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Effect of plasma suppression additives on electrodynamic characteristics of the torch discharge burning in the air

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Abstract. The paper shows the results of measurements of wave number of electromagnetic wave, which supports burning of high-frequency torch discharge in the mixture of air with water vapor and carbon dioxide. The nonmonotonic dependence of attenuation factor of electromagnetic waves is set on a concentration of water vapor. It is shown that the attenuation degree of electromagnetic field in the plasma with water vapor significantly exceeds the attenuation degree of electromagnetic field in the plasma with carbon dioxide.

1. Introduction

Burning of high-frequency torch discharge is carried out due to the dissipation of the electromagnetic wave energy. Therefore the characteristics of torch discharge are largely determined by the characteristics of its electromagnetic field. The most important quantity characterizing the propagation of electromagnetic waves in the discharge plasma is its wave number. The real part of the wave represents the damping coefficient of the electromagnetic wave in the discharge plasma; the imaginary part of the wave is a phase factor that characterizes the slowdown of the electromagnetic wave in the discharge plasma.

High-frequency discharge recently often used [1] as a plasma generator during various plasma-chemical processes. In particular, high-frequency plasma systems on the basis of torch discharge are used for sludge combustion, as well as for disposal of spent nuclear fuel. Conducting this process involves the formation of carbon dioxide and water vapor. Water vapor has a high heat capacity, which has a significant influence on the process of discharge burning. We should also note electronegative properties of water molecules as a result of which the electron density of the plasma discharge is significantly reduced. Changing the concentration of electrons of discharge plasma, in turn, has an effect on the propagation of electromagnetic waves, which supports the discharge. In particular, there is an increase of the attenuation coefficient of electromagnetic wave, and accordingly the changing density of energy sources in the discharge plasma. Carbon dioxide also has similar effect on the discharge burning process.

In this paper we were investigated the dependence of the wave number of the electromagnetic wave that supports the burning discharge, on the concentration of water vapor and carbon dioxide in the discharge chamber of plasma torch.

2. The scheme of experimental setup and methods of measurements

Determination of the wave number was conducted according to the method given in [2]. The scheme of experimental setup is given on the Fig. 1. Torch discharge excited in the air. Electromagnetic field frequency was 37 MHz. High-frequency torch discharge was excited in the cylindrical quartz chamber with the diameter of 28 mm. The discharge channel length ranged from 5 cm to 27 cm. It is depends on the water vapor concentration. The steam was fed into the discharge coaxial of plasma gas forming. Air humidity was controlled by a hygrometer PCE - 310. The air temperature was 30ºC. The measurements of torch discharge characteristics of combustion in the mixture of air and carbon dioxide have been separately. Carbon dioxide concentration in the plasma-forming gas mixture was in a range 0...30%.

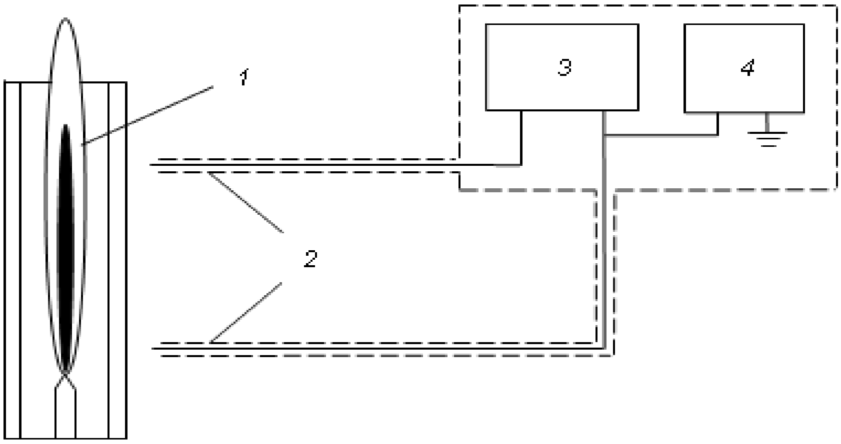

Figure 1. Scheme of the experimental setup. 1 - high-frequency torch discharge; 2 - capacitive and inductive probes; 3 - measuring device; 4 - generator "reference" signal.

Measurement of intensity of electric field of flame discharge was made by probes of capacity moved along plasma blob of discharge. Capacitive probe was a copper rod with length of 3 ... 5 mm. The signal from probes across the wire with double shielding was delivered on the input of measuring device. Depending on the type of the measured value as the measuring device used either oscilloscope or phase meter. When measuring the phase shift to increase the accuracy of the measurements was used a generator of "reference" signal. Defining the wave number of electromagnetic wave supporting burning of the discharge, was conducted by comparison calculated radial distribution of radial component of electrical field discharge with experimental data.

Note that, in the near zone of radiation of torch discharge, its electromagnetic field would be described by Hankel function. Namely, radial distribution of radial component of electric field might be presented by the [3] following equation:

$$E_r = AH_1^{(1)}\left(r\sqrt{k^2 - h^2}\right) \tag{1}$$

Where, A - constant; k - the constant of electromagnetic wave propagation in the air; h - the wave number of the electromagnetic wave; r - radial coordinate.

Thus, comparing the results of calculation of intensity value of radial component of the electric field E_r, conducted according to the formula (1) with the results of experimental measurements, the information about wave number might be gained and by doing so determine the mean of coefficient of phase and decreasing of electromagnetic wave in the discharge. As wave number from equation (1) is a complex value and is determined by two parameters α and β, so for it definite allocation it is required to conduct comparison of calculating and experimental data according to two parameters. In this case these parameters were in the form ratio of amplitude $E_r|_{r=30}/E_r|_{r=90}$ and difference of phases $\Psi_{Er}|_{r=30}-\Psi_{Er}|_{r=90}$ of radial component of electric field at a distance 30 mm and 90 mm from a discharge axis. The calculation data of the values of the amplitude ratio $E_r|_{r=30}/E_r|_{r=90}$ and phase difference

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$\Psi_{Er}|_{r=30}-\Psi_{Er}|_{r=90}$ of radial component of the electrical field using the formula (1) with different meanings α and β, is presented on the Fig.2 and Fig.3.

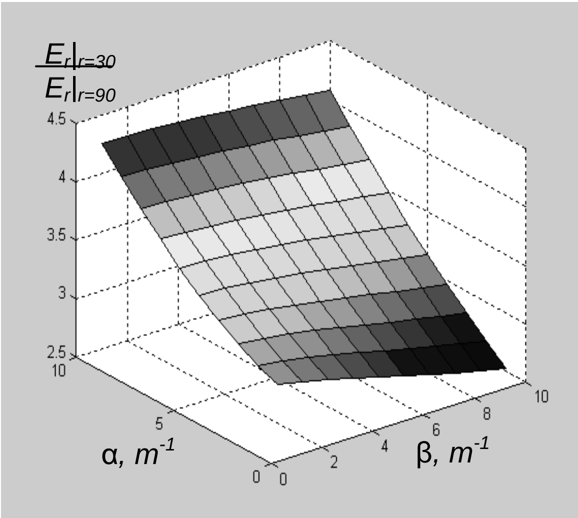

Figure 2. Dependence ratio between amplitude of electric field intensity from coefficient of phase and decrease of electromagnetic wave.

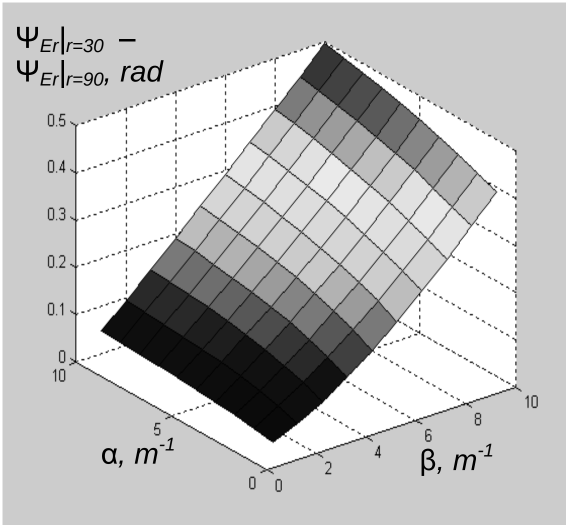

Figure 3. Dependence of phase shift of electrical field intensity versus coefficient of phase and decrease of electromagnetic wave.

As seen from these figures amplitude ratio depends mainly on the value of the phase coefficient, while the damping coefficient is determined primarily by the phase difference.

3. Results of measurements and their discussion

The results of measurements of the radial distribution of the radial component of the electric field in the case of torch discharge burning in the air with water vapor and having a power of 1 kW are presented in Figure 4. The dashed line shows the calculated data performed in accordance with equation (1). As can be seen from the data, the calculated and experimental results are practically identical, which in turn indicates the correctness of determining the value of the wave number by using the formula (1). When the concentration of carbon dioxide and water vapor in the plasma-forming gas are changing, then geometric characteristics of the discharge are also changes. Dependence the length of the channel of torch discharge from the concentration of water vapor and carbon dioxide for the discharge power of 1 kW is shown in Fig. 5. and Fig. 6, respectively. It is compared the experimental and calculated values. The values of the phase and attenuation coefficients of the electromagnetic wave that supports burning torch discharge were obtained. These values are determined depending on the concentration of water vapor and carbon dioxide in the plasma-forming gas. Results for torch discharge power of 1 kW, burning in the mixture of air and carbon dioxide are shown in Fig. 6. The figure shows that the increasing in carbon dioxide concentration in the air leads to increase in the attenuation coefficient and the coefficient of the phase of the electromagnetic wave. Resulting dependences has monotonic character. The value of the electromagnetic wave attenuation coefficient is slightly different from the value of the phase factor. The results of the measurement of the wave number of the electromagnetic wave propagating in the plasma torch discharge air with water vapor are shown in Fig. 7. The figure shows that in this case, with increasing concentrations of plasma-suppressing additive is increasing in the attenuation coefficient and phase coefficient of the electromagnetic wave. However, the dependence of the phase coefficient is nonmonotonic. By increasing the relative humidity of more than 90% there is a slight decrease in the phase factor.

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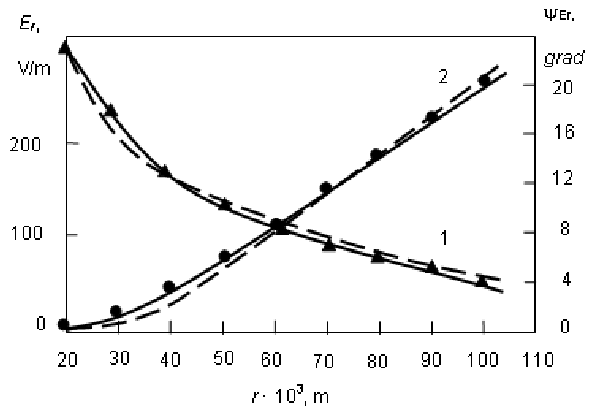

Figure 4. The radial distribution of amplitude and phase shift of the radial component of the electric field torch discharge.

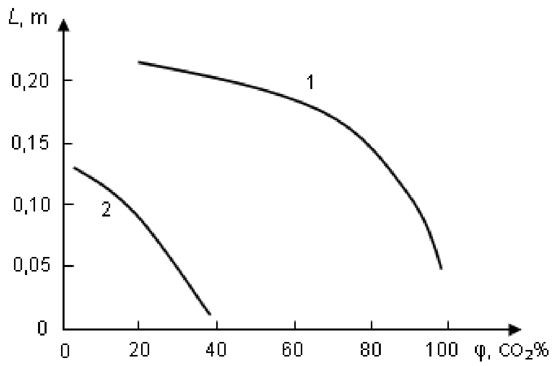

Figure 5. The dependence of channel length of the torch discharge power of 1 kW from plasma-suppression concentration of additives: 1 - the humidity φ; 2 - the concentration of CO_2 in the air.

This anomalous behavior of the electrodynamic characteristics of the torch discharge in this range humidity changes may be due to the changing nature of the interaction between the water molecules. Changing the conductivity of the discharge plasma due to an increase in the concentration of negative oxygen ions, it can also be accompanied by a change in the value of its dielectric constant. It is known that the magnitude of the wave number of the electromagnetic wave propagating along the channel of torch discharge is described [4] the following expression:

$$h = j\sqrt{\frac{2}{5}}\frac{1}{a}\left(\varepsilon_0 + j\frac{\sigma}{\omega}\right)^{-1/2} \tag{2}$$

Where j - imaginary unit; a - the radius of the discharge channel; ε_0 - dielectric constant of the plasma discharge; σ - electrical conductivity of the plasma discharge; ω - frequency electromagnetic field.

Thus, according to the expression (2), the wave number and respectively the phase and attenuation coefficients of the electromagnetic waves will depend both on the conductivity of the discharge plasma, and on the value of its dielectric constant.

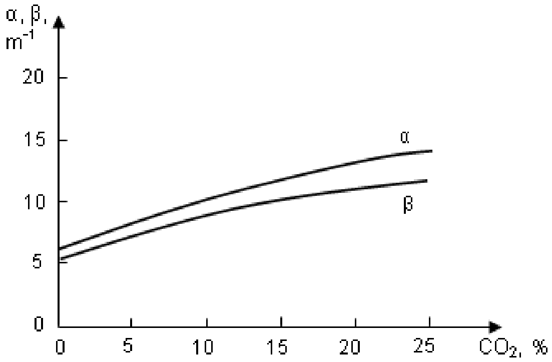

Figure 6. Dependence of the attenuation coefficient α and the coefficient β phase of the electromagnetic wave from the CO_2 concentrations in the plasma forming gas.

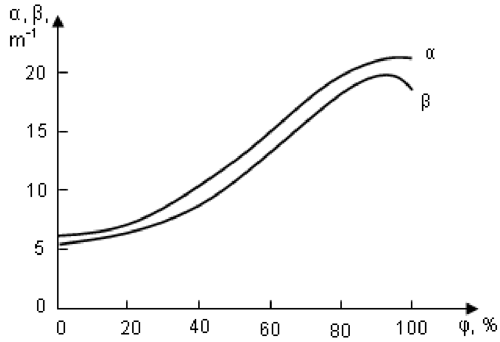

Figure 7. Dependence of the attenuation coefficient α and β phase coefficient of the electromagnetic waves from the humidity of the plasma gas.

From Fig. 7 also shows that the increase in air humidity reduction coefficient phase of the electromagnetic wave is less pronounced than the corresponding change in its damping coefficient.

Comparison of the results shown in Fig. 6 and Fig. 7 suggests a more pronounced effect of water vapor in the process of attenuation of the electromagnetic field in the plasma discharge, compared with carbon dioxide. The moisture content of the air is several times smaller than its relative humidity. At a temperature of 30° C and 30% humidity air the moisture content is 0.01 kg water vapor / kg dry air. Thus, to obtain the same damping effect of the electromagnetic field in the plasma discharge it should be added the water vapor into the plasma-forming gas in several times smaller by mass than carbon dioxide.

4. Conclusion

As a result of the measurement are defined phase growth coefficient and the damping coefficient of the electromagnetic wave that supports burning discharge with an increase in the plasma suppression concentration additives in the plasma forming gas. It is shown that the water vapor compared to carbon dioxide have a greater effect on the propagation of electromagnetic waves in a discharge plasma. It was found an anomalous reduction in attenuation of the electromagnetic field in the discharge plasma with increasing relative humidity of 90%. It is suggested that such a change in the electromagnetic wave attenuation coefficient caused by changing in the character the interaction between the water molecules. The experimental patterns can be used in the development of plasma chemical technologies based on the use of torch discharge burning a mixture of air with carbon dioxide and water vapor.

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