Numerical simulation of high power RF–RF hybrid plasma torch

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Abstract. In this paper the possibility of operation of a high-power RF-RF hybrid plasma torch for materials processing is shown with help of numerical simulation. That kind of plasma torch consists of two coaxial ICP/RF torches connected in series. A mathematical model is presented which includes assumptions, basic equations, a computational domain with main sizes. The results of the calculation i.e. the temperature distributions inside the plasma torch for two modes of operation are shown. In the first mode the power is fed only to the first plasma torch \( P_1 = 40 \) kW, \( P_{2} = 0 \), in the second mode the both parts of the RF-RF hybrid plasma torch \( P_1 = 40 \) kW, \( P_2 = 600 \) kW) operate. The obtained results can serve as a basis for further analysis of the operation of a high-power RF-RF hybrid plasma torch.

1. Introduction

Radio-frequency inductively coupled plasma (ICP/RF) torches are used in various technologies such as a powder processing, a spectral analysis, a surface treatment, plasma-chemical technologies, a synthesis of nanopowders etc. [1, 2]. One type of the design of such plasma torches is a RF-RF hybrid plasma torch which consists of two coaxial ICP/RF torches connected in series so that the outlet of the first torch is connected to inlet of the second one [3, 4]. The diameters of these two torches as well as the frequencies of the coil current, the dissipated power etc. may differ.

RF-RF hybrid plasma torches are efficient applied in the following cases:
- it is necessary to provide a large length of the high temperature region – when the injected material is fed through the plasma torch [3, 4];
- it is necessary to provide ignition conditions for high-power ICP/RF plasma torch and/or when using high-enthalpy plasma-forming gas [5].

The paper is devoted to a development of a high power RF plasma torch (500-1000 kW) with a high-enthalpy plasma-forming gas (for example, air) for processing materials. To improve ignition conditions, it was proposed to use a RF-RF hybrid plasma torch.

Since the goal is to generate a RF plasma with the power of 500-1000 kW then the frequency of 440 kHz was chosen which is connected to possibilities of modern power sources. This power and frequency are related to the second part of the RF-RF hybrid plasma torch:

\[ P_2 = 500-1000 \text{ kW}, f_2 = 440 \text{ kHz}. \]

It was assumed that in order to ignite the second part of the RF-RF hybrid plasma torch it suffices to apply to its input a plasma jet generated by an RF plasma torch with a power of 30-40 kW. A higher...
frequency of 5.28 MHz was chosen in order to facilitate ignition of the first part of the RF-RF hybrid plasma torch:

\[ P_1 = 30-40 \text{ kW}, f_1 = 5.28 \text{ MHz}. \]

The study of the possibility of operating of such RF-RF hybrid plasma torch was carried out through numerical simulations which is widely used in analyzing plasma processes [6–11] and is also necessary when analyzing the influence of such a consumer on the electrical network [12–15].

An overview of works on the simulation of ICP/RF plasma torches is given in the book [16]. Papers on the development of a two-dimensional model of the electromagnetic field of the ICP/RF plasma torch appears in the 1990s [17–20] including the space surrounding the plasma torch [21–23]. At the same time the first models which take into account the turbulence of the plasma flow in the ICP/RF plasma torches appear [24, 25]. They use a k-ε model of turbulence. It was shown that the main part of the plasma inside the torch is laminar, a turbulence takes place in the near-wall regions.

Modern software such as ANSYS Fluent [26], Comsol Multiphysics [27], CFD ACE + [28] etc. have begun to apply to simulation of plasma processes in plasma torches in the past 20 years.

The research team of V. Colombo et al. achieved significant results in this area; the model’s features and the main results were published particularly in papers [29–32]. In particular, the paper [32] is devoted to a very detailed study (by numerical modeling) of the operation of a RF-RF hybrid plasma torch with a power of up to 40 kW (plasma-forming gas was argon).

2. Mathematical model

The basic equations of used model of plasma processes (it is assumed that plasma is in a state of local thermodynamic equilibrium and optically thin), express the fundamental conservation laws (of energy, momentum and mass), and for the elementary volume are written as follows [11]:

- energy equation:
  \[ \nabla \cdot (\rho \hat{\vartheta} h) = \sigma E^2 - u_{rad} - \nabla \cdot \left( -\frac{\lambda}{c_p} \nabla h \right); \tag{1} \]
- motion equation:
  \[ \nabla \cdot (\rho \hat{\vartheta} \hat{\vartheta}) = -\nabla p + \vec{F}^e + \rho \hat{\vartheta} + \nabla \cdot (\mu \nabla \hat{\vartheta}); \tag{2} \]
- continuity equation:
  \[ \nabla \cdot (\rho \hat{\vartheta}) = 0. \tag{3} \]

Equations (1) – (3) include:
- thermophysical parameters such as enthalpy \( h \) that related to temperature \( T \); velocity \( \hat{\vartheta} \); pressure \( p \);
- thermophysical plasma properties such as density \( \rho \); thermal conductivity \( \lambda \); specific heat \( c_p \); viscosity \( \mu \); electrical conductivity \( \sigma \); specific radiation power \( u_{rad} \);
- electromagnetic values such as electric field intensity \( E \); electromagnetic force \( \vec{F}_B = \vec{j} \times \vec{B} \).

Since plasma exists in an electromagnetic field the system of equations (1) – (3) is supplemented by Maxwell's system of electromagnetic equations:

\[
\begin{cases}
\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}, & \nabla \cdot \vec{E} = \frac{\rho_{el}}{\varepsilon_0}, \\
\nabla \times \vec{H} = \vec{j}, & \nabla \cdot \vec{B} = 0,
\end{cases}
\]

where \( \vec{E} \) and \( \vec{H} \) are electric and magnetic field intensities; \( \vec{B} \) is magnetic induction; \( \vec{j} \) is current density; \( \rho_{el} \) is volume density of electrical charge; \( \varepsilon_0 \) is electric constant.

For thermal plasma processes the Maxwell’s system of equations reduces to equations for the scalar (\( \varphi \)) and vector (\( \vec{A} \)) potentials:

\[
\begin{align*}
\nabla \cdot (\sigma \nabla \varphi) &= 0, \\
\sigma \frac{\partial \vec{A}}{\partial t} + \frac{1}{\mu_0} \nabla \cdot \vec{A} &= \vec{j},
\end{align*}
\]

where \( \vec{j} = \sigma (-\nabla \varphi + \hat{\vartheta} \times \vec{B}) \), \( \vec{B} = \nabla \times \vec{A} \).
Thus, equations (1) – (4) represent a system of equations that need to be solved simultaneously to obtain the distributions of the required quantities – plasma parameters, namely, temperature, velocity, pressure, electromagnetic quantities. Plasma turbulence was taken into account using the SST model, the advantages of that model were described in [11].

This model was implemented using the software ANSYS Fluent [26]. User-defined functions (UDF) were defined to solve the electromagnetic problem and to take into account the dependences of the plasma thermophysical properties on temperature.

It was assumed that the inductor currents vary according to sine law. In this case a phasor calculus can be used to calculate the electromagnetic field. Moreover, since each inductor coils generate an electromagnetic field of its frequency ($f_1 = 5.28$ MHz, $f_2 = 440$ kHz) the superposition principle was applied: the electromagnetic fields created by the first and second inductor coils were considered separately, and separate variables were used to describe those fields.

3. Data for calculation

The primary selection of the design sizes for the first and second parts of the RF-RF hybrid plasma torch was made on the basis of an approximate calculation using the method described in [33].

The task was solved in a two-dimensional axisymmetric formulation. The computational domain includes the region inside the RF-RF hybrid plasma torch and the region of existence of the electromagnetic field around the inductor coils. The geometry of the computational domain with indicated sizes is shown in Figure 1, the sizes are as follows: $L_1=400$ mm, $L_{01}=230$ mm, $h_1=70$ mm, $D_{r1}=60$ mm, $D_{l1}=94$ mm, $D_i=400$ mm, $L_2=1000$ mm, $L_{02}=200$ mm, $h_2=260$ mm, $D_{r2}=200$ mm, $D_{c2}=350$ mm, $D_2=1200$ mm, $D_{v2}=186$ mm. In addition, the following sizes were used (not shown in Figure 1): the diameter of the coil tube of the first inductor is $d_{c1}=10$ mm; sizes of the coil profile of the second inductor: $a = 20$ mm, $b = 50$ mm. The boundary conditions were set in the usual way, a detailed description can be found in [11].
The investigation was carried out for the torch operation with air as plasma gas. To calculate the thermodynamic and transport properties of air plasma the method described in [34] was used. To set the specific radiation losses of air plasma the data from the book [35] were used.

Two cases were calculated. In the first case it was assumed that the power is fed only to the first part of the RF-RF hybrid plasma torch: \( P_1 = 40 \text{ kW}, P_2 = 0 \).

Plasma-forming gas with a flow rate of \( G_1 = 35 \text{ l/min} \) was fed to the inlet of the first plasma torch (through the whole diameter of the torch). It was assumed that the gas feeding is tangential, the swirl velocity was 20 m/s.

In the second case it was assumed that the power is fed to the both parts of the RF-RF hybrid plasma torch: \( P_1 = 40 \text{ kW}, P_2 = 600 \text{ kW} \).

In addition to the flow rate \( G_1 = 35 \text{ l/min} \) through the first part of the RF-RF hybrid plasma torch, the plasma-forming gas was fed directly to the inlet of the second part into the gap between \( D_{v2} \) and \( D_{p2} \) (see Figure 1), the gas flow rate was \( G_2 = 1300 \text{ l/min} \). That gas feeding was also tangential, swirl velocity was 10 m/s. The tangential gas feeding method was chosen in order to increase the heat protection of the plasma torch walls [33, 36].

4. Results of calculation
The results of calculation are presented in Figure 2.

Figure 2. Distributions of the plasma temperature in the different operation modes of RF-RF hybrid plasma torch: (a) \( P_1 = 40 \text{ kW}, P_2 = 0 \); (b) \( P_1 = 40 \text{ kW}, P_2 = 600 \text{ kW} \).

Figure 2, a presents the temperature distribution in the case when only the first part of the RF-RF hybrid plasma torch operates \( (P_1 = 40 \text{ kW}, P_2 = 0) \). It can be seen that the high temperature region has a spindle shape which is typical for a highly swirling plasma when using a tangential feed. Also Figure 2
shows that the high temperature plasma jet reaches the region of the second inductor coils. That means that when the electromagnetic field is generated in the second part of the RF-RF hybrid plasma torch (i.e. when a radio-frequency current is fed to the second inductor), the plasma will ignite in the second part of the RF-RF hybrid plasma torch.

Figure 2, b shows the temperature distribution in the case when the both parts of the RF-RF hybrid plasma torch operate \( (P_1=40 \text{ kW}, P_2=600 \text{ kW}) \). It can be seen that the whole area inside the RF-RF hybrid plasma torch is filled with a high temperature plasma. At the outlet of the RF-RF hybrid plasma torch the mass-average temperature is 5895 K, the mass-average velocity is 18 m/s. The power of the plasma jet (i.e. the convective power at the outlet of the plasma torch) is 365.8 kW. Considering it as the useful power and dividing it by the input power (640 kW) one determines the efficiency of the RF-RF hybrid plasma torch in the calculated mode of operation: 57.2%.

5. Conclusions
In this paper the possibility of operation of a high-power RF-RF hybrid plasma torch for materials processing is shown with help of numerical simulation.

Of course, this investigation is not enough for development of an optimal design. It is necessary to study the influence of such parameters as diameters and lengths of different elements of the design, gas flow rates, swirl velocities, powers etc.

As one of the next steps, the development of power sources for a RF-RF hybrid plasma torch is also required.

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