Experimental evaluation of the temperature of inductively coupled water vapor plasma using the Fourier law

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Abstract. The paper presents the results of experimental evaluation of the temperature of inductively coupled water vapor plasma using the Fourier law. The power of the inductive discharge is in the range from 1280 to 2800 W at a frequency of 40 MHz and a pressure from 1 to 5 mbar. The temperature values are found to be from 2.4 to 2.8 kK. Plasma temperature evaluation is verified on the Balmer hydrogen series using relative intensities method. It is shown that in this pressure range, the plasma is not in equilibrium and at a power of 1650 W, the resulting temperatures $T_{αβ}$, $T_{αγ}$, and $T_{βγ}$ are 3500 K, 2200 K, and 1200 K, respectively, while the temperature obtained by the Fourier method for the same power is 2500 K.

1. Introduction

Industrial applications of inductively coupled water vapor plasma are due to its unique properties such as low cost, availability, and the presence of atmospheric oxygen and OH radicals. To design plasma facilities, it is necessary to know what generator power is sufficient to heat the plasma to a given temperature.

In this study, the temperature of inductively coupled water vapor plasma is experimentally evaluated as a function of input power using the Fourier law. The obtained temperature values are compared with the results of calculation using the Boltzmann relative intensities.

2. Experimental

The following equipment was used (figure 1): an RF generator with a frequency of 40 MHz and a maximum power of 4 kW, a matching unit with controlled variable capacitors, a copper inductor with four turns and water cooling, an U-shaped quartz tube with a discharge chamber 9.5 mm in outer diameter, a flask with water, a roughing pump, a spectrometer, and a vacuum gauge. The plasma pressure range was from 1 to 5 mbar. The roughing pump was connected through the Testo 512 vacuum gauge to the right end of the quartz tube (indicated by number 2 in figure 1), and a water tank was connected to the left end of the tube (indicated by number 1 in figure 1). The fiber of spectrometer Kolibri-2 (range from 190 to 1120 nm, resolution 0.5 nm) was connected to the upper edge of the tube (indicated by number 3 in figure 1). The range of input power was from 1280 to 2800 W.
The experiment was carried out as follows. The tube with the flask filled with water was inserted with the generator and the roughing pump being turned off. Then the roughing pump was turned on. Once the vacuum gauge readings stabilized at a certain value from 1 to 5 mbar, the RF generator at a power from 100 to 150 W was turned on with a constant signal supply, and the matching parameters were adjusted for the system without plasma until the power reflected to the generator became equal to 0 W. After that, the generator was turned off, the output power setting was increased, and the generator was turned on again. This step was repeated until the plasma was ignited. Matching was adjusted at each step. After plasma ignition (whose burning time was several seconds), the exposure and signal level of the spectrometer were adjusted with the PC being turned on. After adjustment of the spectrometer, a spectrum was taken at the next step (figure 2).

Figure 1. Experimental setup diagram.

3. Temperature evaluation
Temperature was evaluated using the following physical model (figure 3): the inductively coupled plasma was represented as a toroidal plasma coil with an axial radius of 3.5 mm. The coil was elongated in the tube along the entire length of the inductor, and its center was at a distance of 0.75 mm from the inner wall of the quartz tube. The cross section of the plasma coil was an ellipse with half axes of 0.5 mm and 11 mm. It was assumed that all the power consumed by the plasma was released in the form of heat by the plasma and radially propagated through the side walls of the tube into the environment due to heat conduction without heat absorption by the material.

For this model, the Fourier law can be written in the form (1):

$$\frac{P}{S} = -\lambda \nabla T \approx -\lambda \frac{T_1 - T_2}{x},$$

(1)
where $S$ is the heat release surface area, $\lambda$ is the thermal conductivity, $x$ is the thickness of the heat release area, $P$ is the input power to the plasma, and $T_{1,2}$ is the temperature at the boundaries of the region considered.

Figure 3. Physical analog. 1 – cylindrical symmetry axis, 2 – plasma coil, 3 – quartz discharge.

Applying formula (1) two times in succession, we obtain the following equations (2)-(3), which are solved assuming that the temperature of the outer wall of the quartz tube ($T_{\text{out}}$) is equal to room temperature, i.e., 300 K.

\[
P / S' \approx - \lambda_1 \frac{T_{\text{out}} - T_{\text{in}}}{d},
\]

\[
P / S'' \approx - \lambda_2 \frac{T_{\text{in}} - T_{\text{pl}}}{\Delta},
\]

where $\lambda_1 (1.36 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1})$ is the thermal conductivity of quartz glass, $\lambda_2$ is the thermal conductivity of water vapor, $T_{\text{in}}$ is the temperature of the inner wall of the quartz tube, $T_{\text{out}}$ is the temperature of the outer wall of the quartz tube, $T_{\text{pl}}$ is the average plasma temperature, $d$ is the thickness of the quartz tube (0.5 mm), $\Delta$ is the distance from the inner wall of the quartz tube to the center of the plasma coil (0.75 mm), $S'$ is the side surface area of the quartz tube, estimated as the side surface area of a cylinder with a radius of 4.5 mm (distance from the symmetry axis to the middle of the tube wall) and a height of 22 mm (corresponds to the height of the plasma coil), equal to 622 mm$^2$, and $S''$ is the outer surface area of the torus calculated by integration (581 mm$^2$).

The thermal conductivity of water vapor was taken from reference data tables at a pressure of 100 mbar in the temperature range from 2000 to 2800 K with a linear approximation of the data between the given values [1, p. 70–71]. Thermal conductivity values were selected to match the plasma temperature. The obtained data is presented in figure 4. Radiation losses were not taken into account in this estimate, since they can be neglected at input power below 3 kW and at pressure below 1 mbar [2].

Figure 4. Dependence of plasma temperature on input power according to formulas (2, 3).
In addition, temperature was measured by the method of relative intensities [2, p. 86–89, 136–137] using formula (4) under the following assumptions: the plasma is in local thermodynamic equilibrium; the plasma is optically thin at the recorded wavelengths; there are at least two sufficiently separated non-resonant wavelengths; the difference in excitation energy between the upper levels must satisfy the condition $\Delta E \geq E_{\text{LET}}$ [eV] – the local thermodynamic equilibrium.

For this, we used experimental spectra of water vapor containing the Balmer hydrogen series.

$$T = \frac{E_p - E_m}{k \left[ \ln \frac{J_{mn}}{J_{pq}} + \ln \frac{A_{pq} g_p}{A_{mn} g_m} \right]}$$  \hspace{1cm} (4)

where $g_p$ and $g_m$ are the statistical weights of the excited levels $p$ and $n$, respectively, $A_{pq}$ and $A_{mn}$ are the Einstein coefficients for spontaneous emission, $J_{mn}$ and $J_{pq}$ are the local intensities of emission lines, $\lambda_{mn}$ and $\lambda_{pq}$ are the wavelengths, $E_m$ and $E_p$ are the atomic energies of the levels $m$ and $p$, respectively, and $k$ is the Boltzmann constant. For the calculation, we used the Balmer hydrogen series and reference data described elsewhere [4]. These temperatures are integral and the result of formula (4) can be used just as an estimate.

At a power of 1650 W, the resulting temperatures $T_{\alpha\beta}$, $T_{\alpha\gamma}$, and $T_{\beta\gamma}$ were 3500 K, 2200 K, and 1200 K, respectively, while the temperature obtained by the Fourier method for the same power was 2500 K.

4. Analysis of results
Using the method of relative intensities, it is found that the order of the integral plasma temperature is from 0.2 to 0.3 eV (around 2 to 3 kK) at a power from 1.3 to 2.8 kW, which is consistent with the results obtained using the Fourier law. The evaluated temperatures are from 2400 to 2800 K at an input power of 1.28 to 2.8 kW. If the plasma is in local thermodynamic equilibrium, it can’t be detected by our measurement, since only integral plasma temperature is measured.

Conclusions
The temperature of gas mixture in inductively coupled water plasma at a pressure from 1 to 5 mbar has been evaluated using formulas (2–4) by two methods: the method of relative intensities and the Fourier law. The temperature values are found to be from 2.4 to 2.8 kK for input powers from 1.28 to 2.8 kW. The average temperature obtained by the method of relative intensities coincides with that calculated by the Fourier formula.

References
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