2D numerical modelling of the gas temperature in a high-temperature high-power strontium atom laser excited by nanosecond pulsed longitudinal discharge in a He-SrBr₂ mixture

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Abstract. Assuming axial symmetry and a uniform power input, a 2D model \((r, z)\) is developed numerically for determination of the gas temperature in the case of a nanosecond pulsed longitudinal discharge in He-SrBr₂ formed in a newly-designed large-volume high-temperature discharge tube with additional incompact ZrO₂ insulation in the discharge-free zone, in order to find the optimal thermal mode for achievement of maximal output laser parameters. The model determines the gas temperature of a nanosecond pulsed longitudinal discharge in helium with small additives of strontium and bromine.

1. Introduction
It is well-known that gas the temperature is one of the basic gas-discharge plasma parameters, which determines the heavy-particles interaction, the heavy-particle concentration, the gas discharge stability, etc. Therefore, the experimental and theoretical determination of the gas temperature is obviously of significant and fundamental importance; it is performed 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 that are widely used for gas temperature measurement based on measurements of the Doppler broadening of spectral lines and of the focal distance of a thermal lens are definitely imprecise, i.e., characterized by an inadmissible experimental error.

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

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2. Experimental setup
A schematic diagram of a new high-temperature large-volume discharge tube is shown in figure 1. The basic tube with an inner diameter of 71.5 mm and an outer diameter of 76 mm is made of fused quartz. A ceramic insert, confining the discharge zone, with a 30.5-mm inner diameter, a 38.5-mm outer diameter and a length of 98 cm is sleeved coaxially in the basic tube. The zone between the ceramic insert, the basic quartz tube and the holders of the ceramic insert is incompactly filled with ZrO\(_2\) fibrous insulation. The discharge operates in a self-heating regime. The temperature at the quartz tube surface is measured by a thermocouple.

![Discharge tube design](image)

**Figure 1.** Discharge tube design.

The electrodes of the discharge tube are made of porous copper and are of 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 scheme).

3. Results and discussion
A 2D numerical solution of the steady-state heat conduction equation is found 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 discharge-free zone within \(R_2 \leq r \leq R_3\) incompactly filled with ZrO\(_2\) fibrous insulation, and a basic tube made of quartz within \(R_3 \leq r \leq R_4\). The dependence of the thermal conductivity \(k\) has the form \(k = B T_g^a\), 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, can be obtained through fitting the existing experimental data taken from [3]. The thermal conductivities needed are presented in table 1.

|        | He     | Al\(_2\)O\(_3\) | ZrO\(_2\) | He-ZrO\(_2\) | quartz |
|--------|--------|----------------|-----------|--------------|--------|
| \(B\)  | 34.9×10\(^{-4}\) | 4432.1 | 7326.2×10\(^{-4}\) | 655.9×10\(^{-4}\) | 705.9×10\(^{-4}\) |
| \(a\)  | 0.670  | -1.227        | 0.130     | 0.366        | 0.487  |

Table 1. \(k = B T_g^a\) – thermal conductivity in W m\(^{-1}\) K\(^{-1}\).

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

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

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

The equations are solved at the following boundary conditions:

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

and for \(i = 1, 2, 3\)
The problem formulated above is solved by using homogeneous difference schemes and an iteration procedure for solving the non-linear set of algebraic equation obtained.

The gas-discharge temperature distribution in axial (a) and radial (b) directions are shown for a nanosecond pulsed longitudinal discharges in He (45 Torr) in figure 2 and in He (45 Torr) with small admixtures of strontium (0.6 Torr) and bromine (1.2 Torr) in figure 3 and 4, respectively.

![Figure 2](image1.png)  
**Figure 2 (a) and (b).** Gas-discharge temperature distribution in axial (a) and radial (b) directions for nanosecond pulsed longitudinal discharges in He (45 Torr).

![Figure 3](image2.png)  
**Figure 3 (a) and (b).** Gas-discharge temperature distribution in axial (a) and radial (b) directions for nanosecond pulsed longitudinal discharges in Sr-He (0.6 Torr - 45 Torr) mixture.
Figure 4 (a) and (b). Gas-discharge temperature distribution in axial (a) and radial (b) directions for nanosecond pulsed longitudinal discharges in Br-He (1.2 Torr - 45 Torr) mixture.

4. Conclusions
A new discharge tube design was developed with incompact ZrO$_2$ active-volume insulation of the discharge-free zone, in order to increase additionally the operating temperature; its experimental investigation is in progress. Assuming axial symmetry and a uniform power input, results from 2D numerical modeling ($r$, $z$) of the gas temperature in nanosecond pulsed longitudinal discharges in various mixtures are presented for the newly-designed large-volume high-temperature gas discharge tube. The development of a 2D numerical model for determining the gas temperature in this gas discharge is a further, more complex, step toward approaching the real experimental conditions in the discharge studied.

Acknowledgement
This work was supported by Bulgarian Science Fund for under Grant No 106/2013 (University of Sofia) and contract BK-03-13 (ISSP, Bulgarian Academy of Sciences).

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