Theoretical determination of the gas temperature in a nanosecond pulsed longitudinal discharge exciting high-power strontium atom lasers

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Abstract. Assuming that the gas temperature varies only in the radial direction, an analytical solution of the steady-state heat conduction equation is found for a uniform power input in various gas mixtures and for different discharge tube designs. For this purpose, the heat conductivities of several 2- and 3-component gas mixtures are obtained under gas-discharge conditions optimal for the strontium atom laser.

1. Introduction

During the last decade, our efforts have been dedicated to determining theoretically the spatial distribution of the gas temperature by solving analytically or numerically the steady-state heat conduction equation, which is a quite simple and effective method [1, 2]. Our claims concerning the inaccuracy of the well-known experimental techniques for gas temperature determination, e.g. using measurements of the Doppler broadening of spectral lines or the focal distance of thermal lens, have not so far been met with adequate objections.

For binary gas systems, Brokaw’s empirical method of [3, 4] is widely used, as it is not dependent on the way of determining the heat conductivity of pure components, such as experimental data fit, rigid sphere and Lennard-Jones approximations. The complex character of Wassiljewa’s equation for the heat conductivity of a multicomponent mixture [3, 5] impedes its wide application. Several methods with varying complexity and accuracy have been proposed and used for calculation of the matrix elements (the number of matrix elements for a $k$-component gas mixture is $k^2$) in Wassiljewa’s equation [6-9]. A new simple method based on an iterative application of Brokaw’s empirical method to binary gas systems was proposed and applied to determining the heat conductivity of various multicomponent gas mixtures used as active media of several prospective metal atom and ion lasers, namely, deep ultraviolet Cu$^+$ Ne-H$_2$-CuBr and middle infrared (MIR) He-(Ne-)SrBr$_2$ lasers [10, 11] excited in nanosecond pulsed longitudinal discharges (NPLDs). Using Wassiljewa’s equation and the new method, the heat conductivities of various 2- and 3-component gas mixtures were comparatively calculated under optimal gas-discharge conditions for the abovementioned lasers [12]. It was shown that the discrepancy was comparable with the ones presented in [3], where different methods were used and compared [4-9]. It was concluded in [12] that the use of the new method for heat

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conductivity calculation is definitely preferable when dissociation of molecules occurs in a gas discharge.

In this paper, assuming that the gas temperature varies in the radial direction only and using the heat conductivities calculated, the gas temperature radial distribution is obtained in various laser tube designs in the case of a uniform power input.

2. Experimental setup
One of the important features of our gas-discharge tubes design is that the basic tubes are made of fused quartz. The so-called discharge zone, in which the electric discharge is located, is confined by a ceramic or quartz insert, which is coaxially sleeved in the basic quartz.

Schematic diagrams of the discharge tubes used for the MIR strontium atom laser are shown in figure 1 (a) and (b), respectively. Additional heat insulation of the discharge zone, i.e. the zone between the insert, the basic quartz tube and the holders of the insert, is compactly filled with Al$_2$O$_3$ powder insulation (a) or Al$_2$O$_3$:ZrO$_2$ fiber insulation (b). Cylindrical electrodes made of niobium or molybdenum are used. Sr pieces are placed inside the insert along its length. The vapor pressure necessary for laser oscillation is obtained by discharge heating; i.e. the laser operates in a self-heating mode.

The laser tube studied is excited by an innovative electrical pulsed excitation scheme presented in figure 2. It is based on a commandingly charged symmetrical Blumlein scheme with a peaking capacitor and magnetic pulse compression circuits. The switch T is a hydrogen thyratron EEV 1000/35 or TGI 1000/25. The capacitors used are of the low-inductance KVI-3 type.

3. Results and discussion
Details for the discharge tubes and gas-discharge parameters are given in table 1 and table 2, respectively. Assuming that the gas temperature varies only in the radial direction, the steady-state heat conduction equation is solved at uniform power input as in [1]. The well-known solution of this equation is found for the case of one discharge zone with radius $R_1$, and three discharge-free zones, namely ceramic (BeO or Al$_2$O$_3$) or quartz insert within $R_1 \leq r \leq R_2$ filled compactly with Al$_2$O$_3$ powder or Al$_2$O$_3$:ZrO$_2$ fiber insulation within $R_2 \leq r \leq R_3$, and a basic quartz tube within $R_3 \leq r \leq R_4$. The dependence of the heat conductivity $k$ of gases and gas mixtures has the allometric form $k = BT^a$, where $B$ and $a$ are constants (within a certain temperature range) specific for each gaseous or solid medium. These constants, which determine the heat conductivity, could be obtained through fitting the existing experimental data taken from [13]. The heat conductivities of the materials used are shown in table 3.
Table 1. Discharge tube details: $d_{i.d.}$ – inner diameter; $d_{o.d.}$ – outer diameter; $l_a$ – discharge (active) zone length; $V_a$ – discharge (active) volume.

| Discharge tube | Tube material | $d_{i.d.}$ (mm) | $d_{o.d.}$ (mm) | $l_a$ (cm) | $V_a$ (cm$^3$) | Discharge zone insulation |
|----------------|---------------|-----------------|-----------------|------------|----------------|--------------------------|
| DT1            | BeO           | 19              | 25              | 55         | 156            | Al$_2$O$_3$ powder        |
|                | quartz        | 40              | 46              | 100        | –              | –                        |
| DT2            | Al$_2$O$_3$   | 11              | 15              | 60         | 57             | Al$_2$O$_3$ powder        |
|                | quartz        | 24              | 30              | –          | –              | –                        |
| DT3            | quartz        | 34              | 40              | 100        | 908            | Al$_2$O$_3$;ZrO$_2$ fiber |
|                | quartz        | 59              | 60              | 150        | –              | –                        |
| DT4            | Al$_2$O$_3$   | 37              | 45              | 100        | 1075           | Al$_2$O$_3$;ZrO$_2$ fiber |
|                | quartz        | 60              | 66              | 140        | –              | –                        |

Table 2. Gas-discharge parameters: $p_{Ne-He}$ – buffer-gas mixture pressure; $T_w$ – temperature of the outside quartz tube surface; $P_{in}$ – average electrical input power for 60%- efficiency; $q_V$ – heat source, i.e. electrical power density ($P_{in}/V_a$).

| Discharge tube | $p_{Ne-He}$ (Torr) | $T_w$ (K) | $P_{in}$ (W) | $q_V$ (W cm$^{-3}$) |
|----------------|---------------------|----------|--------------|-------------------|
| DT1            | 4.5-40.5            | 575      | 454          | 2.910             |
|                | 45-0                | 495      | –            | –                 |
| DT2            | 4.5-40.5            | 575      | 239          | 4.193             |
|                | 22.5-22.5           | 520      | 2470         | 2.720             |
| DT3            | 4.5-40.5            | 575      | 695          | –                 |
|                | 0-45                | 495      | –            | –                 |
| DT4            | 22.5-22.5           | 520      | 3881         | 3.610             |
|                | 4.5-40.5            | 575      | –            | –                 |
|                | 0-45                | 695      | –            | –                 |

Figure 3. Heat conductivities as a function of the gas temperature for various 2- and 3-component gas mixtures.

Table 3. $k = B.T_e^a$ – heat conductivity ($B$ and $a$ are for $k$ in W m$^{-1}$ K$^{-1}$).

|        | BeO       | Al$_2$O$_3$ | Al$_2$O$_3$ powder insulation | Al$_2$O$_3$;ZrO$_2$ fiber insulation | quartz |
|--------|-----------|-------------|-------------------------------|-------------------------------------|--------|
| $B$    | $6.6 \times 10^6$ | 44323.1     | 113.2 $\times 10^4$             | 226.4 $\times 10^4$                 | 705.9 $\times 10^4$ |
| $a$    | -1.714    | -1.227      | 0.361                         | 0.361                               | 0.487  |

In order to calculate heat conductivities of gas mixtures, the newly developed method is used. In figure 3 the heat conductivities as a function of the gas temperature are shown for various 2- and 3-component gas mixtures.

Figure 4 presents the radial temperature distribution in discharge tubes DT1 (a) and DT2 (b).

The radial temperature distributions are plotted in figure 5 for the two studied discharge tubes DT3 (a) and DT4 (b), respectively.
4. Conclusions
Heat conductivities of various 2- and 3- component gas mixtures are calculated. Using the calculated heat conductivities and assuming that the gas temperature varies in the radial direction only, the radial gas temperature distribution is obtained in several discharge tubes with different designs.

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