Theory and Experiment of Electric Discharge CO_2 Convection Lasers

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Theme

A THEORETICAL model has been developed for high flow rate molecular gas electric discharge lasers which considers the complete problem of coupling flow parameter variations with excitation and relaxation processes in the active region of a high-velocity laser system. Other studies[1-3] have investigated specific aspects of such systems, particularly at low flow rates where flow parameter variations are negligible, but none has considered the complete problem presented here. To validate the use of this model, numerical results of small signal gain for a coaxial system with premixed flows of CO_2, N_2, and He in a cylindrical discharge tube were generated and shown to agree favorably with experimental results obtained over a restricted (experimentally) range of flow rates. Theoretical results for the saturation intensity were generated also. With minor modifications the model is applicable to transverse geometries.

Content

The theoretical model is one-dimensional since, for the high flow rates considered, convective cooling and variations in the flow direction dominate. Conventional macroscopic conservation equations of species, mass, momentum, energy, and electron energy are employed with the electron energy equation simplified by neglecting gradient terms. Ohm's law in the form $j = \sigma_o E$ relates the current density j (assumed constant along the tube) to the electric field strength E and scalar conductivity σ_o. The optical gain coefficient $\gamma = (1/I)\,dI/dx$ (I is the radiation intensity) is that for a single frequency vibration-rotation transition with the effects of pressure and Doppler line broadening included.

The kinetic portion of the model includes pertinent excitational and collisional reactions between the following energy states: 1) the ground state, the first three bending modes, the symmetric stretch mode (lower laser level), and the asymmetric stretch mode (upper laser level) of CO_2; 2) the ground state and first vibrational level of N_2 along with ionized N_2; and, 3) the ground state of He. Molecules in these different energy states are treated as separate species, and several species conservation equations are required. Production rates for the different species are obtained by summing over the appropriate reactions using forward reaction rates obtained from the literature and backward rates determined by detailed balancing. Maxwellian distribution functions are used to determine those reaction rates depending on the electron distribution. For comparison, reaction rates obtained from non-Maxwellian distributions[4] were used for the electron vibrational excitation reactions, and it was found that this had very little effect on the gain calculations. Additional work is under way to incorporate the effects of non-Maxwellian distributions into the model in a more general way, particularly with regard to the ionization rate.

The numerical solution requires solving six simultaneous non-linear first-order differential equations using a variable increment version of Treanor's integration method.[5] The parameters which must be specified are the gas temperature and electric field strength at the tube entrance, the mass flow rates, and the current density (or input power) along with the pressure, velocity, or Mach number at either the tube entrance or exit. The electron concentration and temperature at the tube entrance are determined from Ohm's law and the electron energy equation, while the heavy particle entrance concentrations are determined by assuming equilibrium at the gas temperature and pressure.

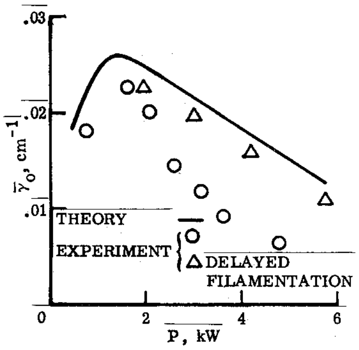

Fig. 1 Average small signal gain vs discharge power (mass flow rates of CO_2, N_2, and He are 1.29, 1.64, and 0.7 g/sec, respectively).

Typical results are shown in Figs. 1 and 2 for the $P(20)$, $(0, 0°, 1)$ to $(1, 0°, 0)$ transition of CO_2 at 10.6 μm with mass flows as indicated in Fig. 1. For the theoretical results, initial conditions were taken as $T = 300°K$ and $E = 100$ v/cm at the tube entrance and Mach number equal one at the exit. Experimental results were obtained from conventional laser gain measurements performed on a high-flow coaxial electric discharge laser, using an insulating disk with sonic orifices in the flow to distribute current in the tube and delay discharge filamentation to higher pressures and current densities. Figure 1 shows a typical comparison between theory and experiment for the effect of discharge power on the small signal gain $\bar{\gamma}_0 = (1/L)\int_0^L \gamma_0 dx$ (L and γ_0 are the tube length and local gain coefficient). Agreement is good, particularly when filamentation is delayed.

A significant conclusion reached in this research is that, for the sonic exit case, decreases in $\bar{\gamma}_o$ with increasing discharge power (see Fig. 1) are due primarily to gradients (in the flow

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Index categories: Reactive Flows; Thermochemistry and Chemical Kinetics.

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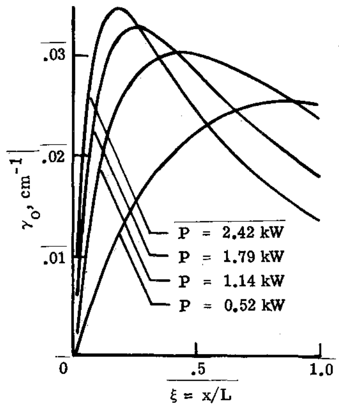

Fig. 2 Local small signal gain coefficient vs axial distance.

direction) of particle concentrations and velocity, and to a lesser extent to increased temperature in the downstream portion of the tube. These gradients lead to inefficient use of the downstream portion of the tube as illustrated in Fig. 2 which shows the variation of the local gain γ_o along the tube for various discharge powers. The results shown in Fig. 2 can be explained by examining the species conservation equation for the upper laser level

$$R_5 = u\, dn_5/dx + n_5\, du/dx$$

where R_5, n_5, and u are the net particle production rate per unit volume for the upper laser level, the upper laser level particle concentration, and the flow velocity. As discharge power is increased the term $n_5\, du/dx$ becomes larger than R_5 due to an increased velocity gradient. To maintain species conservation, the term $u\, dn_5/dx$ becomes negative, and γ_o, which is proportional to n_5, decreases. This effect is due primarily to the large velocity gradients required by the sonic exit condition. Calculations were carried out for total mass flows up to five times that of Figs. 1 and 2, and the conclusions were the same as for Figs. 1 and 2 although the peak in $\bar{\gamma}_o$ was shifted to a higher power level.

In summary, a computer model applicable to high flow rate CO_2 electric discharge lasers with either coaxial or transverse geometries has been developed and has been validated with limited experimental data. Application of this model has shown the importance of velocity and particle concentration gradients in determining the spatial dependence of the gain coefficient and emphasized the importance of including fluid mechanical properties of molecular lasers when high-flow rates and sonic or near-sonic velocities are present.

References

[1] Cool, T. A., "Power and Gain Characteristics of High Speed Flow Lasers," *Journal of Applied Physics,* Vol. 40, No. 9, Aug. 1969, pp. 3563–3573.

[2] Bullis, R. H., Nighan, W. L., Fowler, M. C., and Wiegand, W. J., "Physics of CO_2 Electric Discharge Lasers," AIAA Paper 71-64, New York, 1971.

[3] Hassan, H. A. and Bordeaux, J. W., "Analysis of an Electric Discharge CO_2 Mixing Laser," AIAA Paper 71-66, New York, 1971.

[4] Nighan, W. L., "Electron Energy Distributions and Collision Rates in Electrically Excited N_2, CO, and CO_2," *Physical Review,* Vol. 2, No. 5, Nov. 1970, pp. A1989–2000.

[5] Treanor, C. E., "A Method for the Numerical Integration of Coupled First-Order Differential Equations With Greatly Different Time Constants," *Mathematics of Computation,* Vol. 20, No. 93, Jan. 1966, pp. 39–45.