Gas temperature spatial distribution in air corona discharge with plane comb of metal rod electrodes derived from schlieren images

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Abstract. Gas temperature fields in the air corona discharge with a plane comb electrode system have been determined for the negative and positive polarities of the applied voltage. Highly sensitive schlieren technique used in the study allowed detecting a temperature change in tenths of a degree centigrade at room temperature of the gas flow. The obtained results suggest that the gas in the studied electrode system does not undergo heating at the given range of working parameters.

1. Introduction
Sources of low-temperature non-equilibrium atmospheric pressure plasma have broad prospects for application in technologies for modifying surface properties (production of functional coatings, change in hydrophilic properties of the surfaces, etc), in agriculture (preparation, stimulation of seed material in the framework of an organic agriculture concept), food industry (antimicrobial processing and taste modification of food products) and medicine (bactericidal treatment, wound healing, stimulation of processes in cells and tissues, etc) [1–3].

Almost all prospective applications demand strict temperature control during the processing of the treated object. The heating plasma action on the object is especially critical in the case of living materials [4]. For instance, electron microscopy analysis of E. coli M17 cells and biofilms after corona exposure [5] demonstrated several qualitatively different destructive effects. Some morpho-functional changes were likely caused by the thermal effects [5]. Also, as example, the morphology of treated cells greatly depends on the gas-dynamics conditions in DBD-driven helium plasma jet [6]. But it is difficult to distinguish clearly the thermal effect from other active agents of plasma sources on treating object. The current state of the task of measuring temperature fields for relatively low gas flow rates of 0.1–10 l/min, which are typical for cold plasma sources, in the presence of large electric fields, especially of high frequencies, is still unsolved.

Usually, thermal imagers are used to control the temperature onto the treated surface [7], a gas flow temperature is determined by thermocouples [8, 9] or optical spectroscopy [10].

At the same time, there are various types of optical methods [11–13] for visualization gas flows and thermal gradients, such as shadow and interference techniques. The shadow technique is...
relatively simple to implement in comparison with the interference one, and therefore, it is used for visualization of qualitative imaging more often. The temperature distribution is obtained by comparing these qualitative images \[8, 9\] with data from other measurements.

The quantitative shadow method allows us to obtain the temperature distribution over the entire field of view for axisymmetric discharges and plane systems in a gas of the same nature. The example of such task realized by the calibrated schlieren technique for an axisymmetric dc microdischarge in the air can be found in \[14\]. Along with the classical shadow systems \[15, 16\], very interesting versions of the technique, such as a background oriented schlieren (BOS) \[16\], have recently been developed. Here, note the successful implementation of BOS method for restoring the temperature profile in the microjet \[17\].

The quantitative analysis of the shadow image is very difficult both when gases are mixed and when the object is asymmetric. In this case, it is exceedingly difficult to distinguish the contribution in the refractive index from gas mixture components and gas heating. But, in some cases, it is possible to separate the contribution from different components and, using special techniques, to obtain the contribution of the temperature impact to the change in the refractive index and recalculate the shadow image into the temperature field \[9, 18, 19\].

In this paper, temperature fields for a planar electrode system in atmospheric air corona discharge have been determined. We studied a long comb of rod electrodes which are connected with the constant negative or positive voltage and placed over a flat grounded plate.

2. Experimental setup and methods

The corona discharge was ignited with the plane electrode comb system consisting of a line of the rods assembled above the grounded plate. The discharge burned in the moist air at atmospheric pressure with temperature of $18 \pm 0.2 ^\circ\text{C}$. High voltage $U_{dc}$ was applied to the comb electrode system. A gap between rod tips and grounded plate was of 10 mm. The comb length $L$ was of 150 mm. The measurements were carried out for negative and positive polarities of the constant applied voltage $U_{dc}$ in range from 4 to 8 kV.

To obtain schlieren images, shadow instrument IAB-458 (Russia) was applied in Toepler geometry, so called schlieren system. The focal length $F$ of the main mirror lenses was 1970 mm. The illuminating slit width $d_{sl}$ was set in the range of 200–1000 $\mu$m to obtain a shadow image in the whole dynamic range. Most of the images were obtained with the slit width of 500 $\mu$m. A standard high-pressure mercury arc lamp for the device IAB-458 was used as a light source. A standard yellow filter of the shadow instrument was used for spectral filtering of the mercury emission lines of 577.0 and 579.1 nm, highly emitting in the spectrum of the lamp. This was done in order to exclude a change in the refractive index with a wavelength for the quantitative calculations.

The experimental setup layout with the photo of the comb electrode system is presented in figure 1.

Optical adjustment of the system was carried out using standard alignment techniques \[15, 20\]. In our experiments, a coordinate system was used so that the $Oz$ axis coincides with the probe optical beam, i.e., the $Oz$ axis is the optical system axis; $Ox$ is the direction perpendicular to the plane of the Foucault knife and the slit, i.e., $Ox$ is the direction in which the light deviation was observed and the calculation of the refractive index gradient was made; $Oy$ is the direction up, parallel to the knife, the slit and the gap.

A rectangular prism mounted on the grounded plate was used for the optical axis aligning parallel to the grounded plate \[15, 20\]. The way of the aligning is that the prism base is set on the plate to which the shadow instrument needs to be oriented. If the optical axis is parallel to this plate, then the slit image, passing through the prism, coincides with the slit image outside it. That is, if there is no image shift at the edge of the prism, the system is aligned exactly. For the shadow instruments IAB-458, it is possible to adjust parallel alignment up to one arc
second by this method with a high quality prism [15] (up to \(2.5 \times 10^{-6}\) rad [20]). In our case, the value of precision recording of the beam alignment is better than \(\approx 10^{-5}\) rad.

The next important point is to set the Foucault knife, slit and comb electrode parallel with each other and simultaneously perpendicular to the grounded plate. The whole system must be positioned relatively to the surface of the Earth with the adjusting plumb weight bob located in the field of view of the shadow device.

Our schlieren instrument is configured in such a way that the image of the slit without an object under research is halved by the Foucault knife. And only a half of the light enters to a charge-coupled device (CCD) camera in the absence of the optical disturbances of the studied object. When the light is deflected in an inhomogeneity, some part of the light begins to be cut by the knife or avoids the knife. When the deflection angle is greater than \(e_{\text{max}} = \pm d_{\text{sl}}/(2F)\), all the light is not got the camera. The range from \(-e_{\text{max}}\) to \(+e_{\text{max}}\) defines the dynamic range of the optical system.

An illumination pattern is formed in the CCD image plane. The image intensities have been corrected by the subtraction of the background intensity. The background intensity is taken from the dark parts of objects in the image field. And, further, the image intensities have been normalized to the intensity of the image without the knife corrected with the background intensity.

In the absence of other distorting factors, the normalized image intensity \(I(x, y)\) corresponds to the deflection angles field \(e_x(x, y)\) along the \(Ox\) axis. The absence of deflection \(e_x = 0\) will corresponds to \(I_{\text{max}}/2 = 0.5\), where \(I_{\text{max}} = 1\) is the background corrected intensity of the image without the knife. The light deflection in an inhomogeneity corresponds to the displacement of the knife in the focal plane of the schlieren instrument without the inhomogeneity. The dependence of the normalized intensity versus the knife position is shown in figure 2(a).
Figure 2.  
(a) Averaged normalized image intensity depending on the position of the Foucault knife and (b) normalized intensity depending on the defocusing position of the knife in squares of $5 \times 5$ mm$^2$: 1—the square center at optical axis; 2—the square center at radius of 20 mm perpendicular to the knife. Y-error bars correspond to standard deviation of normalized intensity in full frame image for (a) and in the squares for (b). The slit width $d_{sl} = 500$ µm.

So, the formula for recalculation of the image intensity into the deflection angles field was used:

$$e_x(x, y) = \frac{d_{sl}}{2F} \left( \frac{I(x, y)}{I_{max}} - 0.5 \right).$$  
(1)

From this relation, the deflection angle error $\delta e_x$ is proportional to the error of the intensity measuring $\delta I$, i.e.,

$$\delta e_x = \frac{d_{sl}}{2F}\delta I.$$  
(2)

The main error in the intensity measuring was set by the CCD matrix noise. We operated with 256 gray scale images with typical background of $\approx 20$, so full dynamic gray scale range of signal was $\approx 200$ levels. The standard deviations of the intensity in full frame of the calibration images were $\leq 4$ levels. From these values, the error $\delta e_x \approx 5 \times 10^{-6}$ rad.

Other sources of instrumental errors do not exceed this value because of the quality of the instrument and its alignment. All dependences closely correspond to geometric optics, including because of the used wide slit $d_{sl}$.

Defocusing the knife out of the focus point results in non-uniformity of the image intensity for the points at different radii relatively to the optical axis and to the knife [15]. Experimental intensity in squares of $5 \times 5$ mm$^2$ with center at optical axis and with center at radius of 20 mm perpendicular to the knife are shown in figure 2(b). With the knife defocusing of 1 mm, the image intensity non-uniformity is not more than 4%. But, in reality, the accuracy of the knife positioning is higher than 0.1 mm.

The electrode comb was also aligned parallel to the optical system along the prism. Visually, the correct installation was also determined by the absence of a shift in the image outside and in the prism field image when the prism base was installed along the electrode comb. The angle $\alpha \leq L \partial^2 n(x, y)/\partial x^2$ defines the allowable non-parallelism of the comb system installation to plane $OyOz$. 
The plane geometry of the system \([n(x, y, z) \equiv n(x, y)]\) and \([n(x, y) = n(-x, y)]\) allows us to use the simple formula for calculating the gradient of the refractive index \(\frac{\partial n}{\partial x}\) along the direction \(Ox\):

\[
\frac{\partial n(x, y)}{\partial x} = \frac{n_0 e_x(x, y)}{L},
\]

where \(e_x(x, y)\) is the field of the deviation angles for the light probing beams in the direction \(Ox\), \(L\) is the length of the electrode comb.

Let us estimate the contribution of the electron and gas densities to the beam deviation.

For refraction by free electrons, refractive index can be written as

\[
n_{\text{e}} = 1 - \frac{4}{5} \times 10^{-14} \lambda^2 N_e\]

[11, 12] in the approximation \(\omega \gg \nu\), where \(\omega\) is light wave frequency; \(\nu\) is collision frequency of free electrons with heavy particles; \(\lambda\) wavelength, [cm]; \(N_e\) electron concentration, [cm\(^{-3}\)].

The electron concentration for corona streamers in air is in range of \(10^8\)–\(10^{15}\) cm\(^{-3}\) [12, 21]. The contribution of electrons to the refractive index becomes comparable to the gas molecules when the degree of ionization is greater than 1% [11, 12]. In the corona discharge, even in the channel of the streamer, the degree of ionization is lower. The light deviation due to the electron concentration gradients is much lower compared due to the temperature gradients. The narrow streamer channels are surrounded by a thick layer of air. Thus, we can neglect the influence of free electrons on the change in refraction.

As for the contribution of gas molecules, local change in temperature causes local change in density for essentially subsonic flow under the given conditions.

Far from the absorption bands, the refractive index \(n\) can be determined by the ratio [15]

\[
n = 1 + \frac{\rho}{\rho_0}(n_0 - 1),
\]

where \(\rho\) is the gas density, and the index “0” corresponds to some reference point, for example, normal conditions; \(n_0 = 1 + 2.92 \times 10^{-4}\) at \(\lambda = 580\) nm and \(\rho_0 = 1.293\) kg/m\(^3\) at \(t = 0\) °C.

The refractive index field is obtained by integration over the entire region from the beginning of the unperturbed area at the edge of a gradient field, which is just the schlieren image border:

\[
n(x, y) = n_0 + \int_{x_0}^{x} \frac{\partial n(x, y)}{\partial x} dx = n_0 + \frac{n_0 d_x}{2 FL} \int_{x_0}^{x} \frac{I(x, y)}{I_{\text{max}}} - 0.5\] \(dx\).

Integration was carried out by script in Scilab [22] with using SIP package [23]. The correctness of the calculation was checked by comparing the integration from left to right and from right to left. Both variants of calculations are in a good agreement with each other.

The gas density \(\rho\) [kg/m\(^3\)] is

\[
\rho = \frac{n(x, y) - 1}{K_1},
\]

where \(K_1 = 0.000226\) m\(^3\)/kg.

And temperature \(T\) [K] and \(t\) [°C] were calculated by the relations

\[
T = \frac{K_2}{\rho},
\]

\[
t = T - T_0,
\]

where \(K_2 = 353\) m\(^3\)K/kg and \(T_0 = 273.15\) K.

3. Experimental results

The schlieren images for negative and positive polarities of the applied voltage of 8 kV are shown in figure 3. The colors in the picture have been processed for a better visual quality.
Figure 3. Schlieren images for the (a) negative and (b) positive polarities of the applied voltage of 8 kV: 1—rods; 2—grounded surface.

Figure 4. Calculated temperature fields for (a) negative and (b) positive polarity of the applied voltage 8 kV, corresponding to the schlieren images in figure 2.

The calculation temperature fields for the schlieren images are presented in figure 4.

The calculated temperature near the rod tips has been obtained to be low. But this result is not true, because of the plane geometry used. Such approach is not correct near the narrow tips with long gaps between the rods in a line of the comb. Narrow high-temperature regions were averaged by long low-temperature gaps between the rods. But in the middle of the discharge gap and near the grounded plate the gas flow geometry is close to plane, thus the calculations gave the correct result.

Usually the treated object is placed onto the grounded plate. So, the temperature near it is more important for practical purposes. The change in maximum temperature $t_{\text{max}}$ depending on the applied voltage is shown in figure 5. This maximum temperature $t_{\text{max}}$ corresponds to the narrow layer of 3 mm thickness over the grounded plate. Air heating near the surface does not exceed tenths of a centigrade.
Figure 5. Maximum temperature near the grounded plate at different polarities of the applied voltage: 1—negative; 2—positive.

4. Conclusion
A schlieren technique with the plane geometry was used to determine the gas temperature fields in the air corona discharge between the comb active electrode and the grounded plate depending on the polarity of the applied voltage. The used approach is suitable to detect the temperature change in tenths of a degree centigrade in the discharge gap region and can be used to find a quantitative result near the grounded plate with high sensitivity. However, the presented approach cannot be used to obtain gas temperatures in the gaps between the rods of comb because of the non-planar geometry of the gas flow. The obtained results suggest that the gas in the studied electrode system does not undergo heating at the given range of working parameters.

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