COMPUTER STUDY OF THE TEMPERATURE DISTRIBUTION OF THE GAS DISCHARGE TUBE OF A STRONTIUM BROMIDE VAPOR LASER

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Abstract: An object of study is a $SrBr_2$ vapor laser source with its emission at a wavelength 6.45 µm. This type of laser finds applications in medicine and biology. A temperature model, determining the laser medium's temperature profile under forced convection is used in this study on the basis of quasi-stationary heat conduction equation. It was established that the working temperature can change in a wide range while the airflow velocity changes. Computer simulations that let increase of supplied electrical power for holding optimal temperature in the center of the tube were performed.

Keywords: gas temperature, temperature model, cooling by forced convection, gas discharge tube

1. INTRODUCTION

Laser generation with wavelength 6.45 µm is the most applicable in medical practice and biology. It is in particular the most effective means of removing soft tissues and bones with minimal thermal damage and without infection when performing operations [1, 2]. Free-electron lasers and Strontium vapor laser were basic sources of this emission. Strontium bromide vapor laser ($SrBr_2$) ranges among the most modern inventions in this field. Stable laser generation was achieved firstly in 2002 [3]. It is constructed on the basis of Strontium vapor laser when Strontium bromide replaced atomic Strontium. One of the most important perspectives for this laser is related to its emission of 6.45 µm. For this cause Strontium bromide laser replaces Free-electron lasers used so far, surpassing them in technical characteristics, price and a significantly simpler maintenance in a variety of clinical systems. $SrBr_2$ vapor laser significantly surpasses Strontium atom laser in laser tube's longer life time expiration as well. All these advantages make a commercial attraction of $SrBr_2$ vapor laser which is an object of an active development. A laser generation with its power of 4.26 W was obtained to the present moment, as 90% of the emission in the wavelength λ = 6.45 µm [4 - 6]. When replacing Strontium Metal with $SrBr_2$ the operating temperature of the active medium in the gas tube increases from 600^{o}C to 1100^{o}C.

Almost double increase of the SrBr2 vapor laser's working temperature turns temperature mode into one of its most important characteristics. This is referred to all metal vapor lasers and their compounds. The life-time expiration of the tube, thermo-chemical degradation of laser medium, and quality of laser beam are determined by high temperature to a wide extend. Analytic model for laser tube temperature profile determination was developed for studying the heat exchange in the tube. Models referring to Copper bromide vapor laser, emitting in visible and ultraviolet field were developed initially in [7 - 10]. Later these methods were successfully applied to the Strontium bromide vapor laser temperature profile study [11 - 13].

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All the developed models to the present moment have one common feature- the temperature of the outer side of the tube, measured properly is known. This method of approach is unacceptable for new designed lasers, where this temperature remains unknown. For this reason, a model with a given surrounding temperature (most often 300 K) and without fixing the temperature of the external tube wall was firstly developed in [12]. This was obtained by mixed boundary conditions describing the interaction of the external surface of the tube with the surroundings through natural convection and heat radiation processes.

Lasers are constructed for working in natural convection conditions. Due to various reasons - a temporary increase of supplied input electric power, surrounding temperature increase, operation in closed or semi-closed devices, where natural convection is hardened, the laser can ease of the indicated temperature mode. In such cases one possible decision is its forced cooling, for example by a pointed airflow of fans.

Natural convection processes where laser tube is forcedly cooled are not considered in the previous studies to the present moment.

The purpose of this study is to complete the existing temperature models by analyzing thermal behavior of the laser tube in conditions of forced convection.

2. DESCRIPTION OF THE NEW TEMPERATURE MODEL

A high powered $SrBr_2$ vapor laser described in [5, 6] is an object of study. The cross section of the active volume is presented in Figure 1. The total length of the laser tube is 2.30 m, and the active volume length (the distance between the electrodes) is 98 cm. The laser was completely made of quartz (position 3), and an additional ceramic tube Al_2O_3 (position 1) was inserted in the active volume. There is free space, filled with Helium buffer gas (position 2) in between the two tubes. The active volume was covered with heat insulating coating of ZrO_2 from the external side (position 4). The total consumed electric power of the laser is 2.1 KW. When indicating losses, electric power Q = 1365W or average volume power density $q_v = 4.55\ \mathrm{W/cm^3}$ is supplied in the active volume. The total initial laser power is 4W, and the line 6.45 μm is 90% of the emission.

For solving the problem it is necessary to solve the following heat conduction equation in cylindrical coordinates in the cross-section of laser tube:

$$\mathrm{div}\left(\lambda \,\mathrm{grad} T_g\right) + q_v\left(r\right) = 0 \tag{1}$$

where λ is a thermal conductivity coefficient of the gas, $\lambda = \lambda_0 T_g^m$; q_v is the density of the internal heat source, and T_g is the unknown gas temperature of the discharge in the internal tube.

The following boundary conditions of the first and second kind are used for the gas temperature of the discharge:

$$T_g\left(R_1\right) = T_1 \tag{2}$$

$$\left.\frac{dT_g}{dr}\right|_{r=0} = 0 \tag{3}$$

In the boundary condition (2) the temperature T_1 of the outside surface of the quartz tube, Figure 1, will be considered as known quantity. The boundary condition (3) shows the existence of the maximum temperature value in the center of the tube, with regard to the symmetry at $r = 0$.

The corresponding diameters are $d_1 = 19.8$ mm, $d_2 = 25.5$ mm $d_3 = 40$ mm, $d_4 = 46$ mm, and $d_5 = 52$ mm.

Mixed boundary conditions are used for solving equation (1) in a geometric design in Figure 1.

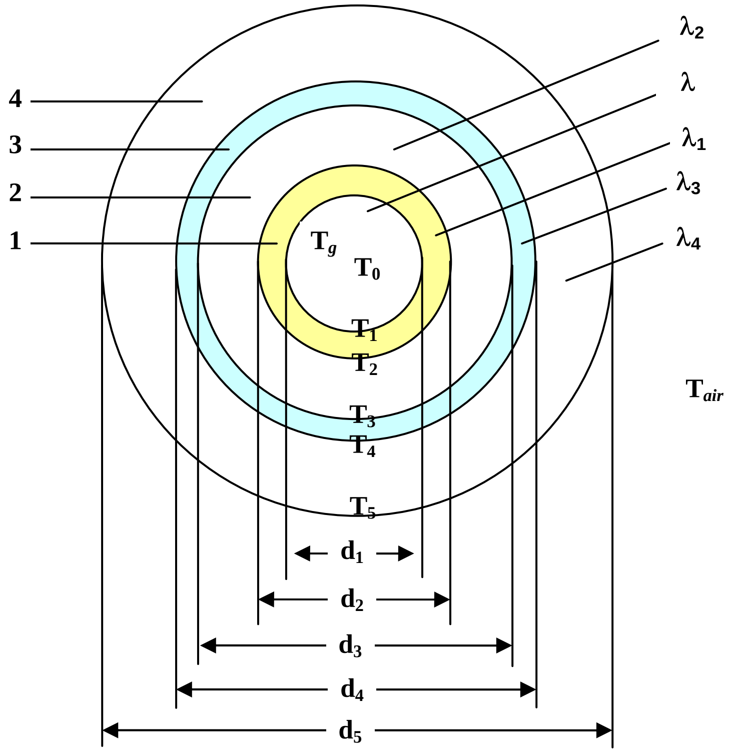

Fig. 1. Geometry of the cross-section of the laser tube of a $SrBr_2$ laser:
1 - ceramic (Al_2O_3) tube; 2 - space filled with helium; 3 - quart tube; 4 - insulation.

2.1. Boundary condition for the surroundings and outside tube wall

Normally the temperature of the surroundings is taken to be $T_{air} = 300\,\mathrm{K}$.

For defining the unknown temperatures T_4 and T_5 we impose the following new boundary conditions:

$$Q = \alpha F_5 \left(T_5 - T_{air}\right) + F_5 \varepsilon c \left[\left(\frac{T_5}{100}\right)^4 - \left(\frac{T_{air}}{100}\right)^4\right] \qquad (4)$$

$$T_4 = T_5 + q_l \ln\left(d_5/d_4\right)/\left(2\pi\lambda_3\right) \qquad (5)$$

Boundary condition (4) expresses the heat transfer between the external surface area of the laser tube and the surrounding area. It contains two addends. The first addend is the Newton-Richman law for heat transfer through convection, and the second is the Stefan-Boltzmann law for heat transfer through radiation. The quantity Q is the overall heat flow which is equal to electrical power consumption of the tube, α is the heat transfer coefficient, F_5 is the external active surface area of the tube insulation , ε is the integral radiation coefficient, depending on the material, $c = 5.67\,\mathrm{W/(m^2K^4)}$ - radiation coefficient. There are two unknown quantities - α and T_5 in boundary condition (4). A preliminary definition of the quantity α is needed to define the quantity T_5.

2.2. Boundary condition on the walls of the quartz tube

In cylindrical configuration, the following equation is valid on the walls of the quartz tube (see Figure 1) [9]:

$$T_3 = T_4 + q_l \ln\left(d_4/d_3\right)/\left(2\pi\lambda_3\right) \qquad (6)$$

2.3. Boundary condition in the intermediate space between the two tubes

The space between the two tubes, Figure 1, position 2, is filled with Helium. The boundary condition has the following form:

$$Q = \varepsilon_{eff} c \left[\left(T_2 / 100\right)^4 - \left(T_3 / 100\right)^4 \right] S_2 + 2\pi\lambda_2 l_a / \ln\left(d_3/d_2\right)\left(T_2 - T_3\right) + 2\pi\lambda_{eff} l_a / \ln\left(d_3/d_2\right)\left(T_2 - T_3\right) \quad (7)$$

i.e. $Q = Q_1 + Q_2 + Q_3$, where

$$\varepsilon_{eff} = \frac{1}{\frac{1-\varepsilon_1}{\varepsilon_1} \cdot \frac{S_2}{S_3} + \frac{1}{F_{23}} + \frac{1-\varepsilon_2}{\varepsilon_2}};$$

$$\lambda_{eff} = 0.386\lambda_2 \left(\frac{\mathrm{Pr}}{0.861 + \mathrm{Pr}} \right)^{1/4} \left(Ra_{cyl}^* \right)^{1/4};$$

$$\left(Ra_{cyl}^* \right)^{1/4} = \frac{\ln\left(d_3/d_2\right)}{\delta^{3/4} \left(d_2^{-3/5} + d_3^{-3/5} \right)^{5/4}} Ra_\delta^{1/4};$$

$$Ra_\delta = \frac{g\beta\left(T_2 - T_3\right)\delta^3}{\upsilon^2} \mathrm{Pr}; \qquad \delta = 0.5\left(d_3 - d_2\right)$$

2.4. Boundary condition for the ceramic tube

The following equation is valid for the ceramic tube:

$$T_1 = T_2 + q_l \ln\left(d_2/d_1\right) / \left(2\pi\lambda_1\right) \quad (8)$$

The notations are as follow: $Q = 1365\,\mathrm{W}$ is the heat flow, equal to the consumed electric power; $q_l = Q / l_a$, $l_a = 0.98\,\mathrm{m}$ is the active length; $\lambda_1, \lambda_2, \lambda_3$ are the heat conductivity coefficients of the Al_2O_3 tube, quartz tube and the heat insulation, respectively; $d_j,\ j = 1, 2, 3, 4, 5$ are the corresponding diameters of the tubes (see Figure1). The coefficient ε_{eff} is an effective radiation coefficient, giving the multiple space reflections between the two tubes (2), Figure 1, $\varepsilon_1 = 0.52$ and $\varepsilon_2 = 0.72$ are the respective integral radiation constants of the ceramic and the quartz tube, $S_2 = \pi l_a d_2$, $S_3 = \pi l_a d_3$ are surface areas. The quantity F_{23} is a geometric factor, defined by the ratios r_2 / r_3 and l_a / r_2 and is $F_{23} = 0.8$ [9].

3. DETERMINATION OF THE UNKNOWN QUANTITIES

3.1. Defining the heat transfer coefficient α in the case of forced convection

By using Nusselt number for any type of convection we have [9]:

$$Nu = \alpha H / \lambda \quad (9)$$

In addition, the Raynolds number is valid in case of forced convection in the form [9]:

$$Re = vH / \upsilon \quad (10)$$

For horizontal tubes with forced cross direction of the airflow the following ratio between the two upper numbers is valid [10]:

$$Nu = 0.615\,\mathrm{Re}^{0.466} \tag{11}$$

Equation (11) is valid when $5 < Re < 10^3$. The quantities used in (9)-(11) are as follows: *H* is a typical tube size (here $H = d_5$), T_{air}=300K [10].

Through (9) - (11) the quantity α is expressed by the following formula:

$$\alpha = 0.753 v^{0.466} / d_5 \tag{12}$$

Boundary condition (4), using (12), using power per unit length gets the completed form:

$$q_l = 0.753 v^{0.466}\left(T_5 - T_{air}\right) + \pi d_5 \varepsilon c\left[\left(T_5/100\right)^4 - \left(T_{air}/100\right)^4\right] \tag{13}$$

In equation (13) T_5 is the only unknown quantity. After having defined it by (4), (6) - (8), T_4, T_3, T_2, T_1 are calculated successively.

3.2. Defining the temperature in the active volume cross section

In case of known temperature T_1 the determination of temperature profile of the cross sectioned laser volume is possible.

To the present moment we don't have reliable experimental results, showing concrete distribution of $q_v(r)$.

In the referred literature $q_v(r)$ is recommended to be presented as a second degree polynomial [11, 12]:

$$q_v\left(r\right) = K_1 q_0\left(a + br^2\right) \tag{14}$$

where K_1 = 1.43424; *a*=1.0237072; *b*= -9993.0943.

According to this, the temperature distribution in the tube cross section is given by:

$$T_g(r) = \left(T_1^{m+1} - \left(1+m\right)K_1 q_0\left(r^2 - R_1^2\right)\left(4a + br^2 + bR_1^2\right)/\left(16\lambda_0\right)\right)^{-1-m} \tag{15}$$

4. RESULTS

In Figure 2 temperature distribution is shown in two cases: cooling with cross flow with velocities *v* = 2 m/s and *v* = 5 m/s. Temperature distribution in the case of natural convection (*v* = 0 m/s) is shown in the same figure for comparison. The presented computer simulations show that forced cooling has great opportunities for relieving the optimal temperature profile. In case of a comparably not very big flow velocity (*v* = 5 m/s) the temperature shows a decrease of 180^{o}C. Forced cooling has its own natural restriction: The temperature T_1 cannot be below the optimal for the emission of $SrBr_2$ laser. Otherwise $SrBr_2$ condenses on the internal side of the quartz tube which could cause laser generation collapse.

One of the ways of a higher output laser power is the increase of the supplied electric energy. This has its own natural restriction. Gas temperature increases with the increase of the supplied power. Processes of thermionization instability, which can lead to laser generation interruption, arise when reaching critical values.

Thermo-chemical degradation of the medium is increased as well. The active use of the processes of forced cooling of laser medium gives the opportunity possible increase of supplied electric power. Higher electric power can combine with more active forced cooling aiming to keep the initial temperature profile, which could be taken as optimal. For example the temperature at v = 5 m/s (Figure 2) has a decrease of 180°C below the initial one at v = 0 m/s (case of natural convection). Which means that we could increase the supplied power until it reaches its initial temperature profile at v = 0 m/s, that we accept as an optimal.

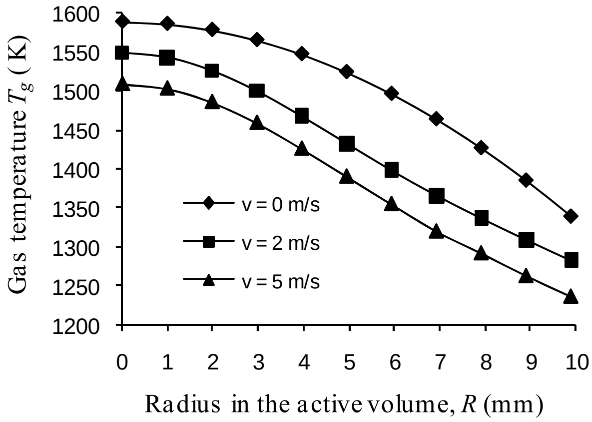

Fig. 2. Distribution of the gas temperature for different values of the cooling velocities at a constant total electric power $Q_t = 2100\,\mathrm{W}$.

Results obtained from computer simulations are shown in Figure 3. For each supplied velocity of forced cooling the supplied electric power increases until it reaches its initial optimal temperature in the center of the tube $T_0 = 1588\,\mathrm{K}$. In this figure we can see that the new temperature profile is not identical with the initial one although the temperature in center of the tube is one and the same. In the rest of the temperature points the laser medium is lower than the optimal one. This is also referred to the temperature T_2 of the internal side of the quartz tube. This fact imposes natural restriction as well. In case of T_2 lower than the optimal, $SrBr_2$ vapors condense on the tube which could cause laser generation collapse.

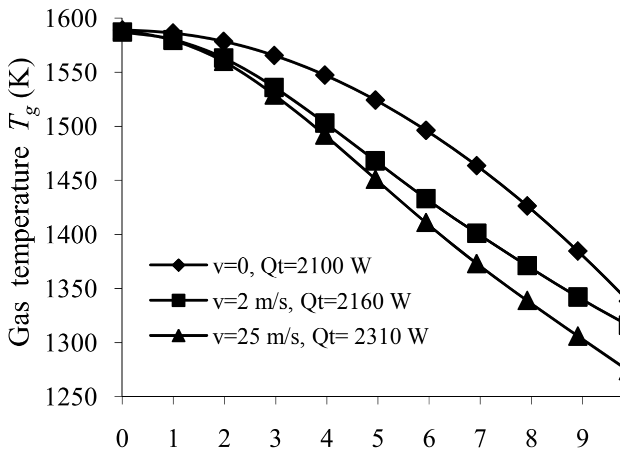

Fig. 3. Distribution of the temperature $T_g(r)$ for different values of the forced airflow and supplied electrical power at a constant temperature $T_0 = 1588\,\mathrm{K}$.

The dependence between cooling velocity and relative increase of supplied electric power at constant temperature $T_0 = 1588\,\mathrm{K}$ is shown in Figure 4. As a base here a total electric power of 2100 W is taken. The total electric power increase turned out to be able of sensible limits of 10 - 12%.

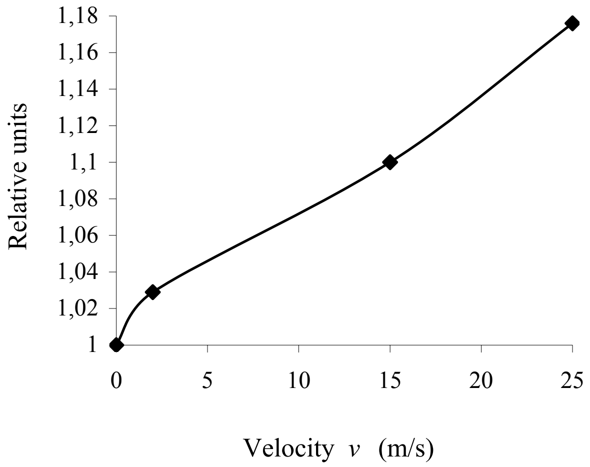

Fig. 4. Dependence between the relative increase of the total electric power and the velocity of the cooling flow at a constant optimal temperature $T_0 = 1588\,\mathrm{K}$.

4. CONCLUSION

On the basis of previously developed temperature models, related to metal halide vapor lasers a temperature model studying $SrBr_2$ vapor laser behavior in conditions of forced convection is obtained for the first time. It was demonstrated that forced cooling can significantly impact on temperature profile in active laser volume. Computer simulations that let increase of supplied electric power in case of maintaining constant temperature in the center of a laser tube were done. Natural restrictions of forced cooling process were indicated.

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