2D numerical modeling of the gas temperature in a large-volume high-temperature nanosecond pulsed longitudinal discharge in helium with small admixtures of neon, strontium and bromine

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Abstract. A numerical 2D model (r, z) of the gas temperature was developed for the case of axial symmetry and uniform power input. The model determines the gas temperature of a nanosecond pulsed longitudinal discharge in helium with small additives of neon, strontium and bromine. The gas discharge is excited in the newly designed large-volume high-temperature discharge tube.

1. Introduction
It is well known that the gas temperature is one of the basic gas-discharge plasma parameters, which determines the heavy particles interaction, heavy particles concentration, gas discharge stability, etc., The experimental or theoretical determination of the gas temperature is of fundamental importance and is, therefore, applied to problems in various fields, such as gas-discharge laser physics, gaseous discharges, plasma technologies, gas-discharge mass spectroscopy, absorption and emission spectroscopy and plasma in general. It is also well known that the techniques widely used for gas temperature measurement based on measurements of spectral lines Doppler broadening and thermal lens focal distance are definitely imprecise, i. e. with inadmissible experimental error.

Assuming that the gas temperature varies only in the radial direction and considering uniform and non-uniform power input, we calculated gas temperature distributions through analytical solution of the steady-state heat-conduction equation for nanosecond pulsed longitudinal discharge in a series of gas-discharge tube designs [1, 2]. Unfortunately, despite the tremendous efforts, solving analytically the abovementioned steady-state heat conduction equation for 2D (r, z) and 3D (r, φ, z) cases encountered some insuperable obstacles.

2. Experimental setup
A schematic diagram of the new high-temperature large-volume discharge tube is shown in figure 1. The basic tube with a 71.5-mm inside diameter and a 76-mm outside diameter is made of fused quartz.

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A ceramic insert, confining the discharge zone, with a 30.5-mm inside diameter and a 38.5-mm outside diameter and a length of 98 cm is coaxially sleeved in the basic tube. The discharge operates in a self-heating regime. The temperature at the quartz tube surface is measured by a thermocouple.

The electrodes of the discharge tubes are made of porous copper with a special design. CaF$_2$ windows are glued to the ends of the discharge tubes. The nanosecond pulsed longitudinal discharges investigated are excited by an electrical circuit based on a high-voltage rectifier and a high-voltage pulsed excitation circuit with interacting circuits (IC circuit).

3. Results and discussion
A 2D numerical solution of the steady-state heat-conduction equation was derived for the case of one discharge zone with radius $R_1$, and three discharge-free zones, namely a ceramic tube within $R_1 \leq r \leq R_2$, a gaseous discharge-free zone within $R_2 \leq r \leq R_3$, and a basic tube made of quartz within $R_3 \leq r \leq R_4$.

The dependence of the thermal conductivity $k$ of gases and gas mixtures has the form $k = B \cdot T_g^a$, where $B$ and $a$ are constants (within a certain temperature range), which are specific for each gaseous or solid medium. The constants $B$ and $a$, which determine the thermal conductivity, were obtained through fitting the existing experimental data taken from [3]. The thermal conductivities of He and Ne-He mixtures, a ceramic tube made of Al$_2$O$_3$, and a basic tube made of quartz are presented in table 1.

|                | He (45 Torr) | Ne (45 Torr) | Ne-He (5-40 Torr) | Ne-He (10-35 Torr) | Ne-He (15-30 Torr) | He-Sr | He-Br | Al$_2$O$_3$ | quartz |
|----------------|--------------|--------------|-------------------|--------------------|--------------------|-------|-------|-------------|--------|
| $B$            | 34.9x10$^{-4}$ | 9.7x10$^{-4}$ | 30.5x10$^{-4}$    | 26.4x10$^{-4}$    | 22.9x10$^{-4}$    | 26.8x10$^{-4}$ | 28.9x10$^{-4}$ | 44323.1 | 705.9x10$^{-4}$ |
| $a$            | 0.670        | 0.685        | 0.672             | 0.673              | 0.675              | 0.680 | 0.675 | -1.227      | 0.487   |

A brief description of the 2D numerical model is given in the appendix. Figure 2 shows two-dimensional gas temperature distributions for a nanosecond pulsed longitudinal discharge in He (a), Ne (b), Ne-He mixtures (c), (d) and (e), and in He with small admixtures of strontium (f) and bromine (g). The partial pressure of Ne in the Ne-He mixtures is 5 (c), 10 (d) and 15 (e) Torr, maintaining the total Ne-He mixture pressure of 45 Torr constant, while the partial pressures of strontium and bromine are 0.6 Torr and 1.2 Torr, respectively.
Conclusions
The results are presented of 2D numerical modeling \((r, z)\) of the gas temperature in a nanosecond pulsed longitudinal discharge in various mixtures, considering axial symmetry and uniform power input. The development of a 2D numerical model for determining the gas temperature in this type of gas discharge is a further and more complicated step in approaching the real experimental conditions for the discharge studied. A new discharge tube design with incompact \(\text{ZrO}_2\) active-volume insulation was developed in order to increase additionally the operation temperature; its investigation is in progress.

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Appendix A. Description of the 2D model

For the four zones considered the 2D heat-conduction equations have the following form:

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r k_i(T^{(i)}) \frac{\partial T^{(i)}}{\partial r} \right) + \frac{\partial}{\partial z} \left( k_i(T^{(i)}) \frac{\partial T^{(i)}}{\partial z} \right) + q_v = 0, \quad R_{i-1} < r < R_i, \quad 0 < z < L, \quad R_0 = 0, \quad (A.1)
\]

where \( q_v = 1.9 \text{ W.cm}^{-3} \) is the power deposited into the discharge zone per unit volume and \( i = 1, 2, 3, 4 \).

The equations are solved considering the following boundary conditions:

\[
\left. \frac{\partial T^{(i)}}{\partial r} \right|_{r=0} = 0, \quad T^{(i)}|_{r=R_i} = T_w, \quad 0 \leq z \leq L,
\]

and for \( i = 1, 2, 3 \)

\[
T^{(i)}(R_i - 0, z) = T^{(i+1)}(R_i + 0, z), \quad 0 \leq z \leq L,
\]

\[
k_i(T^{(i)}) \left. \frac{\partial T^{(i)}}{\partial r} \right|_{r=0} = k_{i+1}(T^{(i+1)}) \left. \frac{\partial T^{(i+1)}}{\partial r} \right|_{r=R_i}, \quad 0 \leq z \leq L,
\]

\[
T^{(i)}|_{z=0} = T^{(i)}|_{z=L} = T_{w,i}, \quad R_{i-1} \leq r < R_i,
\]

\[
T^{(i)}|_{z=0} = T^{(i)}|_{z=L} = 0.5(T_{w,i} + T_{w,i+1}), \quad r = R_i,
\]

\[
T^{(i)}|_{z=0} = T^{(i)}|_{z=L} = T_{w,i}, \quad R_3 < r \leq R_4,
\]

References

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