Effects of the Spectral Line Broadened Model on the Performance of a Flowing Chemical Oxygen–Iodine Laser *

GAO Zhi(高智), HU Li-Min(胡利民)
Institute of Mechanics, Chinese Academy of Sciences, Beijing 100080

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A new gain saturation model of chemical oxygen–iodine lasers (COILs) is deduced from the conservation equations of the population number of upper and lower lasing levels. The present model is compared with both the Voigt profile function model and its low-pressure limit model. The differences between the Voigt profile function model or its low-pressure limit model and the model presented here are pointed out, such as the length of power extraction, the optimal range of the threshold gain. These differences are useful for the optimization of COIL adjustable parameters.

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The experimental, theoretical and numerical researches of flowing chemical oxygen–iodine lasers (COILs) have received extensive attention and have been developed rapidly in the past two decades. The spectral line broadening (SLB) model is a basic factor for both the prediction of the COIL performance and the optimization of adjustable parameters. By optimizing adjustable parameters, the output power was raised from a few watts of multi-mode to several thousand watts of near-diffraction limit during the development of flowing HF chemical lasers.[1] There are also great differences among the chemical efficiencies of supersonic COIL experiments,[2] and the SLB model here is an important factor in explaining the differences. An appropriate SLB model can play a large role in the optimization of COIL adjustable parameters. Thus, it is important to examine and develop different SLB models.

A well-known SLB model called the Voigt profile function (VPF) model, or sometimes its low-pressure limit model,[1,3] is usually utilized in the COIL.[4,5] The Voigt profile function is a convolution integral of the product of the Lorentzian profile and the Gaussian profile with respect to frequency. When gas pressure is not high in the laser cavity, a low-pressure limit expression of the VPF model, i.e. the low-pressure limit model, is also used.[4,5] The correlation of both models is shown in Fig. 1. These two SLB models imply that all lasing particles can interact with a monochromatic laser radiation field.

However, as pointed out by other authors, when inhomogeneous broadening of low gas pressure is dominant, this kind of VPF model becomes inadequate.[6,7] The gas pressure in the laser cavity of the COIL is generally several Torr and thus the spectral line shape is inhomogeneously broadened. Only some of the laser level particles can directly interact with the monochromatic radiative field, while the others, whose Doppler shift is large, would not interact. However, the VPF model is unable to distinguish these two groups of particles and is unable to predict correctly the inhomogeneous broadening effects. Another comprehensive Lamb theory is applied to inhomogeneous broadening effects in a steady-state laser oscillator wherein gas properties do not vary with position, but the extension to gas flow lasers wherein fluid properties are functions of spatial coordinate is not straightforward.[6]

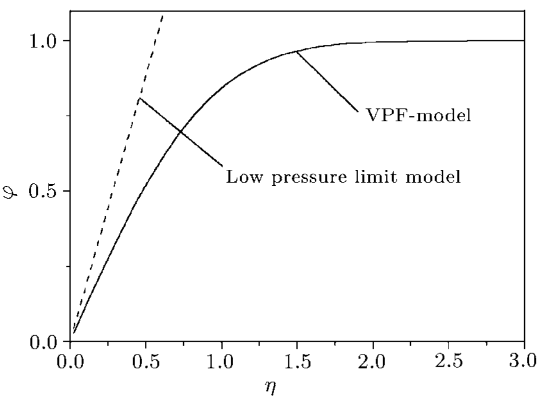

Fig. 1. Lorentzian profile ϕ versus the broadening parameter for the VPF model and its low-pressure limit model.[3–5]

A model can consider the inhomogeneous broadening effect of the flowing gas chemical laser requiring considerations of finite translational relaxation rates. However, it is rather difficult to solve simultaneously the Navier–Stokes (NS) equations governing macroscopic motion of the mixed gas and the conservation equations of the population number of lasing particles of per unit volume and per unit frequency interval, i.e. the velocity distribution function. Fortunately, in the operation condition of flowing COIL, both the translational relaxation rate k_T and the characteristic radiation rate k_v are larger than the characteristic flow

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rate u/L (u and L are the characteristic gas flow velocity and the length of the cavity along flow direction, respectively). Thus, two small parameters u/Lk_T (the ratio of the characteristic flow rate to the translational relaxation rate) and u/Lk_v (the ratio of the characteristic flow rate to the characteristic radiation rate) are introduced to seek a double-parameter perturbation solution of the conservation equation of the velocity distribution function of lasing particles. Herein a new gain saturation model can be derived. This model can predict correctly the interactions between monochromatic light and the upper laser level atoms. Thus the spectral line shape is simultaneously Doppler broadened and collisionally broadened. In addition, this model is also applicable to the case in which lasing frequency is either coincident or not coincident with that of the centre of the line shape.

In order to illustrate the effects of inhomogeneous broadening on the performance of COIL with a mathematical model, it is better to simplify some aspects of the COIL, such as variations of flow parameters and the chemical reaction system. As in Refs. [4] and [5], the flow field in the laser cavity is assumed to be a pre-mixed one-dimensional flow. The iodine molecules have dissociated completely in the upstream of the laser cavity so that the chemical kinetic processes are greatly simplified to be

$$\mathrm{O_2}(^1\Delta) + \mathrm{I} \underset{k_r}{\overset{k_f}{\longleftrightarrow}} \mathrm{O_2}(^3\Sigma) + \mathrm{I}^*. \tag{1}$$

The lasing radiation process can be expressed by

$$\mathrm{I}^* + h\nu \to \mathrm{I} + 2h\nu, \tag{2}$$

where $O_2(^3\Sigma)$ and $O_2(^1\Delta)$ are the ground and excited levels of oxygen molecules, and I and I* are the ground and excited states iodine atoms, respectively; $h\nu$ is the photon energy with ν being the photon frequency. The conservation equations of the velocity distribution functions of upper and lower laser levels are[3]

$$\begin{aligned} u\frac{\partial f_2}{\partial x} =& r f_1 - k_p f_2 + k_T(f_2^0 - f_2) \\ & - \frac{h\nu B\varphi}{4\pi}(f_2 - \alpha f_1) f_v, \end{aligned} \tag{3}$$

$$\begin{aligned} u\frac{\partial f_1}{\partial x} =& - r f_1 + k_p f_2 + k_T(f_1^0 - f_1) \\ & + \frac{h\nu B\varphi}{4\pi}(f_2 - \alpha f_1) f_v. \end{aligned} \tag{4}$$

Here x is the coordinate along the flow direction; f_2 and f_1 are the velocity distribution function of upper and lower lasing level particles; f_2^0 and f_1^0 are the Maxwellian velocity distribution functions of upper and lower laser level particles; $r = k_f n_\Delta$ and $k_p = k_r n_\Sigma$ are the pumping and quenching rates of the upper lasing level, respectively; B is the Einstein excited radiant coefficient; α is a constant related to level degeneracy; f_v is the distribution function of photons; n_Δ and n_Σ are the population number of $O_2(^1\Delta)$ and $O_2(^3\Sigma)$, respectively; φ is the Lorentzian profile. When the lasing flux direction is perpendicular to the flow direction, φ can be expressed as

$$\varphi(\nu, \nu_0) = \frac{\Delta\nu_N/2\pi}{(\nu - \nu_0)^2 + (\Delta\nu_N/2)^2}, \tag{5}$$

where ν_0 is the central frequency of the spectral line profile, and $\Delta\nu_N$ is the full width at half maximum of homogeneous broadening line profile. Because r, k_T, k_p, and the characteristic radiation rate $h\nu B\varphi f$ are all much larger than the characteristic flow rate u/L, a double-parameter perturbation method is used.[3] From the constant gain approximation,[1,3] we obtain

$$\begin{aligned} g =& \int \frac{B\varphi}{4\pi}(f_2 - \alpha f_1)\mathrm{d}\nu \\ \cong& \int \frac{B\varphi}{4\pi}\Big[1 + \frac{B\varphi I}{4\pi}(1-\alpha)\Big]^{-1}(f_2^0 - \alpha f_1^0)\mathrm{d}\nu \\ \cong& \frac{g_{\mathrm{on}}\psi(\xi, \eta, \bar{I})}{1 + \bar{I}}, \end{aligned} \tag{6}$$

$$\psi(\xi, \eta, \bar{I}) = \frac{\eta^2(1+\bar{I})}{\sqrt{\pi}} \int_{-\infty}^{\infty} \frac{e^{-t^2}}{\eta^2(1+\bar{I}) + (\xi - t)^2}\mathrm{d}t,$$

where $\Delta\nu_D$ is the full width at half maximum of the Doppler broadening line profile. $\eta = \Delta\nu_N/\Delta\nu_D\sqrt{\ln 2}$ is the broadening parameter, which indicates the relative dominance of homogeneous and inhomogeneous broadening effects. The frequency-shift parameter $\xi = 2(\nu - \nu_0)\sqrt{\ln 2}/\Delta\nu_D$, which expresses the relative deviation of the light frequency with respect to the central frequency of the line profile. $t = 2(\nu' - \nu_0)\sqrt{\ln 2}/\Delta\nu_D$ is the temporal integral variable, g_{on} is equal to the small signal gain when $\xi = 0$, ψ is the corrected line-shape factor, and $\bar{I}$ is the dimensionless optical intensity. If the light frequency is coincident with the central frequency of the line profile ν_0, i.e., $\xi = 0$, Eq. (6) can be simplified as

$$g = K\sigma n \frac{\eta\sqrt{\pi}}{\sqrt{1+\bar{I}}} \cdot \exp[(1+\bar{I})\eta^2] \cdot \mathrm{erfc}(\eta\sqrt{1+\bar{I}}), \tag{7}$$

where

$$\begin{aligned} & I = h\nu f_v, \quad \bar{I} = I/I_s, \\ & K = (k_f n_\Delta - \alpha k_r n_\Sigma)/(k_f n_\Delta + k_r n_\Sigma), \\ & I_s = 2(k_f n_\Delta + k_r n_\Sigma)h\nu/3\sigma, \end{aligned}$$

$[O_2](= n_\Delta + n_\Sigma)$ and n are the total number density of oxygen molecule and iodine atom, respectively. $\sigma(= B/4\pi)$ is the stimulated radiative area, I and I_S are the optical intensity and the saturation optical intensity of the present model, respectively. K is a variable introduced for convenience. By expanding the error function, Eq. (7) can be approximately simplified as

$$g = K\sigma n/(1+\bar{I}), \quad \eta \gg 1, \tag{8}$$

$$g = K\sigma n\eta\sqrt{\pi}/\sqrt{1+\bar{I}}, \quad \eta \ll 1. \tag{9}$$

The gain-saturation relations (8) and (9) are in agreement with the well-known theory in the gas laser.[8] For the VPF model, the gain-saturation relation is ($\xi = 0$) [1]

$$g = K\sigma n\frac{\eta\sqrt{\pi}\,\mathrm{erfc}\,\eta\exp(\eta^2)}{1+\bar{I}_v\eta\sqrt{\pi}\,\mathrm{erfc}\,\eta\exp(\eta^2)}. \tag{10}$$

The gain saturation relations corresponding to Eqs. (8) and (9) are, respectively,

$$g = K\sigma n/(1+\bar{I}_v), \quad \eta \gg 1, \tag{11}$$

$$g = K\sigma n\eta\sqrt{\pi}/(1+\eta\sqrt{\pi}\bar{I}_h), \quad \bar{I}_v = \bar{I}_h \quad \text{when} \quad \eta \ll 1, \tag{12}$$

where $\bar{I}_v = I_v/I_S$, I_v is the optical intensity of the VPF model and $\bar{I}_v$ is the dimensionless optical intensity of the VPF model. $\bar{I}_v$ is substituted by $\bar{I}_h$ when $\eta \ll 1$. The saturation Eq. (12) is called the low-pressure limit model and is used when the gas pressure is low.[4,5] In the following, the present model is discussed and compared with both the VPF model and its low-pressure limit model.

The power of a COIL is deduced in the same way as in Refs. [4] and [5], i.e., by combining the energy relation

$$u\frac{\mathrm{d}n_\Delta}{\mathrm{d}x} = -\frac{gI}{h\nu} \tag{13}$$

with the gain-saturation relation (10). Thus, a comparison of the results of different models and experimental data can be obtained.

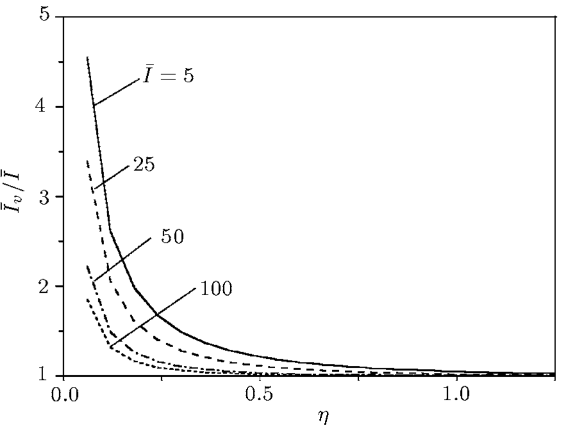

Fig. 2. Optical intensity ratio of $\bar{I}$ of Eq. (7) to $\bar{I}_v$ in Eq. (12) versus the broadening parameter.

Figure 1 indicates the correlations between the VPF model and its low-pressure limit model. The latter is the tangent of the former at $\eta = 0$, which simplifies considerably the treatment of problems with a good approximation when the pressure is low. Figure 2 shows the correlations between $\bar{I}$ and $\bar{I}_v$ when different $\bar{I}$ values are taken. $\bar{I}$ and $\bar{I}_v$ are nearly the same when η is not so small, for example, the differences between both models are nearly negligible when $\eta = 0.75$; and the smaller the η value, the larger the difference between $\bar{I}$ and $\bar{I}_v$.

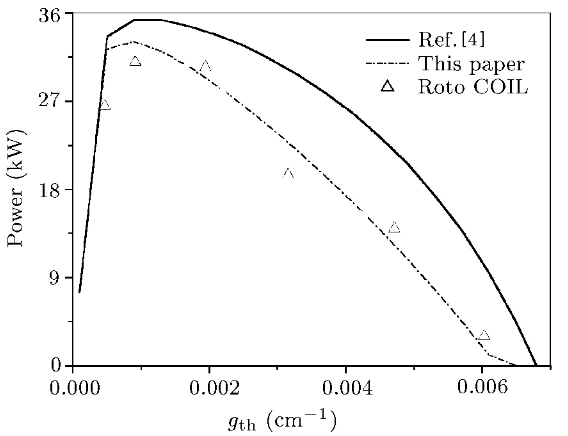

Fig. 3. Comparison of calculated power of present model and the low-pressure limit model in Ref. [4] with the Roto COIL experimental data.[9]

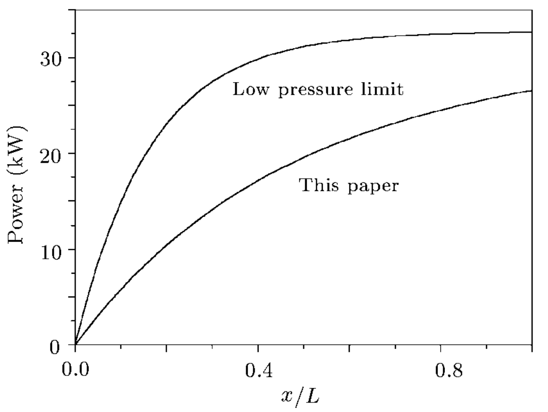

Fig. 4. Variations of output powers with the distance along the flow direction.

Figures 3 and 4 show the calculated results from the experiment of Ref. [9]. The working parameters were presented in Ref. [10] and the broadening parameter η is here estimated to be 0.08. Figure 3 shows a comparison of the output powers calculated by using both the present model and the low-pressure limit model[4,5] with the Roto COIL experimental data.[9,10] It is shown that the output power values of both models are consistent with the experimental data, but the results of the present model are better than those of the low-pressure limit model. An in-depth review of the calculated results shows that the range of the optimal threshold gain g_{opt} (here it takes the range in which its output power P satisfies $|P - P_{\max}|/P_{\max} \leq 0.1$, and $P_{\max}$ is the maximum output power) is 0.00047–0.00162 cm^{-1} by using the present model, and 0.00047–0.00276 cm^{-1} if the low-pressure model is used, i.e. the former is much less than the latter. Figure 4 shows the variations of output powers with the distance along the flow direction, but the decrement predicted by the present model is slower than that of the low-pressure limit model, and longer extraction length is needed in the present model. This difference is important to the design of a laser cavity.

In this Letter, three gain saturation models used in the performance analysis and computation of COIL are compared. Attention should be paid to the obvious differences existing between the usual VPF model (or the low-pressure limit model) and the present model since there is more adequate physical consideration in the present model. The different results, i.e. optimal range of threshold gain and length of output power extraction, obtained by the present model should be useful for the design of optical reflectors, such as the choice of threshold gain value, the position and length of the optical reflectors. The optimization of these parameters is favourable for the power extraction and the quality of laser beam.

References

[1] Gross R W F and Bott J F 1976 *Handbook of Chemical Lasers* (New York: Wiley) chap 8 p 469

[2] Hon J F, Plummer D N, Crowell P G, Erkkila J, Hager G D, Helms C A and Truesdell K A 1994 *25th AIAA Plasmadynamics and Laser Conference* (Colorado Springs, CO, June 1994) p 2422

[3] Gao Z 1981 *Acta Phys. Sin.* **12** 1591 (in Chinese)

[4] Hager G D, Helms C A, Truesdell K A, Plummer D, Erkkila J and Crowell P 1996 *IEEE J. Quantum Electron.* **32** 1525

[5] Barmashenko B D and Rosenwaks S 1996 *Appl. Opt.* **35** 7091

[6] Copeland D A 1994 *25thAIAA Plasmadynamics and Laser Conference* (Colorado Springs, CO, June 1994) p 2430

[7] Mirels H 1988 *Appl. Opt.* **27** 89

[8] Chen Y Q and Wang J H 1992 *Principles of Laser* (Hangzhou: Zhejiang University Press) chap 5 p 299 (in Chinese)

[9] Truesdell K A, Helms C A and Hager G D 1994 *25th AIAA Plasmadynamics and Laser Conference* (Colorado Springs, CO, June 1994) p 2421

[10] Buggeln R C, Shamroth S, Lampson A I and Crowell P G 1994 *25th AIAA Plasmadynamics and Laser Conference* (Colorado Springs, CO, June 1994) p 2435