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Research Note

Numerical Investigation of Fast Axial Flow High Power CW CO_2 Laser: Considering the Effect of Intensity Variation

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The effect of intensity variation on the quantum densities of active medium and thermodynamic characteristics of a high turbulent flow CO_2 laser has been investigated. Comparison between the calculation of constant and variant intensity on the quantum densities and thermodynamic characteristics of turbulent gas flow shows a $\sim$ 10% drop in the output power of the laser, which is only 50 cm long.

INTRODUCTION

It is usually possible to predict the output power and active medium characteristics of a laser by use of a suitable model [1].

A suitable model for a high power, high-speed flow CO_2 laser has been investigated theoretically and experimentally by Muller and Uhlenbush [2] and Baeva and Atanasove [3].

In the above articles, the active medium was separated into two regions of external, without radiation, and internal with average constant intensity. The article also investigated the effects of turbulent convection and diffusion on the quantum densities and output power.

In the present article, the same model as above has been used, but the effect of variable intensity in the internal region has also been considered on the quantum densities, flow thermodynamic characteristics and output power of a CO_2 laser.

In addition, due to diffusion and convection of turbulent flow, the contributions of quantum densities from external to internal regions, have been considered in the equations of quantum densities in the external region.

These calculations are compared with calculations of the constant intensity model.

LASER MODEL

According to the 5-temperature model, the energy of each vibrational-rotational mode of molecules is introduced by its own temperature:

T_1	for symmetrical mode of CO_2 molecules,
T_2	for bending mode of CO_2 molecules,
T_3	for non-symmetrical mode of CO_2 molecules,
T_N	for vibrational mode of N_2 molecules,
T	for macroscopic temperature of gas mixture (one-dimensional approximation [2]).

If the quantum densities are defined in the base of the V-V and V-T temperature [1]:

$$q_i = \exp(-\varepsilon_i/kT_i)/1 - \exp(-\varepsilon_i/kT_i), \qquad (1)$$

where $i = 1, 2, 3$ for CO_2 and $i = N$ for N_2 and ε_i is the quantum energy of each vibrational-rotational mode.

The equation of variation of quantum densities along the tube are formulated as follows [2,3]:

$$\frac{dq_1^\alpha}{dt} = q'^{\alpha}_{e,1} + q'^{\alpha}_{1-2,1} + q'^{a}_{\text{diff},1} + q'^{\alpha}_{\text{conv},1} + q'^{\alpha}_{\text{rad},1},$$

$$\frac{dq_2^\alpha}{dt} = q'^{\alpha}_{e,2} - q'^{\alpha}_{1-2,1} - (3/2)q'^{\alpha}_{3-2,3} + q'^{\alpha}_{2-2,1} + q'^{a}_{\text{diff},2} + q'^{\alpha}_{\text{conv},2},$$

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$$\frac{dq_3^\alpha}{dt}=q'^{\alpha}_{e,3}+q'^{\alpha}_{N,3}+q'^{\alpha}_{3-2,3}+q'^{a}_{\mathrm{diff},3}+q'^{\alpha}_{\mathrm{conv},3}+q'^{\alpha}_{\mathrm{rad},3},$$

$$\frac{dq_N^\alpha}{dt}=q'^{\alpha}_{e,N}-\frac{N_{\mathrm{CO_2}}}{N_{\mathrm{N_2}}}q'^{\alpha}_{N,3}+q'^{a}_{\mathrm{diff},N}+q'^{\alpha}_{\mathrm{conv},N}, \qquad (2)$$

where:

α	indicates internal and external regions,
$q'^{\alpha}_{e,i}$	express the evolution of the quantum densities due to collisions with electrons,
$q'^{\alpha}_{i-j,i}$	the V-V and V-T energy transfer due to collision among CO_2, N_2 and He,
$q'^{\alpha}_{\mathrm{rad},1 \text{ or } 3}$	the variation of quantum densities due to stimulated emission,
$q'^{\alpha}_{\mathrm{diff},i}, q'^{\alpha}_{\mathrm{conv}i}$	the variation of quantum density due to diffusion and convection of turbulent flow.

The interaction process among modes are shown in Figure 1; four collision of V-V, three V-T and one stimulated emission in 10.6 μm, in transition from 001 to 100.

The equations for gas mixture dynamic are [3]:

$$\rho V_z = \text{cte} \quad \text{(continuity equation)},$$

$$\rho V_z dV_z = -dp + \zeta\rho V_z\hat{\ }2/2 \quad \text{(momentum equation)},$$

$$\rho V_z C_p(dT_z/dz) + \rho V_z\hat{\ }2(dV_z/dz) + 2h/R(T - T_W)$$

$$= W_E - W_L \quad \text{(energy equation)},$$

$$P = N_{\text{total}}kT \text{(state equation)}. \qquad (3)$$

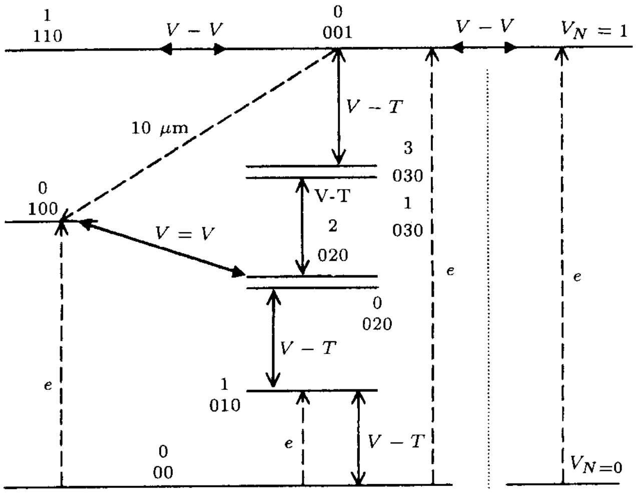

Figure 1. The molecular interaction process and electron excitation model among CO_2, N_2 and He.

where P is gas pressure, T is gas temperature, ρ is gas density and V_z is the gas velocity, T_W is the wall temperature and z is the distance in the direction of gas flow. C_p is heat capacity in constant pressure, ζ is losses of friction and h is the heat flux coefficient. W_E is the input electric power in unit volume and W_L describes the specific laser power.

METHOD OF SOLVING

The system of differential Equations 2 and 3 are solved twice and simultaneously for the inner and outer regions. Once, for zero intensity, where q_i, the quantum densities, γ_0, small signal gain and gas T, P, ρ and V_z, thermodynamic characteristics along the cavity, are calculated. In the second stage, the stimulated emission is considered for the internal region and the quantum densities and thermodynamic characteristics are calculated, while, due to null radiation in the external part, their values were kept constant. Now, the output power, quantum densities and thermodynamic characteristics are compared for constant intensity [2,3] and the model presented for variant intensity. In the above calculations, in the outer regime with q_j^{ext}, the radiation field is zero and, additionally, the diffusive and convective terms are negligible [2].

The laser intensity variations along the cavity, z, in positive and negative directions are as follows [4]:

$$\frac{1}{I_v}\frac{dI_v}{dz} = \frac{\gamma_0(v)}{(1+\bar{g}(v)I_v/I_s)},$$

$$dI^+/dz = \gamma_0/1 + (I^+ + I^-)/I_s,$$

(the laser intensity in positive direction),

$$dI^+/dz = -\gamma_0/1 + (I^+ + I^-)/I_s,$$

(the laser intensity in negative direction), (4)

and in $I = I_s$, the $\gamma[I_s] = \gamma_0/2$ Criterion 1.

Where the boundary conditions on the mirrors are:

$$I^-[0] = R1\ I^+[0],$$

$$I^-[L] = R1\ I^+[L].$$

$R1$ and $R2$ are back and front mirror reflectivity and L is the cavity length.

The system of Equation 2 is solved by trial and error in I_s, until Criterion 1 is established. Then, by solving Equations 2 to 4 for stable operation of the laser, the output power, $P_{\text{out}} = I^+[L]t_mQ$, quantum densities and thermodynamic characteristics of flow in the internal region are calculated, where t_m is the front mirror transmission coefficient and Q is the beam cross-section.

RESULTS AND DISCUSSION

Equations 2 to 4 have been solved for laser assembly of [2] and for one tube. The back mirror is totally reflected with a radius of 10 m and the front mirror is flat ZnSe with 80% reflection. The mode volume of the laser beam is $R_L = 1.2$ cm. The internal and external regions are shown in Figure 2 and the initial conditions for turbulent flow are $P_{st} = 10600$ pa, $P[0] = 6400$ pa, $T[0] = 300$°K, $V_z[0] = 300$ m/s and $W_E = 5.4$ watt/cm^3.

The thermodynamic characteristics of fluid for the external region have been calculated and shown in Figures 3 to 6. For null intensity, these values are equal for internal and external regions.

The system of Differential Equations 3 results in the quantum densities (Figures 7 and 8) and small signal gain (Figure 9) with average gain, $\gamma_0 = 0.642$.

The output power has been calculated and this value for constant intensity is $P_{\text{out}} = 476$ watt, but, considering the variant intensity in the cavity, the output power is $P_{\text{out}} = 426$ watt.

To explain the above difference in output power, the laser intensity inside the cavity has been calculated

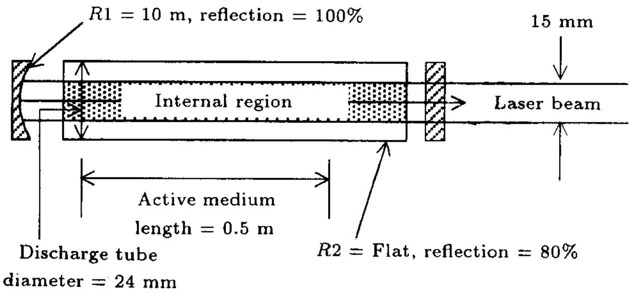

Figure 2. The laser tube. The mode volume $R_L = 7.5$ mm and the tube radius $R = 12$ mm; gas mixture: CO_2, N_2 and He: 4.5, 13.5 and 82, respectively.

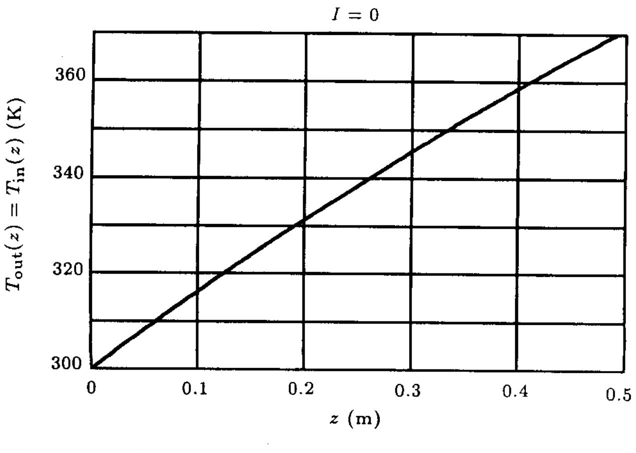

Figure 3. The gas temperature along cavity for $I = 0$, $T_0(z) = 300$°K, $\bar{T}(z) = 337$°K; gas mixture: CO_2, N_2 and He: 4.5,13.5 and 82, respectively.

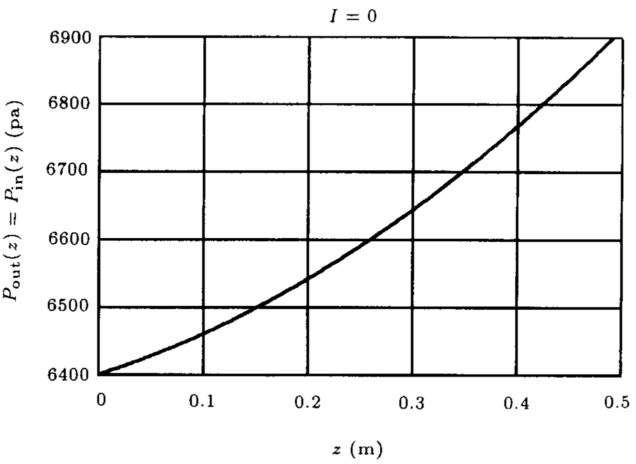

Figure 4. The gas pressure along cavity for $I = 0$, $P_0(z) = 6400$ pa; gas mixture: CO_2, N_2 and He: 4.5, 13.5 and 82, respectively.

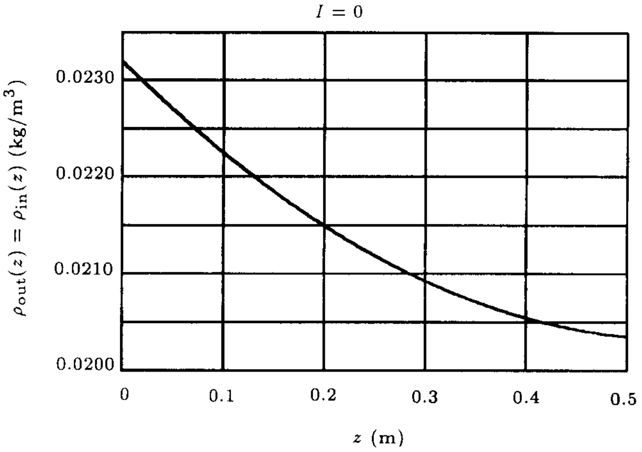

Figure 5. The gas density along cavity for $I = 0$, $\rho_0(z) = 0.0232$ kg/m^3; gas mixture: CO_2, N_2 and He: 4.5, 13.5 and 82, respectively.

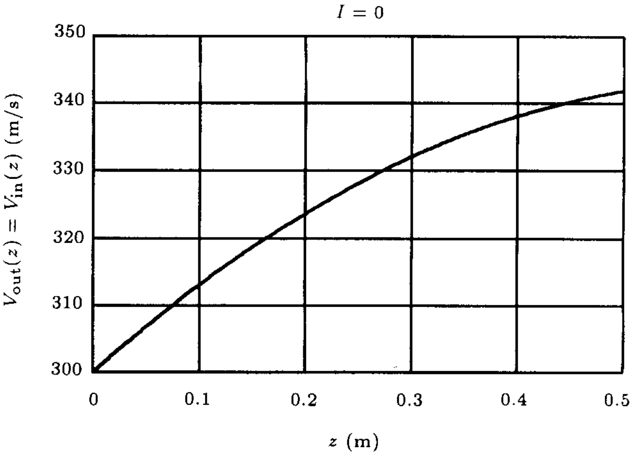

Figure 6. The axial flow velocity along cavity for $I = 0$, $V_0(z) = 300$ m/s, $\bar{V}_z(z) = 326$ m/s; gas mixture: CO_2, N_2 and He: 4.5, 13 and 82, respectively.

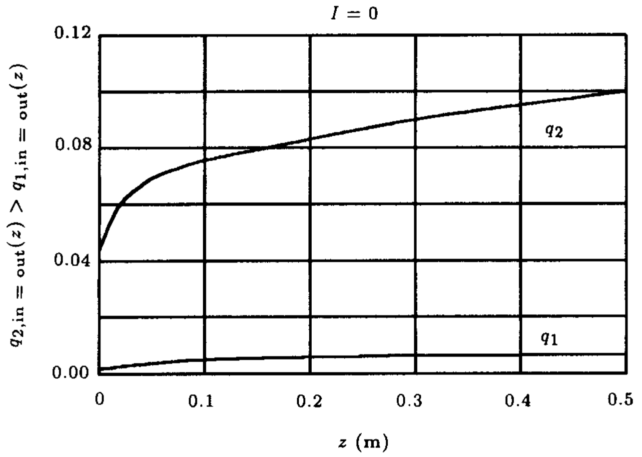

Figure 7. The quantum density q_1 and q_2 along cavity for $I = 0$; gas mixture: CO_2, N_2 and He: 4.5, 13.5 and 82, respectively.

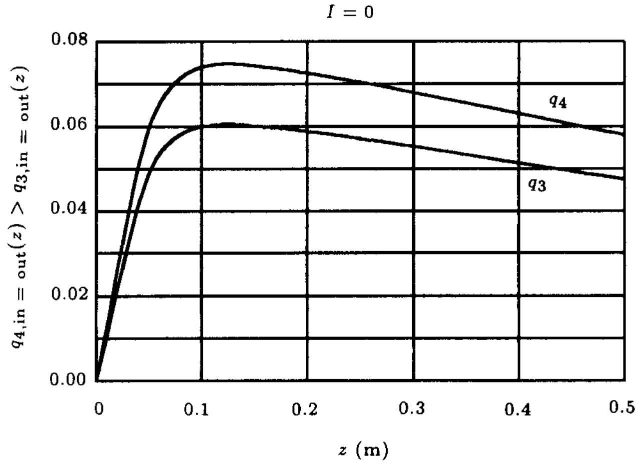

Figure 8. The quantum density q_3 and q_4 along cavity for $I = 0$; gas mixture: CO_2, N_2 and He: 4.5, 13.5 and 82, respectively.

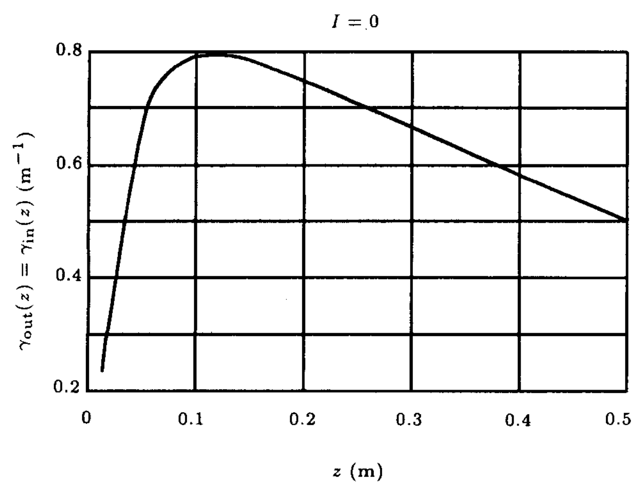

Figure 9. The small signal gain along cavity for $I = 0$, $\bar{\gamma}_0 = 0.642$ m^{-1}; gas mixture: CO_2, N_2 and He: 4.5, 13.5 and 82, respectively.

and shown in Figure 10. From these calculations, one can reach the conclusion that conversion of energy into stimulated emission would be less in variant intensity compared to the average intensity model.

The temperature, $T[z]$, for the variant and average intensity models (Figure 11) shows that more energy would be converted to heat in variant intensity. The pressure $P[z]$, density $\rho[z]$, velocity $V_z[z]$, quantum densities q_i and gain calculated are shown in Figures 12 to 18, respectively, for the variant and average intensity models.

The above calculation shows, in spite of the fact that the turbulent flow intends to homage fluid characteristics, the rapid mechanism of stimulated emission always causes these differences in output power, quantum densities and thermodynamic characteristics for variant and average intensity.

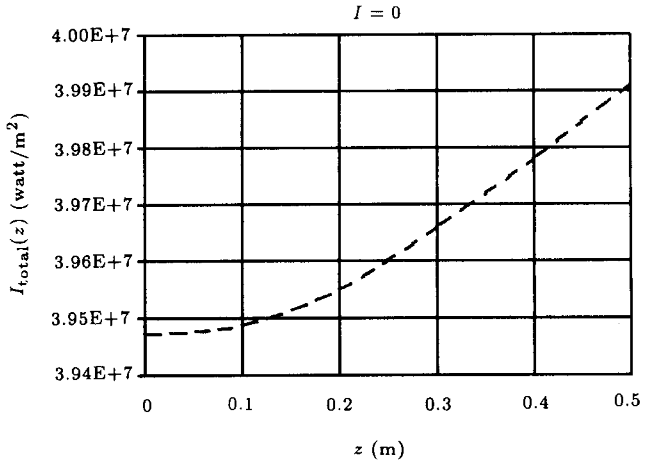

Figure 10. The total intensity $I = (I^+ + I^-)$ along cavity ($I_{\text{average}} = 5 * 10^7$ watt/m^2); gas mixture: CO_2, N_2 and He: 4.5, 13.5 and 82, respectively.

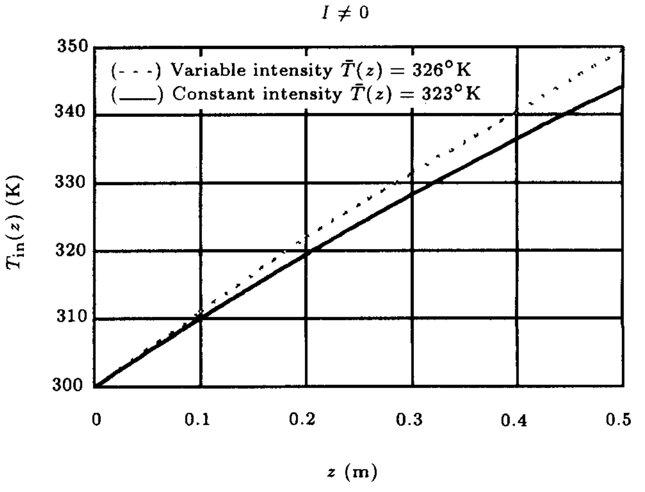

Figure 11. The gas temperature along cavity for $I \neq 0$; gas mixture: CO_2, N_2 and He: 4.5, 13.5 and 82, respectively.

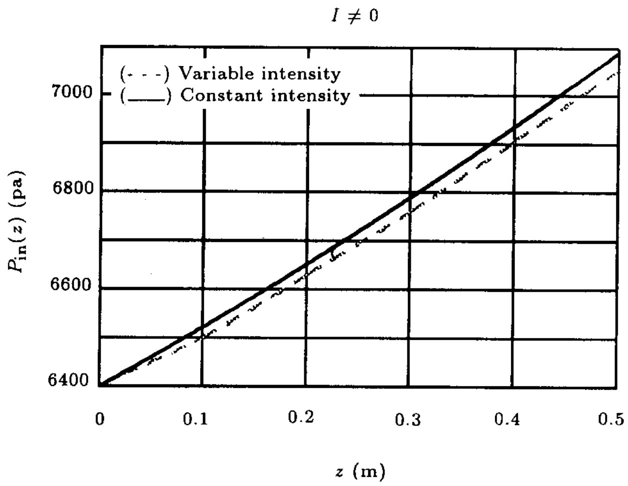

Figure 12. The gas pressure along cavity for $I \neq 0$; gas mixture: CO2, N2 and He: 4.5, 13.5 and 82, respectively.

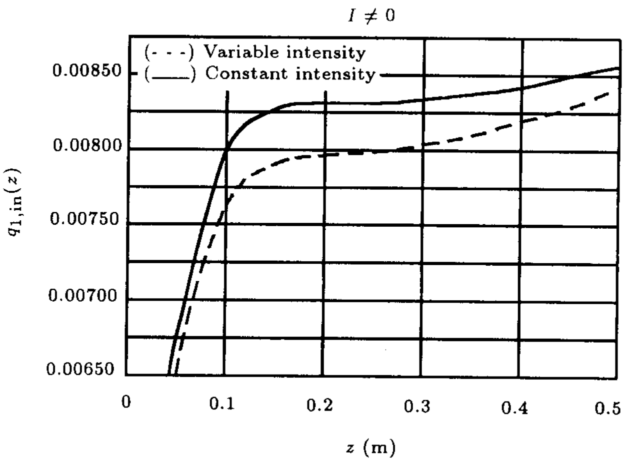

Figure 15. The quantum density q_1 along cavity for $I \neq 0$; gas mixture: CO2, N2 and He: 4.5, 13.5 and 82, respectively.

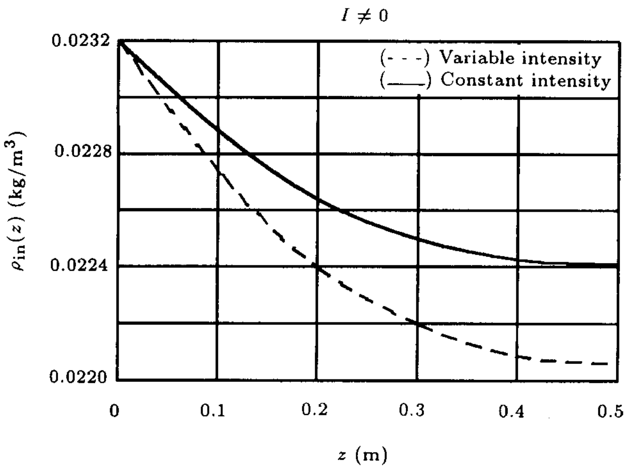

Figure 13. The gas density along cavity for $I \neq 0$; gas mixture: CO2, N2 and He: 4.5, 13.5 and 82, respectively.

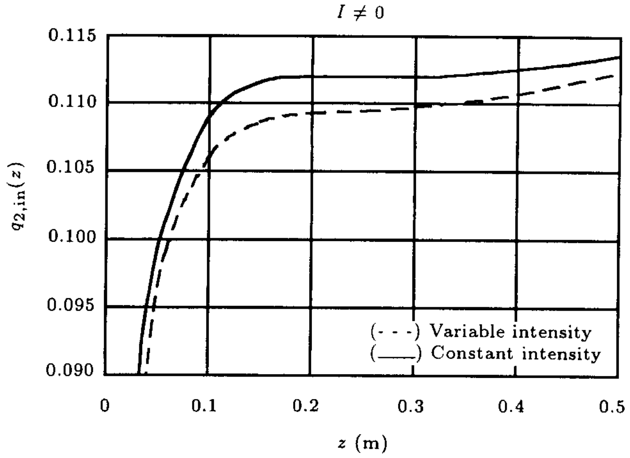

Figure 16. The quantum density q_2 along cavity for $I \neq 0$; gas mixture: CO2, N2 and He: 4.5, 13.5 and 82, respectively.

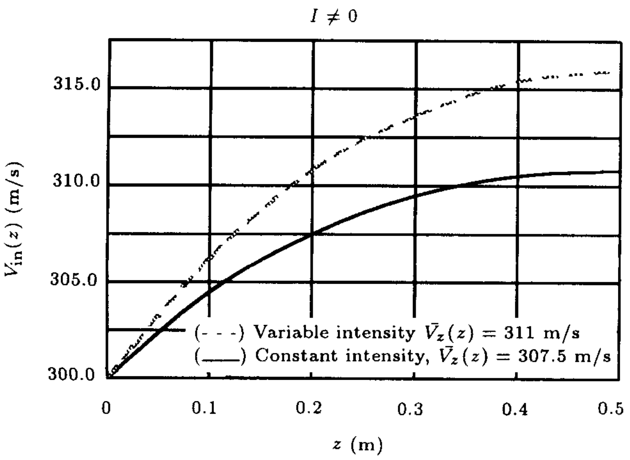

Figure 14. The axial flow velocity along cavity for $I \neq 0$; gas mixture: CO2, N2 and He: 4.5, 13.5 and 82, respectively.

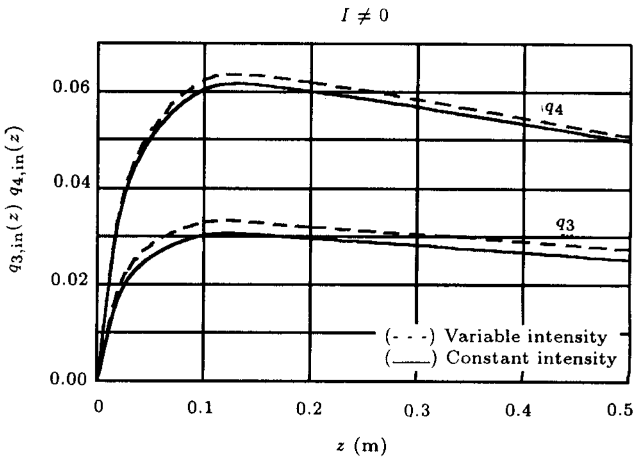

Figure 17. The quantum density q_3 and q_4 along cavity for $I \neq 0$; gas mixture: CO2, N2 and He: 4.5, 13.5 and 82, respectively.

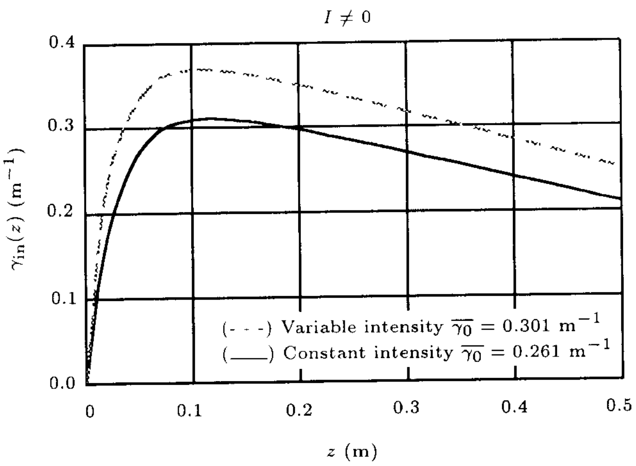

Figure 18. The small signal gain, γ_0 along cavity for $I \neq 0$; gas mixture: CO_2, N_2 and He: 4.5, 13.5 and 82, respectively.

CONCLUSIONS

The effect of intensity variation on the output power, quantum densities and thermodynamic characteristics of a fast axial flow CO_2 laser were investigated. These calculated values give slightly different results in comparison with [2].

Although the difference between the two models is not great in the presented 50 cm long laser active medium, one would expect much more different results as the active medium of the laser became longer. It would also be more important when the number of laser tubes increases. Since the facilities were unavailable to describe the above statement experimentally, the same laser as in [2] was chosen to compare the simulated results.

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