Characteristics of Radiation from a Q-Switched Supersonic Flow Chemical Oxygen-Iodine Laser*

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The flow and optical fields of a Q-switched supersonic flow chemical oxygen-iodine laser are simulated by solving simultaneously the gas flow model coupled with the precise chemical kinetic model and the geometric optical model. The effects of hyperfine relaxation and velocity cross relaxation for iodine atoms and nonuniformity of the three-dimensional flow field on power extraction are investigated. The results show that the peak power under the influence of hyperfine relaxation and velocity cross relaxation, which is normalized by the corresponding continuous wave value, is 15. This value agrees fairly well with previously reported experimental results of Q-switched chemical oxygen-iodine laser operations. The peak power of pulse in the three-dimensional flow field is considerably small compared to that in the equivalent one-dimensional flow field and the pulse is widened roughly twice due to insufficient mixing, shock waves, expansion waves and wakes.

Key Words: Q-Switch, Relaxation, Supersonic Flow, Chemical Laser, Iodine, Oxygen

1. Introduction

The chemical oxygen-iodine laser (COIL) has potential for efficient and high-power extraction. It also has high optical quality at the shortest wavelength ($\lambda = 1.315 \mu m$) among chemical lasers, which is suitable for transmission using optical fibers. In a supersonic flow chemical oxygen-iodine laser (S-COIL), both efficiency and laser power can be raised significantly by gas cooling through supersonic expansion\(^{(13)}\).

Recently, the pulsed operation of COIL is necessary for applications such as cutting or welding materials. It is known that the temporal profile of the pulsed output power greatly affects the characteristics of material processing. A Q-switched operation, in which a Q number of resonator is varied within a very short time to switch the power extraction on/off, is achieved using a mechanical chopper\(^{(14)}\) or a heated I\(_2\) cell\(^{(15)}\), or by applying a magnetic field\(^{(16)-(17)}\). The characteristic time of power extraction in the Q-switched operation is comparable to those of some relaxation phenomena among the energy levels of the active medium. One of the relaxations, which is called hyperfine relaxation (HFR), occurs between the sublevels of the $^3P_{1/2}$ electronic level iodine atom I and the $^3P_{1/2}$ electronic level iodine atom I* manifolds. Another relaxation, which is called velocity cross relaxation (VCR), is caused by the discrepancy of the velocity distribution of iodine atoms from the Maxwellian distribution (the hole-burning phenomenon). Some experiments\(^{(18)-(20)}\) and computations\(^{(8)-(10)}\) of the Q-switched COIL have been reported, but the detailed mechanism of Q-switched power extraction including the relaxation phenomena, and the interaction between Q-switched power extraction and flow field in the cavity remain unclear.

In the present study, a Q-switched S-COIL is

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simulated by solving simultaneously the gas flow model coupled with the precise chemical kinetic model and the geometric optical model. The present model includes the effects of both HFR and VCR. The effects of such relaxations and nonuniformity of the three-dimensional flow field on the unsteady gain field and the power extraction are discussed. The standard S-COIL chemical kinetic model is extended with the HFR model for the upper and lower iodine hyperfine manifolds, and the VCR model for the iodine atom velocity manifolds. The unsteady Navier-Stokes equations and the geometric optical equation are solved simultaneously using the fourth-order Runge-Kutta method.

2. Configuration of Flow Field and Laser Cavity

Figures 1 and 2 show respectively the configuration of I$_2$ injectors and nozzle blades, and the resonator$^{(2)}$ used in the present study. A cylindrical I$_2$ injector is located upstream of each nozzle blade and I$_2$ jets are injected at angles of 90 and 45 degrees with respect to the primary O$_2$ flow through four rows of circular orifices drilled in each cylinder. The flow in which I$_2$ mixes and reacts with O$_2$($^1\Delta$) is choked and expanded through supersonic nozzle blades. As a result of mixing, energy is transferred from the O$_2$($^1\Delta$) to high vibrational levels of the molecular iodine.

$$I_2 + O_2(^1\Delta) \rightleftharpoons I_2^* + O_2(^3\Sigma), \quad (1)$$

where I$_2^*$ is the vibrationally excited (v~40) iodine molecule. Further collisions transfer sufficient energy to dissociate the iodine.

$$I_2^* + O_2(^1\Delta) \rightleftharpoons 2I(^3P_{3/2}) + O_2(^3\Sigma). \quad (2)$$

Then, the electronically excited iodine atom I($^3P_{1/2}$) is produced.

$$I(^3P_{1/2}) + O_2(^1\Delta) \rightleftharpoons I(^3P_{1/2}) + O_2(^3\Sigma). \quad (3)$$

The laser emission can be obtained from a resonator located downstream of the nozzle blades by,

$$I(^3P_{1/2}) \rightleftharpoons I(^3P_{3/2}) + h\nu, \quad (4)$$

where $h$ is the Planck’s constant and $\nu$ is the frequency. Since the forward reaction rate of the reaction (3) is raised by lowering the temperature, supersonic cooling can enhance the laser emission strongly.

In Fig. 1, the x axis is parallel to the primary O$_2$ flow with its origin at the nozzle exit plane, and the y and z axes are perpendicular to x. The z coordinate with its origin at the output mirror is perpendicular to the cylindrical I$_2$ injector and corresponds to the direction in which light propagates. As shown in Fig. 2, there are six pairs of I$_2$ injectors and nozzle blades arranged in the z direction in the experimental apparatus. Therefore, the width (in the x direction) of the cross section is 90 mm. The height (in the y direction) of the cross section of the apparatus at the injector and nozzle blade section is 12 mm.

The flow field created by the I$_2$ injector and the nozzle used in the present study are given in a previous paper$^{(11)}$ which dealt with continuous-wave power extraction. It is noted that the flow field upstream of the laser cavity is not influenced by whether the power extraction is continuous or pulsed.

A Fabry-Perot-type resonator composed of two flat mirrors is assumed in the calculation. The width of the mirror is 15 mm. The reflectivity of the output mirror is 0.98, and the other mirror is a perfectly reflecting mirror.
3. Mathematical Modeling

For simplicity, the condensation of water vapor due to supersonic cooling\(^{12}\) is ignored. It is reasonable to assume that the flow is laminar, since the Reynolds number of S-COIL is only of the order of 10\(^2\) to 10\(^4\). Moreover, the compressibility and the rapid acceleration by the nozzle tend to stabilize the flow.

In addition, the following simplifications are introduced to derive the governing equations for flow and optical fields. 1) The gas mixture consists of ten species: \(\text{O}_2(\Sigma), \text{O}_2(\Delta), \text{O}_2(\Sigma^\prime), \text{I}^\ast, \text{I}, \text{I}^\ast, \text{I}_z, \text{H}_2\text{O}, \text{Cl}_2\) and \(\text{He}\). Both \(\text{I}^\ast\) and \(\text{I}\) contain hyperfine sublevels and velocity manifolds to treat the relaxation phenomena. 2) The specific heat is constant and the equation of state for an ideal gas is used for each species. 3) The bulk viscosity, Soret effect, Dufour effect and diffusion due to the pressure gradient are neglected. 4) External forces such as gravity are neglected. 5) Iodine atom laser uses only at 3.15\(\mu\)m on the transition between the \(F=3\) and \(F=4\) hyperfine sublevels of \(\text{I}^\ast\) and \(\text{I}\), respectively. 6) The optical resonator is of a Fabry–Perot type.

3.1 Relaxation model and kinetic rates

The electronic levels \(^3\text{P}_{3/2}\) and \(^3\text{P}_{1/2}\) of iodine atom are split into four and two hyperfine sublevels characterized by the total electron momentum \(F\) of the atom, respectively. The equilibrium population of the hyperfine sublevels is proportional to their degeneracy. The fast transition between 3\(\rightarrow\)4 hyperfine sublevels disturbs the equilibrium population, causing HFR. In order to treat HFR between the sublevels of the \(^3\text{P}_{3/2}\) and \(^3\text{P}_{1/2}\) manifolds, a four-level relaxation model is used\(^{19}\). In this model, the \(F=1, 2\) and 3 sublevels of the \(^3\text{P}_{3/2}\) manifold are treated as a single \(F=R\). Each sublevel of iodine atom, i.e., \(I_{F}^\ast\) (\(F=3, 2\)) or \(I_{F}\) (\(F=4, R\)) is treated independently.

Iodine atoms move randomly and collide with other atoms in the flow field. It is, for example, observed as the Doppler and collision broadening of gain. When power extraction occurs at the line center (\(A=1.315\mu\)m), only iodine atoms which have the projection of velocity along the optical axis \(v_y\) equal to zero undergo 3\(\rightarrow\)4 transition. The velocity distribution of iodine atoms differs from the Maxwellian distribution and a dip appears on the gain distribution, which is called hole-burning\(^{19}\). Then, VCR due to collision between atoms tends to reestablish the equilibrium population distribution. To treat VCR within the velocity manifolds of the iodine atom hyperfine levels, the strong-collision model is used\(^{19}\). In the present study, it is assumed that each velocity manifold of iodine atoms can be classified into 20 groups with different \(v_y\), i.e., \(I\&y(v_y)\) (\(F=3, 2\)) or \(I_{F}(v_y)\) (\(F=4, R\)) and VCR occurs between these \(v_y\) groups.

The chemical kinetic model is summarized in Table 1 where \(k_i\) denotes the reaction rate of the \(i\)th kinetic process and \(T\) is the temperature. Kinetic processes 1 through 21 belong to the standard COIL chemical kinetic model proposed by Perram and Hager\(^{19}\). Kinetic processes 22 and 23 correspond to HFR reactions and processes 24 through 27 are related to VCR\(^{19}\). In the following section, the kinetic model excluding both relaxations, that including only HFR, and that including both relaxations, are called the HFE model, HFR model and VCR model, respectively.

3.2 Governing equations for the flow field

Based on these assumptions, the governing equations, the full Navier–Stokes equations with a detailed kinetic mechanism, are given in the following form:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} + \frac{\partial \rho w}{\partial z} = 0
\]

\[
\frac{\partial \rho u}{\partial t} + \frac{\partial \rho u^2}{\partial x} + \frac{\partial \rho uv}{\partial y} + \frac{\partial \rho uw}{\partial z} = -\frac{\partial P}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} + S_{\text{chem}} + S_{\text{rad}}.
\]

In this equation, the conservative vector \(Q\), the convection and viscous terms \(F_i\), and \(G_i\) in the \(x\) direction, the source term related to the chemical reaction \(S_{\text{chem}}\), and the source term related to the radiative flux \(S_{\text{rad}}\) are

\[
Q = \begin{pmatrix}
\rho \\
\rho u \\
\rho v \\
\rho w \\
E \\
\rho \gamma \end{pmatrix},
\]

\[
F_i = \begin{pmatrix}
\rho u \\
\rho u^2 + p \\
\rho uv \\
\rho uw \\
(E + p)u \\
\rho u^2 + p \\
\end{pmatrix},
\]

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\[
E = \sum_{i=1}^{n} \rho_i \cdot \frac{u_i}{2} (u^2 + v^2 + w^2),
\]

where \(\rho, u, v, w\) and \(\rho\) denote the density, the velocities in the \(x, y,\) and \(z\) directions and the pressure of mixture, respectively, \(g\) the gain coefficient, \(f\) the radiative flux averaged along the optical axis, \(\rho\) the mass concentration and \(h_i\) the enthalpy of \(i\)th species, \(\tau\) the viscous stress, \(q\) the heat flux due to heat conduction and diffusion and \(f\) the diffusion flux, respectively. In the term \(S_{\text{chem}} - gF\) it means the energy consumption of mixture due to power extraction. The convection and viscous terms \(F_{xx}\) and \(G_{xx}\) are similar to \(F\) and \(G\), respectively, and are not shown here. In the governing equations, the molecular viscosity and thermal conductivity coefficients are calculated using the generalized kinetic-theory formula \((6)\).

The \(i\)th species production rate due to chemical reaction \(\dot{\omega}_i\) in Eq. \((6)\) is evaluated using the chemical kinetic model as shown in Table 1. In the HFR model, in particular, \(I_{F1}\) \((F=3,2)\) and \(I_{F3}\) \((F=4, R)\) production rates due to chemical reaction are given by

\[
\dot{\omega}_{i,0} = W_i(\theta) \cdot k_a \cdot [O_2(\Delta)] [I] - \alpha_a [I_1],
\]

\[
\dot{\omega}_{i,0} = W_i(\theta) \cdot k_a \cdot [O_2(\Delta)] [I_1] + \alpha_a [I_1] - k_{2a} [O_3] [O_2(\Sigma)] - k_{2a} [O_3] [O_2(\Sigma)],
\]

\[
(F=3,2),
\]

\[
\dot{\omega}_{i,0} = W_i(\theta) \cdot k_a \cdot [O_3] [O_2(\Sigma)] [I] - \alpha_a [I_1],
\]

\[
\dot{\omega}_{i,0} = W_i(\theta) \cdot k_a \cdot [O_3] [O_2(\Sigma)] [I_1] + \alpha_a [I_1] - k_{2a} [O_3] [O_2(\Sigma)],
\]

\[
(F=4, R),
\]

where \(f(\nu_f)\) is the Maxwellian velocity distribution.

The \(i\)th species production rate \(\dot{\omega}_i\) due to the stimulated emission in Eq. \((6)\) for HFE and HFR models is

\[
\dot{\omega}_{i,0} = \frac{-W_i(\theta) \cdot \frac{1}{N_{\nu_f}}}{N_{\nu_f}} \nu_i f(\nu_f) f(\nu_f) f(\nu_f) f(\nu_f) f(\nu_f), \quad \text{for I}^* \text{ or I}_0,
\]

\[
\dot{\omega}_{i,0} = \frac{-W_i(\theta) \cdot \frac{1}{N_{\nu_f}}}{N_{\nu_f}} \nu_i f(\nu_f) f(\nu_f) f(\nu_f) f(\nu_f) f(\nu_f), \quad \text{for others},
\]

In Eq. \((11)\), \(N_{\nu_f}\) denotes the Avogadro's number and \(\nu_f\) is the photon energy. Using the Voigt lineshape function, the gain coefficient \(g\) for the HFE model in Eqs. \((6)\) and \((11)\) is evaluated by

\[
g = \frac{7 \cdot A_{\text{left}} \cdot \frac{1}{\Delta_{\nu_c}} \nu_c}{12 \cdot \frac{1}{\Delta_{\nu_c}} \nu_c},
\]

\[
K(\eta) = \exp(\eta \cdot \eta_c) \cdot \eta_c, \quad \eta = \sqrt{\frac{\Delta_{\nu_c}}{\Delta_{\nu_f}}},
\]

where \(A_{\text{left}}\) is the stimulated emission cross section, \(N_{\nu_f}\) is the number density of each species, \(A_{\text{left}}\) is the Einstein coefficient for the 3→4 transition, \(\lambda = 1.315 \mu m\), \(\Delta_{\nu_c}\) is the Doppler linewidth, \(\Delta_{\nu_c}\) is the collision linewidth \((10)\). The gain coefficient \(g\) for the HFR model is evaluated by

\[
g = \frac{7 \cdot A_{\text{left}} \cdot \frac{1}{\Delta_{\nu_c}} \nu_c}{12 \cdot \frac{1}{\Delta_{\nu_c}} \nu_c},
\]

where the Doppler–broadened stimulated emission cross section \(g_{\nu_f}\) is

\[
g = \frac{7 \cdot A_{\text{left}} \cdot \frac{1}{\Delta_{\nu_c}} \nu_c}{12 \cdot \frac{1}{\Delta_{\nu_c}} \nu_c},
\]

For the VCR model, the production rate \(\dot{\omega}_i\) is

\[
\dot{\omega}_i = \frac{-W_i(\theta) \cdot \frac{1}{N_{\nu_f}}}{N_{\nu_f}} \nu_i f(\nu_f) f(\nu_f) f(\nu_f) f(\nu_f) f(\nu_f), \quad \text{for I}^* \text{ or I}_0,
\]

\[
0 \quad \text{for others},
\]

In Eq. \((14)\), the collision–broadened stimulated emission cross section \(c_{\nu_f}\), the Doppler–shifted Lorentzian \(L(\nu_f)\) and population inversion \(N(\nu_f)\) are

\[
c_{\nu_f} = \frac{7 \cdot A_{\text{left}} \cdot \frac{1}{\Delta_{\nu_c}} \nu_c}{12 \cdot \frac{1}{\Delta_{\nu_c}} \nu_c},
\]
L(v_p) = \frac{1}{2} \frac{\Delta \nu_c}{\nu_c v_p^2} + \frac{1}{2} \frac{\Delta \nu^2}{\nu_c^2},

\text{and}

N(v_p) = N_{b(\nu)} - \frac{7}{9} N_{b(\nu)},

respectively. The gain coefficient g for the VCR model is calculated by

g = g_0 \int L(v_p) N(v_p) dv.

(15)

3.3 Governing equations for the optical field

The geometric optical equation for a ray propagating along the z-axis is expressed as

\frac{1}{c} \frac{\partial I^x}{\partial t} + \frac{\partial I^z}{\partial z} = g^x,

(16)

where I^x(x, y, z) and c denote two-way flux and the speed of light, respectively. For simplicity, gain g is assumed to be constant along the optical axis and the averaged radiative flux

\bar{I}(x, y) = \frac{\bar{I}}{2} = \frac{1}{2L} \left( \int_0^L I^x dz + \int_0^L I^- dz \right),

(17)

where L is the gain length, is used to simulate the optical field. Equation (16) is extended to use \bar{I} and to include the effect of optical loss at the mirrors, and is rewritten into the following equation.

\frac{\partial I}{\partial t} = c(\Delta g - g_m) I, \quad \Delta g_m = -\frac{\ln (r_1 r_2)}{2L},

(18)

where r_1 and r_2 are the reflectivity of mirrors 1 and 2, respectively. The extracted power is calculated by

\bar{P}_t = \int_0^L I \exp(-2gL) dA,

(19)

where A and h are the cavity cross section perpendicular to the optical axis and the transmittance of output mirror, respectively.

Then, flow and optical fields are solved by the Navier–Stokes equations (5) and the geometric optical equation (18) simultaneously.

3.4 Numerical methods

In order to calculate the reacting flow field in the complicated flow domain, the governing equations (5) in the physical domain are transformed to the computational domain and discretized with the cell-centered finite volume method. The Harten–Lax–van Leer–Einfeldt (HLLE) scheme with monotone upstream-centered schemes for conservation laws (MUSCL) approach and van Albada’s limiter is applied for space discretization of the convection terms, and the central difference scheme for the viscous terms. The time-dependent solutions of the Navier–Stokes equations (5) and the geometric optical equation (18) are obtained using the fourth-order Runge–Kutta method.

3.4.1 Numerical conditions

It is assumed in the present calculation that each I_2 jet injected from a row of orifices has the same shape and that each jet has a symmetric plane which parts the orifice at the center. Thus, the calculation of the mixing zone structure is carried out in the domain indicated by broken lines in Fig. 1. Using the geometric optical equation with the assumptions mentioned before and assuming the symmetry of the flow field in the y and z directions in the cavity, the calculation of interaction between flow and optical fields is carried out in the domain indicated by broken lines in Fig. 2.

The wall boundary conditions are isothermal, nonslip and noncatalytic, while the mirror reflection rule is applied on the symmetric boundaries. The plenum pressure, total enthalpy and molar fractions are imposed at the upstream boundary of the domain near the injectors, and the velocity, which is assumed to be parallel to the x axis, is obtained using a simple linear extrapolation from the interior cells. On the other hand, all variables on the downstream boundary are calculated using zero gradient conditions. The sonic condition is imposed at the orifice of the I_2 injector. The upstream boundary condition of the domain shown in Fig. 2 is generated by the solution in the domain in Fig. 1.

The plenum conditions of the primary flow from the chemical oxygen generator and the secondary flow supplied by the I_2 injector are listed in Table 2. Here, X_i denotes the molar fraction of the i-th species. The initial excitation efficiency of oxygen is 0.5. The plenum conditions listed in Table 2 are based on a previous experiment and the numerical simulation of continuous-wave (CW) operation. It is noted that the previous numerical simulation could predict the complicated phenomenon in the CW operation of S-COIL fairly well.

In the present study, it is assumed that the cavity is filled with a radiative flux of 1 W/m^2 due to spontaneous emission when the Q-switch is off.

4. Results and Discussion

It is worth examining several lifetimes relevant to power extraction in the Q-switched operation

<table>
<thead>
<tr>
<th>\text{Table 2 Plenum conditions in the present study}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary flow</td>
</tr>
<tr>
<td>X_{O_2}</td>
</tr>
<tr>
<td>4.139 x 10^{-5}</td>
</tr>
<tr>
<td>X_{O_3}</td>
</tr>
<tr>
<td>0.148</td>
</tr>
<tr>
<td>X_{H_2O}</td>
</tr>
<tr>
<td>0.033</td>
</tr>
<tr>
<td>X_{I_2}</td>
</tr>
<tr>
<td>0.656</td>
</tr>
</tbody>
</table>

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Table 3 Lifetimes relevant to power extraction

<table>
<thead>
<tr>
<th>Lifetime</th>
<th>Expression</th>
<th>Value [ns]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas exchange</td>
<td>$\tau_{ge} \equiv \frac{W_r}{U}$</td>
<td>19500</td>
</tr>
<tr>
<td>O$_2$(1$\Delta$) Extraction</td>
<td>$\tau_{o} \equiv \left[ \frac{1}{2} k_{32} [I_{TOT}] {2K_{e2} + 1 - \xi (K_{e2} + 1)} \right]^{-1}$</td>
<td>16600</td>
</tr>
<tr>
<td>1* Pumping by O$_2$(1$\Delta$)</td>
<td>$\tau_{1*} \equiv \frac{1}{k_{18}[O_2(1\Delta)] + k_{16}[O_2(3\Sigma)]}$</td>
<td>448</td>
</tr>
<tr>
<td>Upper-level HFR</td>
<td>$\tau_{u} \equiv (k_{29}[O_2])^{-1}$</td>
<td>253</td>
</tr>
<tr>
<td>Lower-level HFR</td>
<td>$\tau_{l} \equiv (k_{22}[I_{TOT}])^{-1}$</td>
<td>13.7</td>
</tr>
<tr>
<td>Upper-level VCR</td>
<td>$\tau_{v} \equiv (k_{24}[He] + k_{26}[O_2])^{-1}$</td>
<td>28.0</td>
</tr>
<tr>
<td>Lower-level VCR</td>
<td>$\tau_{v} \equiv (k_{26}[He] + k_{27}[O_2])^{-1}$</td>
<td>12.8</td>
</tr>
</tbody>
</table>

At first, to shorten the computation time, an equivalent one-dimensional flow is used to clarify the qualitative behavior of Q-switched operation and the effects of relaxation phenomena. Then, the three-dimensional flow field is discussed for the model including both HFR and VCR to clarify the effect of flow nonuniformity.

The equivalent one-dimensional flow is defined by a uniform flow in the $y$-$z$ plane which has the same flow rate, momentum flux, energy flux and gas composition as the three-dimensional flow. In the present study, the equivalent one-dimensional flow at 3.7 mm upstream of the laser cavity is calculated using the three-dimensional flow field obtained in the previous paper. Using it as the upstream boundary condition, the one-dimensional simulation can be carried out in the domain shown in Fig. 2.

The averaged value of some properties which are discussed in the following sections is defined by

$$\langle X \rangle_x = \frac{1}{W_r} \int_{x_L}^{x_S} x Xdx,$$

where $x_L$ and $x_S$ are the positions of cavity upstream edge and downstream edge, respectively.

4.1 Behavior of Q-switched operation and effects of relaxation phenomena

Figure 3 shows the development of the averaged radiative flux $I_r$, the averaged loaded gain $g_x$ and the instantaneous output power normalized by the corresponding CW value $P_{a0}/P_{cw}$. Here, the equivalent one-dimensional flow with the VCR model is considered. A one-pulsed operation is simulated in the present study and the pulse duration $\tau_p$ is 25 000 ns, i.e., the Q-switch is switched on at $t=0$ ns and off at $t=25 000$ ns instantaneously.

At $t=0$ ns, the 3$\rightarrow$4 transition of iodine atoms starts in the entire region of cavity filled with fresh

![Image](Fig. 3) Development of power extraction in the Q-switched operation for the VCR model with a pulse duration of 25 000 ns. (a) The averaged radiative flux $I_r$, (b) the loaded gain $g_x$ and (c) the instantaneous output power normalized by the corresponding CW value $P_{a0}/P_{cw}$
mixture, then a much higher power than the CW value is extracted. The excited iodine atoms are consumed very rapidly by the power extraction compared with \( I^* \) pumping by \( O_2(\Delta) \) with a characteristic time \( r_\alpha \). As a result, the loaded gain is very rapidly decreased below the threshold gain \( g_{th} \) and a sharp peak of radiative flux appears at \( t \sim 100 \) ns, as shown in Fig. 3(a). The normalized peak power is 15 in the VCR model under the present conditions.

Thereafter, \( I^* \) is pumped by \( O_2(\Delta) \) and the loaded gain \( g \) begins to increase and approach \( g_{th} \). The radiative flux and the output power reach steady states at about 20,000 ns, corresponding to the gas exchange time \( r_\alpha \), after the Q-switch is switched on.

After \( t = 25,000 \) ns, when the Q-switch is switched off, laser oscillation is terminated. Then, the gain increases gradually and recovers its initial value that is equal to the small signal gain (SSG) at \( t = 45,000 \) ns, since the laser cavity is filled with fresh gas.

Figure 4 shows the development of density distribution in the cavity during one pulse of the Q-switched operation. When the Q-switch is on/off, compression and expansion waves appear at the upstream and downstream edges of cavity because of the chemical reaction that is accompanied by sudden enhancement and/or reduction of heat release. These aerodynamic disturbances, however, are very weak and hardly affect the power extraction.

Figure 5(a) shows the initial sharp pulses of the output powers that were obtained using the three relaxation models. An induction period of about 50 ns for the rise of extracted power appears in all models. The peak power is lowered and the pulse is widened in the order of HFE, HFR and VCR models, as shown in Fig. 5(a). Figure 5(b) shows the absolute value of the ratio \( |\omega_{p} / \omega_{c}| \) of the production rate due to chemical reaction to the consumption rate due to radiation. It can be seen that \( I^* \) pumping is delayed markedly by the upper-level HFR, since the upper-level HFR time \( r_{\alpha} \) is comparable to the \( I^* \) pumping time \( r_\alpha \), as shown in Table 3. In addition, \( I^* \) pumping is further limited by the presence of VCR, since only the excited iodine atoms with \( v_\alpha = 0 \), \( \Gamma_{\alpha}(0) \), can emit laser power. Figure 6 shows the gain distribution as a function of frequency. It can be seen that \( \Gamma_{\alpha}(0) \) is consumed considerably due to power extraction and the hole-burning phenomenon occurs in the VCR model. \( I^* \) consumption due to power extraction and \( I^* \) pumping by \( O_2(\Delta) \) are balanced roughly 400 ns after the Q-switch is switched on.

Values of the normalized peak power for HFE,
HFR and VCR models are 42, 24 and 15, respectively. Some experimental studies\(^{(3)(4)}\) showed normalized peak powers of 5 through 16 in the Q-switched operation of COIL. Therefore, both HFR and VCR must be included in the model in order to reliably estimate power extraction.

### 4.2 Flow nonuniformity and power extraction

Figure 7 shows the three-dimensional flow field in the Q-switched operation under the same conditions as those given in Fig. 3. It is shown in Fig. 7(a) that expansion waves followed by weak compression waves emerge from the trailing edge of blades and interact with each other. Wakes issued from the trailing edges of nozzle blades are also clearly observed. As a result of lasing, the Mach number in the laser cavity is lowered to some extent due to the chemical reaction accompanied by enhanced heat release. However, aerodynamic disturbance caused by Q-switching as shown in Fig. 4 is not be observed, since it is negligible compared with the three-dimensional nonuniformity which originally exists in the flow field. It is also observed from Fig. 7 that insufficient mixing of iodine atoms and excited oxygen molecules \(O_2(\Delta)\) leads to a strong nonuniform gain distribution in the laser cavity. Though laser oscillation forces the gain to approach \(g_{\text{on}}\), some

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**Fig. 7** Flow field in the Q-switched operation for the three-dimensional VCR model with a pulse duration of 25 000 ns. (a) Mach number and (b) gain distributions on some planes at \(t=0, 10 000\) and 25 000 ns.
nonuniformity in the gain distribution exists in the wakes and near the flow axes.

Figure 8 shows the development of the instantaneous output power normalized by the corresponding CW value $P_\text{out}/P_\text{cw}$. The initial sharp pulses of the output powers obtained from the equivalent one-dimensional flow and the three-dimensional flow simulation are compared in Fig. 8(b). It can be seen that the induction period for the rise of extracted power is not influenced by the nonuniformity of the flow. However, the three-dimensional nonuniformity reduces the normalized peak power from 15 to 10 and increases the half-width of pulse from 86 ns to 162 ns. Because of the strong nonuniformity, the pulse profile of the radiation flux depends strongly on the position in the output mirror. Therefore, the pulse of the output power expressed as the integration of the radiative flux over the mirror is lowered and widened considerably.

5. Conclusions

A Q-switched S-COIL is simulated by solving simultaneously the gas flow model coupled with the precise chemical kinetic model and the geometric optical model. The present model includes the effects of HFR and VCR.

The values of normalized peak power obtained using HFE, HFR and VCR models, and the equivalent one-dimensional flow are 42, 24 and 15, respectively. Therefore, the present results clearly demonstrate that both HFR and VCR must be included in the model in order to predict well the Q-switched operation.

The three-dimensional simulation shows that aerodynamic disturbance caused by Q-switching is negligible compared to the three-dimensional nonuniformity which originally exists in the flow field. In addition, the normalized peak power is reduced to 10 and the half-width of the pulse is increased to roughly twice that in the equivalent one-dimensional flow owing to the three-dimensional flow nonuniformity.

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