ELECTROMAGNETIC CHANNEL MODEL FOR HIGH-FREQUENCY FLAME DISCHARGE

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Abstract
In this work the results of research of high-frequency (HF) discharges are represented. The model for high-frequency flame discharge has been worked out.

1. Introduction
The high-frequency flame discharge is of great scientific and practical interest. The practical side is connected with the possibility of a widely use of this discharge in plasma technology, e.g., for production of tightly melted chemical substances. This type of discharge lets us use metal discharge liners. Other types of HF discharges let us use only glass discharge liners.

2. The model for high-frequency flame discharge

Equivalent electric scheme for electrode capacitance high frequency (HF) discharges [1,2] are represented in Fig. 1. Here U is the voltage applied to the electrode of HF discharge, R is discharge resistance, C is capacitance of HF plasma to the ground. Fig. 2 shows the scheme for electrode capacitance plasma generator. Sometimes the electrode 3 is absent in this scheme and discharge current closes on the ground through the capacitance between HF discharge and the ground. In Fig. 2 1 is high voltage electrode, 2 is quartz tube so called gas shaper, 3 is co-axial electrode, 4 is discharge.

Fig. 1

Fig. 2

At present time the discharge of such type is badly studied [1,2,4] in spite of wide utilization [3]. The way for support of HF electrode capacitance discharges plays the special role [4] among several ways for injection of HF energy into discharge zone [5]. The discharges of this type are supported by the potential electric fields like the capacitance discharges. There is not clear classification for the discharges of this type and this fact leads to further investigation of these discharges. For instance, in the paper [6] all of the electrode capacitance discharges and plasma generators are mistaken attributed to the flame type [2,3].

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V.N. Sergeev had first aquainted [3] the correct classification for the electrode capacitance discharges. Further investigations confirmed the results and allowed one to find the conditions for transformations of HF electrode capacitance discharges to others. HF discharge properties depend on the excitation conditions, therefore these properties can not be considered without the analysis of equivalent scheme for discharge turning on into resonant circuit of generator. Let us consider the equivalent scheme for HF flame discharge turning on into the parallel resonant circuit (see Fig.3). When the relationship \((L_1/L_2 - L_2) = 1/(Q_1 C_1)\) is fulfilled, this circuit can be attributed to one-circuit scheme like circuit in Fig.4. Here \(Q_1\) is self-capacitance of inductor \(L_1\), \(C_1 = C_p\) is self-capacitance of discharge. It is necessary to take into account the capacitance because of discharge capacitance \(C_p\) is comparable to the capacitance \(Q_1\). Depending on the relation between the capacitances \(Q_0\) and \(C_1 = C_p\) one can select three cases.

Fig.3. Equivalent scheme for HF discharge.

Fig.4. Equivalent scheme for consecutive switching on of HF discharge for a generator.

1. \(Q_0 \gg C_1\). The case of HF flame discharge.
2. \(Q_0 \ll C_1\). The case of two-electrode HF arc.
3. \(Q_0 = C_1\). The discharge with such parameters is the transition form between HF flame discharge and HF arc.

When the modulation of one-electrode discharge submits the harmonic law, there is HF corona discharge with modulation frequencies \(F_m \leq 50\) Hz, if modulation coefficient is varied from 1- \(U_r/E_0\) to 1. The transition forms between HF corona and HF flame discharges are observed inside frequency range from 50 to 300 Hz. When the modulation coefficient is less than 1- \(U_r/E_0\), the HF corona discharge is not found, because of the electrode voltage is not became less than \(U_r\) and discharge is not quenched. When pulsed modulation takes place, HF discharge transforms into corona discharge with pulse spacing \(t_p > (2-5) \times 10^{-3}\) s and pulse duration

\(t_d < 10^{-3} - 10^{-2}\) s. Obviously, in the case of modulation the mean power of discharge is considerably less than without modulation. Therefore the flame discharge transforms into HF corona discharge due to the mean power of discharge decreases.

When the amplitude modulation of HF flame discharge is observed, the thermal non-equilibrium is considerably greater than in plasma without modulation. In the case of harmonic modulation with increasing of modulation frequency up to 300 Hz HF discharge is not differs from the usual non-modulated discharges.
It is necessary to increase the efficiency of plasma chemical set to support sufficient temperatures for progressing of plasma chemical reactions. The efficiency depends on the power for HF electrode capacitance discharge. The combustion of HF flame discharge is sustained due to the dissipation of the energy of electromagnetic wave propagating along the axis of discharge channel. HF flame discharge generated by electrode consists of plasma channel and diffusion shell [3]. The energetic parameters of discharge mainly depend on the type of electromagnetic wave and propagation conditions. It should be noted that only fundamental transversal magnetic (TM) waves are considered in the papers aimed to electromagnetics of HF flame discharge. The problem of generation and propagation conditions for other types of waves is not discussed. It is possible to generate symmetric transversal electric (TE), TM and non-symmetric combined waves [3] in cylinder plasma of HF flame discharge with complex dielectric permeability varied slowly in the direction of the axis. As in the majority of cases the cylinder well conducted bar is HF flame discharge electrode, then let us to consider the propagation of TM waves of symmetric type. Let us select so called fundamental TM wave being characterized by minimal damping factor. This wave plays the key role in energy balance of the wave. Other TM waves quickly damp, when they propagate along the discharge channel. Such TM waves are called accessory waves. Let us define the power of Joule losses in HF flame discharge per one type of electromagnetic wave mentioned above. Let us consider three cases [3,6].

**a) Fundamental TM wave.** Electric field strengths \(E_r\) and \(E_z\) for the fundamental TM wave are expressed by the relationships

\[
E_r = \frac{j\omega A}{\sqrt{K_1^2 - h^2}} J_0 \left( \frac{r}{\sqrt{K_1^2 - h^2}} \right) e^{-\mu \tau \ast j\omega \tau} \tag{1}
\]

\[
E_z = AJ_1 \left( \frac{r}{\sqrt{K_1^2 - h^2}} \right) e^{-\mu \tau \ast j\omega \tau} \tag{2}
\]

Here \(J_0\) and \(J_1\) are Bessel functions of zero order; \(K, I\) is propagation constant for electromagnetic wave in conducting medium; \(h\) is wave number of axial coordinate; \(z\) is axial coordinate; \(A\) is the coefficient depending on the properties of electromagnetic field source; \(\mu\) is angular frequency. It should be noted that Bessel function argument is a small value, that is \(|Er| < |Ez| \approx 2Ae|^{I|Ez| - |Ez|}_2\). When it is taken into account that discharge channel length is several times greater than the value \(l_{inh} - 1 - 1\), one can substitute upper limit of integral in the axial direction by infinity [3,6] and obtain the expression for \(W\) in the form

\[
W = 2\pi \sigma A^2 a^2 \int_0^{l_{inh}} x \left( e^{-\mu \tau \ast j\omega \tau} \right) z dz = \frac{\pi \sigma A^2 a^2}{2|Imh|} \tag{3}
\]

Here \(x = r/a\) is the ratio of radial coordinate to the radius of HF flame discharge channel; \(I_{Imh}\) is absolute value of imaginary part of wave number for the fundamental TM wave.

**b) TM accessory waves.** When the conductivity corresponds to temperature above 3'103 K, the wave number of TM accessory waves is defined by the equation

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\[ J_0 \left( a \sqrt{K_1^2 - h^2} \right) = 0 \quad (4) \]

The power of Joule losses in this case is defined by expression [3,6]:

\[ W_H = 6.7 \times 10^{-2} a^3 \pi \sigma A^2 \quad (5) \]

c) TE waves. In given case Joule losses power is defined by the relationship [3,6]:

\[ W_H = 1.65 \times 10^{-2} \pi \sigma a^3 B^2 \mu \sigma^2 \quad (6) \]

Thus, the expressions (3), (5) and (6) allow us to conclude, that TM fundamental wave dominates and its dissipation supports the HF flame discharge combustion. This conclusion is confirmed by the experiment in HF flame discharge with the weak skin-effect within wide range of the powers releasing into discharge.

Earlier V.V. Marusin and V.N. Sergeev [4] established that amplitude modulation of HF voltage leads to the periodic variation of the power releasing into discharge. It causes the periodic variation of plasma density, that is the oscillations of discharge plasma in the axial and radial directions with modulation frequency. In this case the variation of discharge length is considerably greater than the variation of its radial dimensions. One can investigate the interaction between dispersive particles and plasma of amplitude modulated discharge, if the frequency and depth of modulation and dimensions of the particles injecting into plasma are specified. It was determined by authors, that amplitude modulation of HF discharge leads to more intensive heat exchange between dispersive materials and plasma and increases the efficiency of plasma generator operation. Therefore, the properties and features of the amplitude modulated (AM) plasma in HF discharge are very interested in science and practice. It is known such plasma can emit the powerful sonic and ultra-sonic vibrations and become more non-equilibrium.

Amplitude modulated plasma is obtained using amplitude modulation of HF field generating the discharge. When harmonic oscillations take place, the electric field inside AM plasma varies according to equation

\[ E = E_0 (1 + m \cos \omega t) \cos \omega t \quad (7) \]

where \( m \) is modulation depth, \( COm \) is modulation frequency, \( CO \) is carrier frequency. It was established, that plasma became the source of acoustic oscillations inside sonic or ultra-sonic range according to (Om). Acoustic field can be described using gas dynamics set of equations taking into account the extrinsic energy sources after the transformation of the set under plasma conditions. The joint solution of the set allows one to obtain the wave equation to estimate the acoustic field for AM plasma [4]:

\[ \frac{1}{N^2} \frac{\partial^2 P}{\partial t^2} - \nabla^2 P = \frac{y - 1}{c^2} \frac{\partial Q}{\partial t} \quad (8) \]

Here \( P \) is the pressure; \( y = C_p/C_vC_p \) and \( cv \) are specific heats at constant pressure and volume; \( c^2 = yP/p \) is sound velocity in the medium, \( Q \) is the energy of extrinsic sources. The value \( Q \) in equation (8) can be represented as sum energy releasing by electrons into plasma particles [10]:

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\[ Q = \frac{3}{2} k \left( T_e - T \right) v_e \delta_e N_e \]  

(9)

Here Ne is electrons concentration; T_e is electrons effective temperature; v_e is collisions frequency; \( \delta_e \) is mean part of energy, being given to plasma particles by electrons. Under this consideration the relationship is correct:

\[ \frac{T_f}{T} - 1 = \frac{2e^2 E_a^2}{2m \delta_e v_e kT} \quad \text{and} \quad E_a = E_0 (1 + \cos \omega_n t) \]  

(10)

Taking into account (8), (9) and (10), it can be found the expression for P(t):

\[ P(t) = \frac{2(\gamma - 1)k^2 m N_e E_0^2}{m v_e} \left[ \left( 1 + \frac{m}{4} \right) - \frac{1}{\omega_n^2} \left( \sin \omega_n t + \frac{m}{8} \sin 2\omega_n t \right) \right] \]  

(11)

It is seen from equation (11), that variation of the pressure is determined by superposition of two oscillations. There are enharmonic and harmonic with the frequencies \( \omega_n \) and \( 2\omega_n \). Amplitude of acoustic pressure in AM plasma depends on time of transition into stationary state defined by the parameters of discharge cell, in particular, by its acoustic Q-factor. One can estimate the intensity of acoustic emission \( I = P \text{ac}/2 \), if the amplitude of acoustic pressure \( P \text{ac} \) is evaluated according to (11). For air plasma with \( f_m = \omega_m/2\pi = 10-20 \) kHz and \( m = 0.4-0.6 \) the amplitude of acoustic pressure in plasma can reach 25-100 N/m² and intensity can reach 400-20000 W/m². The comparison with experimental data [3] shows sufficient agreement. The efficiency of such plasma is estimated according to relationship \( \eta = P \text{ac}/W \), where \( W \) is the power of plasma acoustic emission, \( W \) is discharge power. It was established, that not less 2% of discharge power can be transformed into acoustic field of amplitude modulated plasma. Under resonant conditions this value increases up to 10%. For instance, AM plasma emits ultra-sound with power up to 10 kW using discharge with power 100 kW. Such AM plasma emitting sonic and ultrasonic oscillations can be used in technology and equipment. Plasma chemical set with power 10 kW [4] was elaborated to produce ultra-dispersive powders of oxides using plasma thermal decay of solutions including zirconium, tantalum, titanium, niobium, and rare earth elements. Plasma chemical reactor with HF flame plasma generator is main point of this set. Moreover, the set includes the point for raw materials feed and electric filter for receiving ultra-dispersive powders of oxides. HF plasma generator can play the role of not only generator of plasma, but reactor, when heat carrier and reagents come into plasma generator through feed point. Combined axial and vortex motion provides the variety of technological regimes and processes. In plasma generator under consideration the electrode cooling by water is connected with HF generator through isolator using feeder cable. Plasma beam is formed through the nozzle cooling by water. Reagents are both gases and dispersive states of liquid and solid. Injector cell is destined for dispersing of given solutions up to drops with dimensions 0.005-0.01 cm and contacting of this solution with air plasma. Quick evaporation of the water from salt solution
drops and decay of solid salt to oxides occurs inside reaction cell. Additional air flow is
tangentially fed into reaction and discharge cells. This protects the walls of these cells against
the destruction, when super heating or solid deposition take place.

In plasma technology the great attention is given for processing of dispersed water and
non-water solutions to obtain ultra-dispersive powders of metallic oxides and other
substances. The theoretical investigations allow one to model the behaviour of solution drops
under two-phase plasma jet, to determine the parameters of plasma chemical reactors, used for
processing of dispersed solutions. The evolution of solution drop in reactor can be divided by
four stages:
1. Mixing of drops with plasma flow
2. Heating and evaporation of drops up to dry residue
3. Heating of dry residue up to decay temperature
4. Thermal decay of dry residue with explosion. The second stage limits the process over time,
because other stages are finished rather quickly. This fact defines the geometrical dimensions
of the reactor, in particular, its length. Second stage is described by set of equations for one-
dimensional two-phase flow. The calculations are based on the equations for evaporation and
motion of the drop, conservation laws for flow rate, momentum and energy, the state equation
for vapour gas mixture. The set of equations was normalized, converted and solved by
computer. Obtained calculational results allow one to recommend the following conditions for
plasma thermal processing of water solutions to produce ultra-dispersive powders of metallic
oxides: drops velocity is 100 m/s, drops diameter is less than $10^{-4}$ m, temperature is from 3500
to 4000 K, gas velocity is not greater than 30 m/s, mass phase ratio is from 0.8 to 1.2. Reactor
length have to within 0.5-0.8 m range. It is necessary to make more fine dispersed solution to
decrease the reactor dimensions. Moreover, ultra-sonic fields generating in AM plasma are
used to cleanse reactor walls from disseparated materials. During this process the small particles
coagulate and great particles break. Therefore obtained powder composition becomes more
homogeneous under ultra-sound action. This fact allows one to manage by powder
composition and powders separation. Plasma technologies can be used to produce oxide
compositions of rare and scattering elements including zirconium, when high productivity is
not required.

3. Applied aspects of the model under study

The estimation of the temperature field, structure and character of HF discharge burning
was held on the testing ground where a shady apparatus IAB-451. The distribution of density
of HF discharge in space was defined according to the method of non-focus grating. The
decoding of the received shady photographs was held according to the famous method.

In discharge one can single out two typical thermal layers: current channel and diffusion
casing. The current channel has a relatively high radiation intensity. The radial size of the
casing depends on the mode of operation of the supply of plasma gas.

References

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