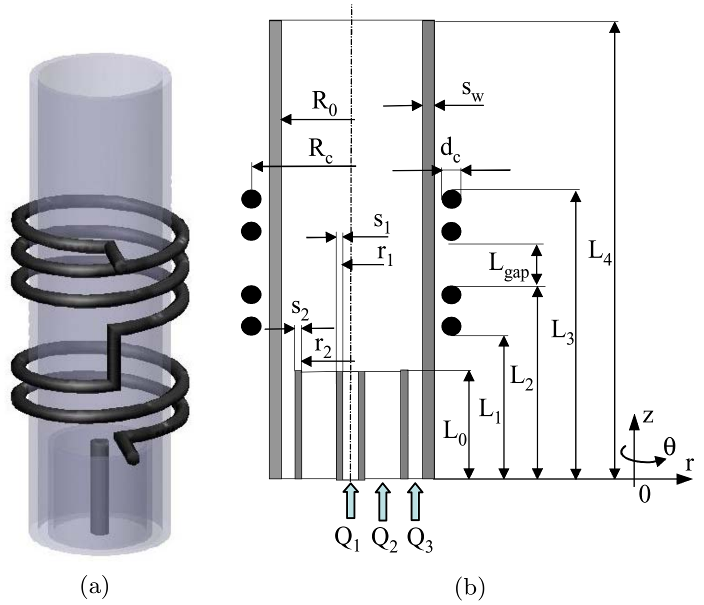


(a) (b)

(c) (d) (e)

Fig. 1. *Conventional coil with 2.5 turns*: (a) 3-D schematic and (b) dimensions of the plasma torch; (c) plasma temperature field [K]; (d) power density distribution [W/m^3]; (e) plasma and wall temperature fields [K] on three horizontal planes located at $z = 60$, 92, 200 mm respectively, from top to bottom. Color figures are available at `http://www.edpsciences.org/epjd/`.

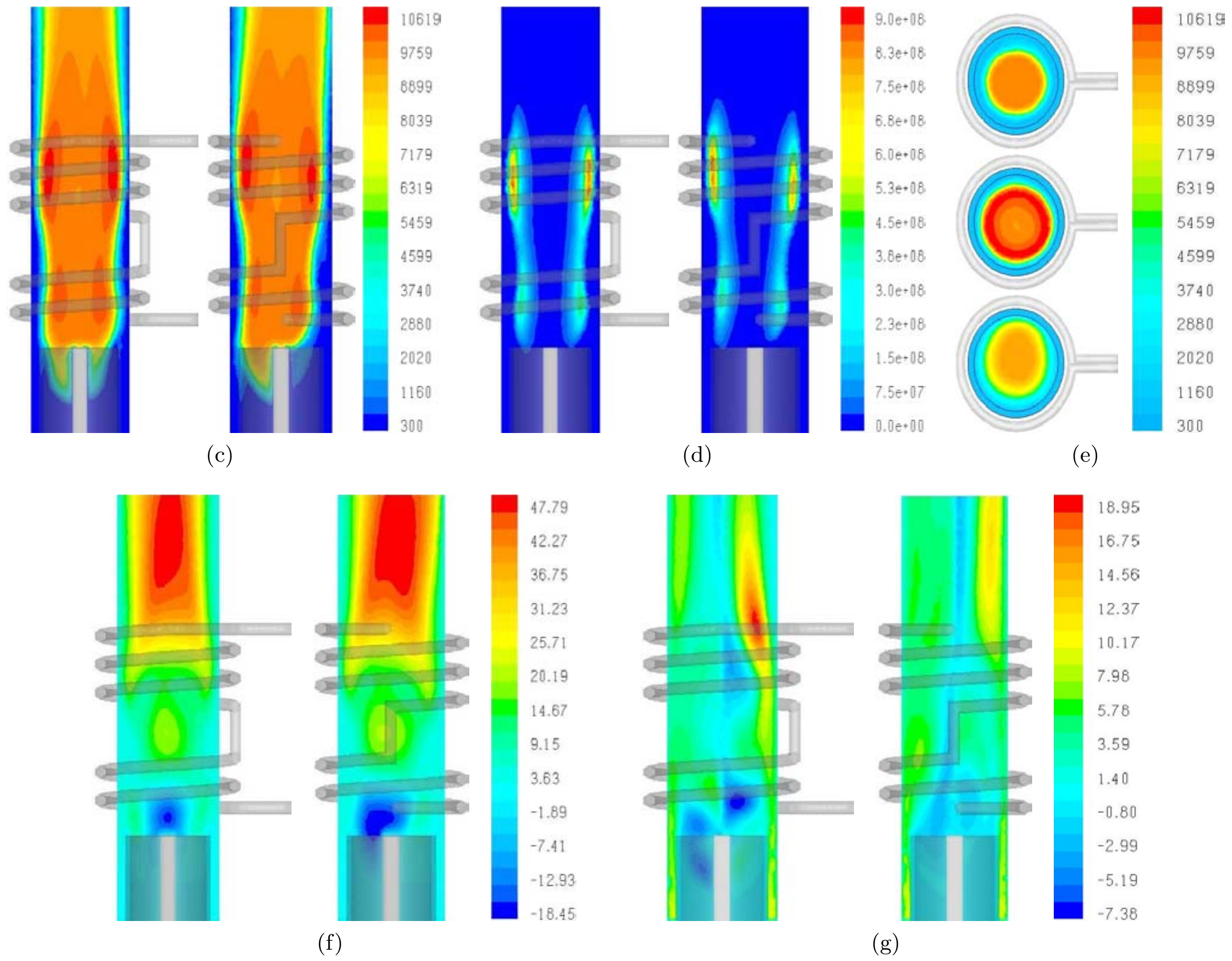
In the following, P denotes the net amount of power dissipated in the discharge, f is the frequency of the RF generator and Q_1, Q_2, Q_3 (or, alternatively, Q) are the carrier, plasma and sheath gas flow rates, respectively (or, alternatively, the total gas flow rate). In Figure 1, plasma temperature and power density distributions are shown for a conventional torch with 2.5 coil turns (with inclination of 6.60° with respect to the horizontal plane). In this case, a significant displacement of the plasma fireball towards the confinement tube and the consequent formation of a hot spot on the wall can be observed, as a result of the strong non-axisymmetry of the coil. In Figure 2, plasma temperature and power density fields, along with the axial and tangential velocity distributions, are presented for a double-stage coil configuration [9,10] in which a swirl velocity component, $v_{\theta s} = 10$ m/s, is introduced in the sheath gas. In particular, Figure 2c shows that such configuration is characterized by an extended discharge volume, while Figure 2d points out that the RF power is mainly dissipated in the upper part of the coil region. The effects of a planar coil geometry [9] on the plasma temperature and power distributions are shown in Figure 3. As evidenced in Figure 3e, this kind of coil configuration modifies significantly the way the RF power is transferred to the plasma with respect to the helicoidal shape. In Figure 4, simulation results including plasma temperature and axial velocity fields, as well as power density distribution, are presented for a torch with elliptical cross-section. Figures 4b, 4d and 4e clearly show that, in this case, the non-axisymmetry effects are mainly located along the minor axis. Finally, in Figure 5, plasma temperature and velocity fields are presented for the same conventional torch studied in the first part of this work [8] but with a shorter post-coil length.



(a) (b)

Table 2. Dimensions and operating conditions.

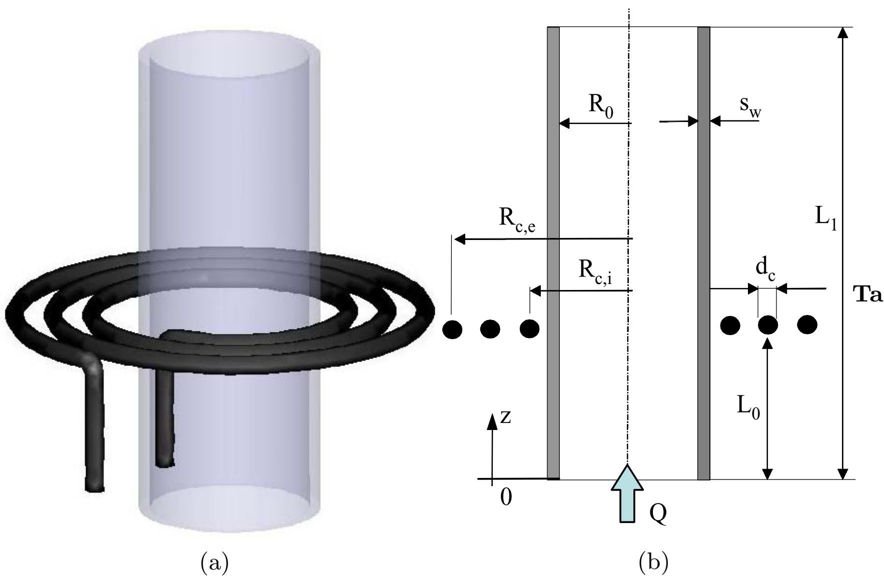
$r_1 = 1.7$ mm	$R_0 = 25$ mm
$r_2 = 18.8$ mm	$R_c = 33$ mm
$s_1 = 2$ mm	$d_c = 6$ mm
$s_2 = 2.2$ mm	$s_w = 3.5$ mm
$L_0 = 40$ mm	$L_{\rm gap} = 18$ mm
$L_1 = 50$ mm	$L_3 = 140$ mm
$L_2 = 80$ mm	$L_4 = 200$ mm
$Q_1 = 1$ slpm	$Q_3 = 31$ slpm
$Q_2 = 3$ slpm	$v_{\theta s} = 10$ m/s
$P = 25$ kW	$f = 3$ MHz
Pressure $= 1.013 \times 10^5$ Pa	



(c) (d) (e)

(f) (g)

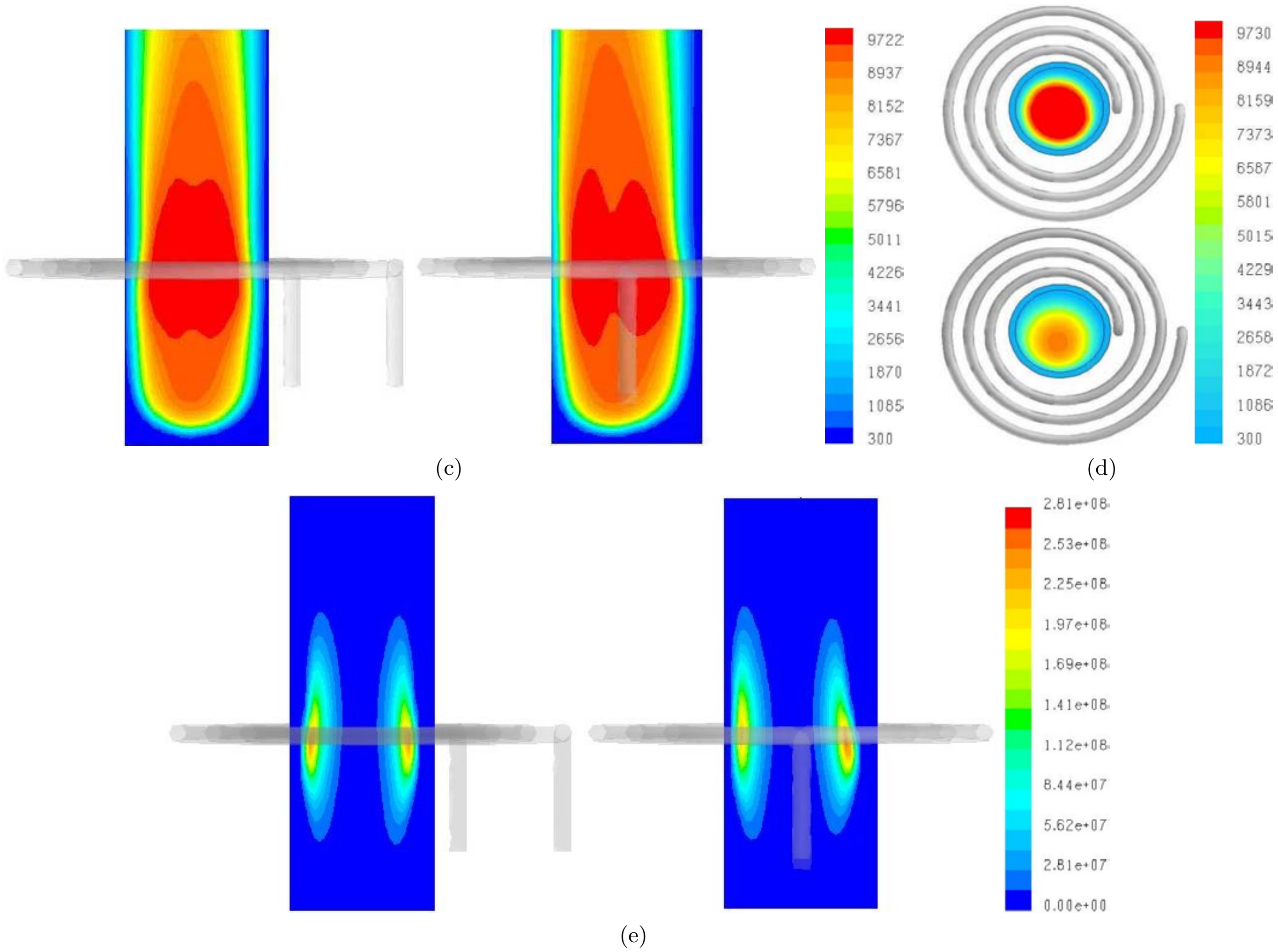
Fig. 2. *Double-stage coil*: (a) 3-D schematic and (b) dimensions of the plasma torch; (c) plasma temperature field [K]; (d) power density distribution [W/m^3]; (e) plasma and wall temperature fields [K] on three horizontal planes located at z = 90, 120, 200 mm respectively, from top to bottom; (f) axial and (g) tangential plasma velocity fields [m/s].



(a) (b)

Table 3. Dimensions and operating conditions.

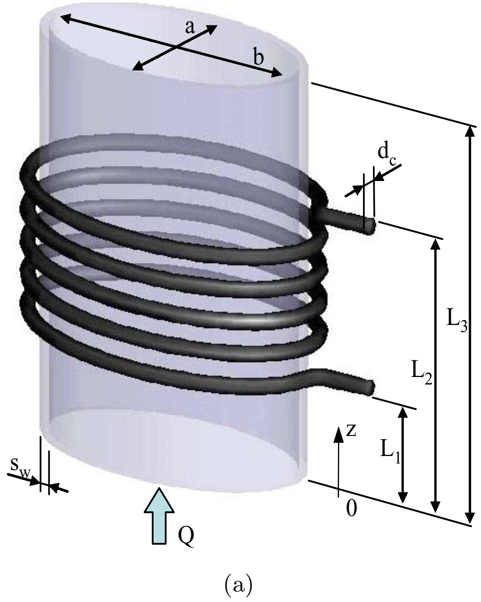
$R_0 = 25$ mm	
$R_{c,i} = 33$ mm	$R_{c,e} = 70$ mm
$s_w = 3.5$ mm	$d_c = 6$ mm
$L_0 = 57$ mm	$L_1 = 140$ mm
$Q = 35$ slpm	
$P = 5$ kW	$f = 3$ MHz
Pressure $= 1.013 \times 10^5$ Pa	



(c) (d)

(e)

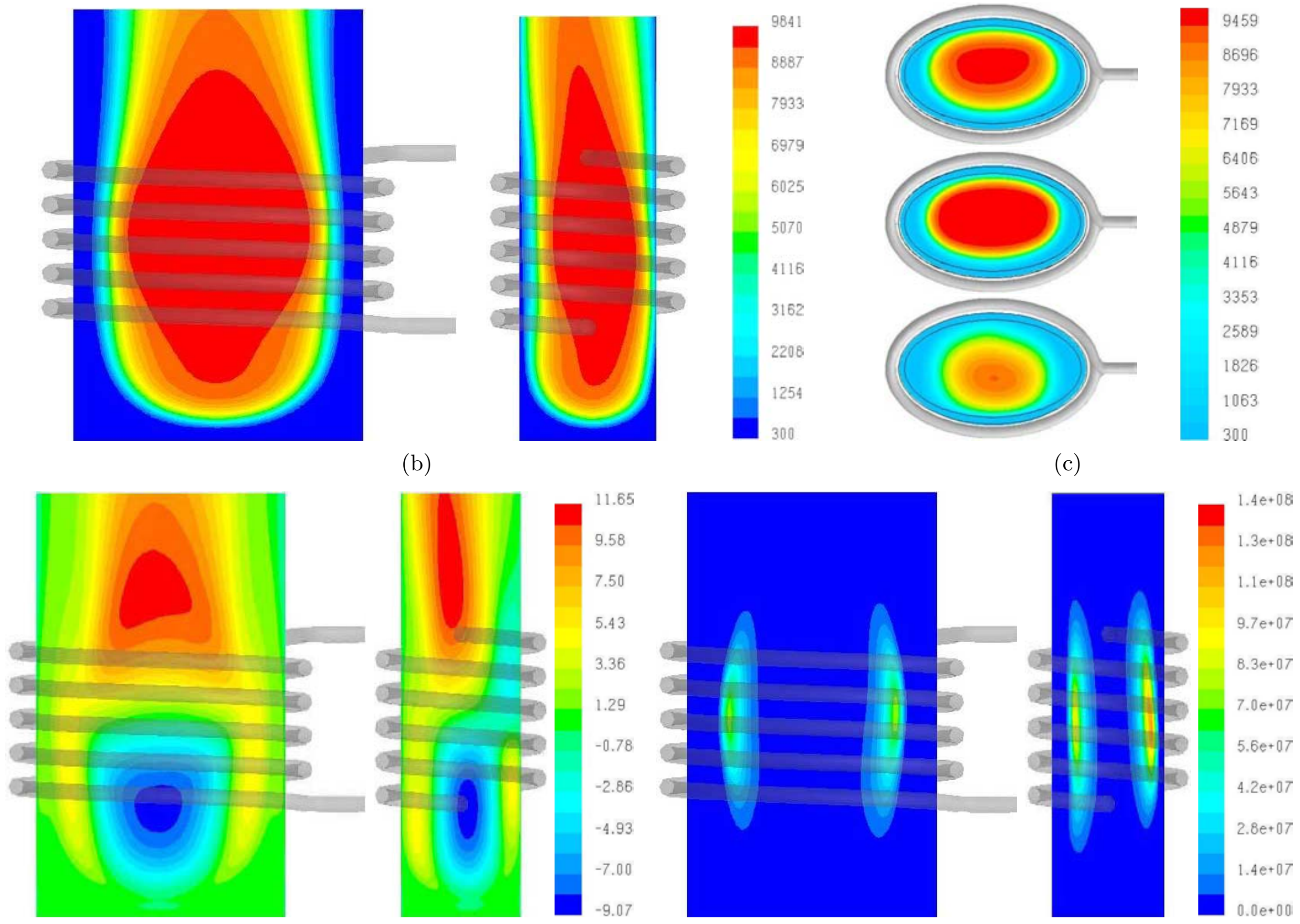
Fig. 3. *Planar coil*: (a) 3-D schematic and (b) dimensions of the plasma torch; (c) plasma temperature field [K]; (d) plasma and wall temperature fields [K] on two horizontal planes located at $z = 60$, 140 mm respectively, from top to bottom; (e) power density distribution [W/m^3].



(a)

Table 4. Dimensions and operating conditions.

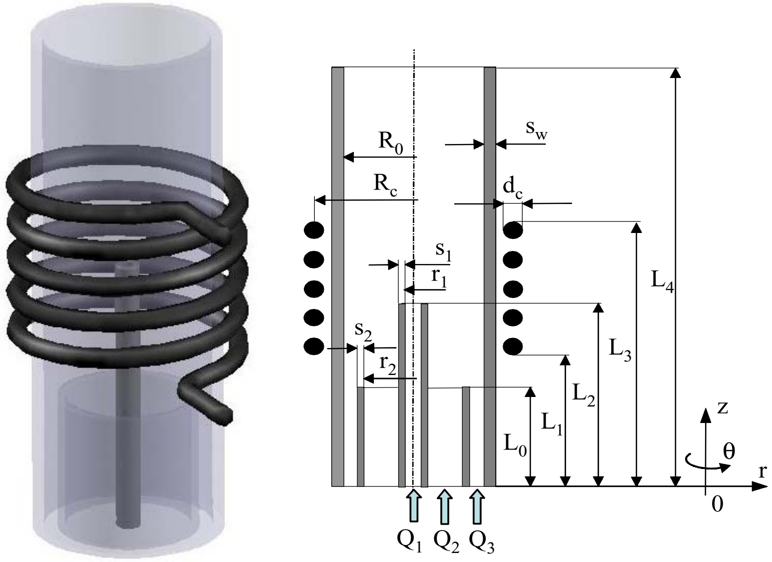
$a = 50$ mm	$d_c = 6$ mm
$b = 100$ mm	$s_w = 3.5$ mm
$L_1 = 37$ mm	$L_3 = 150$ mm
$L_2 = 103$ mm	$Q = 40$ slpm
$P = 5$ kW	$f = 3$ MHz
Pressure $= 1.013 \times 10^5$ Pa	



(b) (c)

(d) (e)

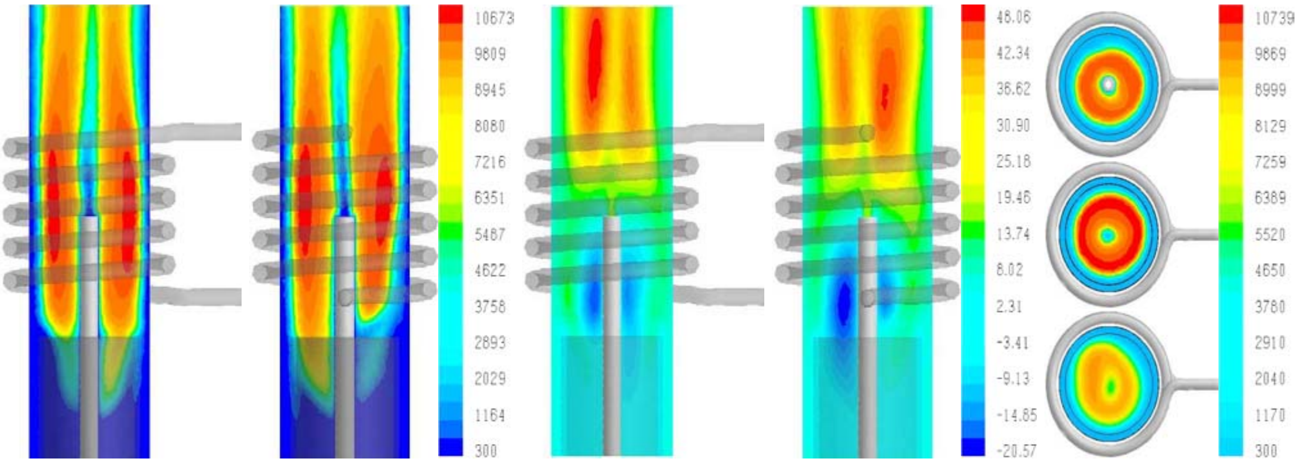
Fig. 4. *Elliptical shaped coil*: (a) 3-D schematic and dimensions of the plasma torch; (b) plasma temperature field [K]; (c) plasma and wall temperature fields [K] on three horizontal planes located at z = 40, 70, 150 mm respectively, from top to bottom; (d) axial velocity field [m/s]; (e) power density distribution [W/m^3].



(a) (b)

Table 5. Dimensions and operating conditions.

$r_1 = 1.7$ mm	$R_0 = 25$ mm
$r_2 = 18.8$ mm	$R_c = 33$ mm
$s_1 = 2$ mm	$d_c = 6$ mm
$s_2 = 2.2$ mm	$s_w = 3.5$ mm
$L_0 = 40$ mm	$L_3 = 110$ mm
$L_1 = 50$ mm	$L_4 = 150$ mm
$L_2 = 80$ mm	
$Q_1 = 10$ slpm	$Q_3 = 120$ slpm
$Q_2 = 30$ slpm	$v_{\theta s} = 20$ m/s
$P = 25$ kW	$f = 3$ MHz
Pressure $= 1.013 \times 10^5$ Pa	



(c) (d) (e)

Fig. 5. *Conventional coil with 5 turns and reduced post-coil length*: (a) 3-D schematic and (b) dimensions of the plasma torch; (c) plasma temperature field [K]; (d) axial velocity field [m/s]; (e) plasma and wall temperature fields [K] on three horizontal planes located at $z = 60$, 90, 150 mm respectively, from top to bottom.

4 Conclusions

The results presented in this paper demonstrate that a 3-D model can be particularly useful in the physical characterization of the discharge in inductively coupled plasma torches, as already shown in the first part of this work [8], as well as in the design stage of such devices, in which a prediction of relevant asymmetry effects especially due to non conventional coil configuration or torch geometry might be important.

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