Numerical Analysis of a Combustion-Driven Gasdynamic Laser

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This paper presents a theoretical analysis and partial optimization of an open-cycle CO_2 cw-GDL (gasdynamic laser) using benzene C_6H_6 and kerosene $C_{12}H_{24}$ combustion with air. The calculations are performed for an equivalency air/fuel ratio equal to 1 and the stagnation pressure p_0 equal to 15 atm, with geometrices dimensions of the lasers being optimized for maximum net output radiation power per unit mass flow. In both cases, the possibility of constructing a high-power cw-GDL supplied with these fuels is suggested. For combustion of C_6H_6 a specific energy $P_g = 11$ kW/kg-sec^{-1}; whereas for the calculated ideal CO_2-N_2-H_2O mixture (containing 12% CO_2 and 0.9% H_2O), $P_g = 18$ kW/kg-sec.^{1}. The influence on laser performance of stagnation pressure, stagnation temperature, expansion ratio, and air/fuel ratio has been examined partially.

Nomenclature

$\bar{B}_{mn},\bar{B}_{nm}$ = modified coefficients of stimulated emission and absorption
c = velocity of light
C_p = specific heat
G = mass flow
$\hbar$ = Planck constant ($\hbar = h/2\pi$)
H_i = local height of the channel ($i = 1,2,3$)
ΔH = reduced heat of formation
I_v = inversion coefficient ($I_v = N_m/N_n$)
J = rotational quantum number
k = Boltzmann constant
L_n = length of supersonic part of the nozzle
L_p = length of subsonic part of the nozzle
L_x = resonator mirror length
L_y = distance between resonator mirrors
M_i = Mach number at station i ($i = 1,2,3$)
M_a = gas mixture component ($a = H_2O$, O, CO, O_2, H_2, A, He)
N = number density
p_i = static pressure ($i = 0, 1, 2, 3$)
P_c = total output power
P_g = output power per unit mass flow
p_v = output power density per unit volume of the cavity
p_x = output power density per unit mirror length
q = enthalpy
Δq_{v-T} = translational enthalpy source due to the $v-T$ relaxation
R = reflectivity
Re_i = Reynolds number ($i = 1,2,3$)
S = mirror absorption losses (both surface and diffraction losses)
T = translational and rotational temperature
T_m = vibrational temperature of CO_2 (ν_3)
T_n = vibrational temperature of both $CO_2(\nu_1)$ and $CO_2(\nu_2)$
T_p = vibrational temperature of $N_2(v)$ and CO (v)
T_s = wall temperature
v = gas mixture velocity; vibrational quantum number (N_2 and CO)
x,y,z = Cartesian coordinates
X_a = mole fractions of gas mixture components
α_s = air/fuel ratio
η_e = total energetic efficiency
η_ι = laser efficiency
η_r = resonator efficiency
η_s = combustion efficiency
η_v = expansion efficiency
η_w = excitation efficiency
ν_i = CO_2 vibrational modes ($v_i = v_1 v_2, v_3$)
κ = isentropic exponent
λ_f = coefficient of gas-wall friction
λ_h = coefficient of gas-wall heat exchange
τ_{st} = relaxation time corresponding to $s \to t$ change of the molecule vibrational state ($s,t = m,n,p,o; o =$ ground state)
ω_k = vibration frequency ($k = v, \nu_i$)
$\Pi_v(x)$ = dimensionless gain coefficient:

$$\Pi_v(x) = l/C \int_0^{L_y} (\bar{B}_{mn}N_m - \bar{B}_{nm}N_n)\,dy$$

ρ = density
2ϕ = initial nozzle divergence angle

Subscripts

a = gas mixture component designation
f = photon
i,j = integers specifying a hydrocarbon
m = upper laser level
n = lower laser level
o = stagnation parameters
p = excited N_2 levels
$v-v$ = vibrational-vibrational energy transfer
$v-T$ = vibrational-translational energy transfer
1 = cross section of the nozzle throat
2 = inlet of the cavity
3 = cavity outlet cross section
rad = laser radiation field

Superscripts

$+, -$ = direction of photon motion
$'$ = change of quantum number

Received June 3, 1974; revision received December 9, 1975.
Index categories: Lasers; Nozzle and Channel Flow.

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I. Introduction

FROM the first suggestion that an expanding, nonequilibrium flow could produce a population inversion,[7] and the first demonstration of a gasdynamic CO_2 laser,[2] ever-increasing attention has been paid to problems related to gasdynamic laser physics and technology. References 3-9 list a growing number of theoretical and experimental works dealing with various aspects of the gain and population inversion creation in rapidly expanding CO_2-N_2 gas mixtures.

Combustion of liquid hydrocarbons in compressed air can be regarded as a promising source of energy because these fuels are cheap, readily accessible, and easily combusted. However, in the combustion products of hydrocarbons the amount of H_2O always far exceeds the optimum value for CO_2-laser performance, which lies in the neighborhood of 1%. This fact promoted research that was centered on establishing the possibilities and limitations of gain and inversion creation during the supersonic expansion of CO_2-N_2 mixtures supplied with large quantities of water vapor.[10-13]

Up to now significantly evolved numerical techniques[14-18] of analyzing cw—GDL channel flows have been developed. However, relatively little attention has been given[3,11,19,20] to the direct answer to the question of the performance of a cw-GDL run by air combustion of a hydrocarbon fuel C_iH_j, the amount of radiation power that can be extracted per unit of mass flow, and the GDL efficiency. The main scope of this paper lies in calculating the performance of such a laser including a particular resonator.

II. Description of Analytical Model

The operation of C_iH_j combustion-driven cw—GDL is calculated in three stages: 1) calculating the composition of a gas mixture produced by burning hydrocarbons in an isothermal and isobaric chamber; 2) calculating expansion of this mixture in a supersonic convergent-divergent nozzle with friction, heat exchange with walls, and vibrational energy transfer between molecules; and 3) solving a system of equations describing interaction between an optically active medium and the radiation field inside a cw-GDL optical cavity. It must be said that nonadiabatic expansion (heat release due to vibrational energy relaxation, friction against walls, and heat losses to the walls) resulted in Mach line being slightly displaced downstream into the divergent part of the nozzle. The parameter H_1, referred to, in what follows, as a nozzle throat height, actually differs from the height of the narrowest part of the nozzle itself.

The geometry of a single-nozzle segment of the GDL under consideration is shown in Fig. 1. The gas mixture composition (X_a) and its temperature (T_0) within the combustion chamber were calculated with the aid of a numerical program[21] suitable for any C_iH_j fuel burned with an oxidizer containing N_2, O_2, A, and, possibly, other molecular and atomic species ($\Sigma_a X_a = 1$). The combustion problem was considered in the steady-state approximation. Rate coefficients of formation and recombination for the general chemical reaction:

$$A[(C_{a1}H_{b1}O_{c1}N_{d1}A_{e1}) + (C_{a2}H_{b2}O_{c2}N_{d2}A_{e2})] \rightleftharpoons n_1CO_2 + n_2CO + n_3H_2O + n_4OH + n_5H_2 + n_6O + n_7N_2 + n_8NO + n_9C + n_{10}H + n_{11}O + n_{12}N + n_{13}A \quad (1)$$

as well as specific heat c_p, and reduced heat of formation ΔH, were related to temperature by semiempirical relations[21] based upon data gathered in standard thermodynamic tables.[22] The interaction with walls was accounted for by fixing the efficiency of combustion $\eta_s = 0.9$.

For calculation of the gas mixture expansion in a nozzle, a one-dimensional model of the flow was assumed with averaged boundary layer gas-wall friction and heat exchange effects [wall temperature, T_s, remained constant ($T_s = 300°K$) inside the channel], as well as apparent heating of the gas from vibrational energy relaxation processes taken into account. The calculated shape of the nozzle assured a shock-free supersonic flow into a laser channel. For calculation of intra- and intermolecular energy exchange processes, a four-temperature model[23] was assumed. Data

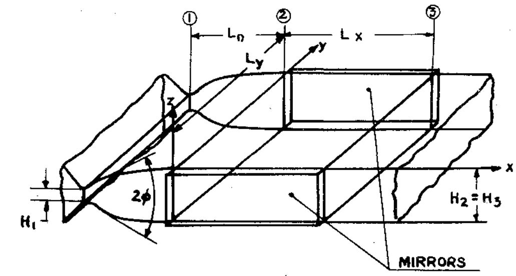

Fig. 1 Geometry of a single-nozzle element of the cw-GDL.

concerning rate constants for $V-V$ and $V-T$ energy exchange reactions

$$CO_2(\nu_1,\nu_2,\nu_3) + M_a \rightleftharpoons CO_2(\nu_1', \nu_2', \nu_3') + M_a \quad (2)$$

$$N_2(v) + M_a \rightleftharpoons N_2(v') + M_a \quad (3)$$

$$CO_2(\nu_1, \nu_2, \nu_3) + N_2(v) \rightleftharpoons CO_2(\nu_1', \nu_2', \nu_3') + N_2(v') \quad (4)$$

were based upon extensive review[24] and, additionally, on Refs. 25 and 26, and kept close to the pessimistic limit of the experimental data. The numerical program provides for possible presence of the species CO_2, N_2, CO, H_2O, O_2, H_2, A, and He in the working gas.

The laser action was calculated on the basis of a kinetic model (nonlinear equations of chemical kinetics) of interaction between the radiation field (represented by photon number densities) and the system of the optically active mixture[27,28] (with pumping, relaxation, and spatial variability of pressure, temperature, and velocity taken into consideration).

The following assumptions were made: 1) laser action taking place between rotational sublevels of the $00°1$ and $10°0$ vibrational energy levels of ν_3 and ν_1 modes, respectively; 2) only the radiation power of $P(J_{opt})$ line is accounted for, where J_{opt} corresponds, for given local values of mixture-state parameters, with maximum gain value; and 3) a high-efficiency[28-30] cavity model is formed by two identical parallel flat mirrors with reflectivity $R(x)$ increasing downstream linearly[28] from a matched value $R_0 = \exp(-\Pi_{v2})$ up to $R(L_x) = 1 - S$. The reasons to design cavities with mirrors of nonconstant reflectivity were discussed in Ref. 30. The main advantage of these hypothetical cavities lies in the possiblity of achieving the optimum matching between the cavity losses $[\sim \ln(1/R)]$ and the local gain value[28,30] which decreases along the flow axis. This tuning can result in about a twofold increase of the resonator efficiency as compared to the efficiency of a constant reflectivity model of the GDL cavity. In practice, the model of the optical resonator in question could be manufactured by coupling the nontransmitting flat mirror with a parallel multihole mirror nonuniformly perforated along the flow axis.[29] The foregoing could constitute but slight modification of the cavities largely used in GDL systems (e.g., Refs. 2 and 8) in which the transmitting multihole mirrors has been built as uniformly perforated along the flow axis.

Under all of the preceding specific assumptions, the following system of equations was integrated:

Continuity Equation

$$\rho v H L_y = G \quad (5)$$

Equation of State

$$p = [(\kappa - 1)/\kappa]\rho q \quad (6)$$

Momentum Equation

$$\rho v(\partial v/\partial x) = -(\partial p/\partial x) - (\lambda_f/2H)(\rho v^2/2) \quad (7)$$

Energy Equation

$$(\partial/\partial x)\ [q+(v^2/2)] = \Delta q_{v-T} - (2\lambda_h/\rho v H)\ (T-T_s) \tag{8}$$

where

$$\Delta q_{v-T} = -(\partial/\partial x)[q_p(T_p)+q_m(T_m)+q_n(T_n)] \tag{9}$$

Relaxation Equations

$$v\frac{\partial q_p(T_p)}{\partial x} = -\frac{q_p(T_p)-q_p(T_m)}{\tau_{pm}} - \frac{q_p(T_p)-q_p(T)}{\tau_{po}} \tag{10}$$

$$v\frac{\partial q_m(T_m)}{\partial x} = -\frac{q_m(T_m)-q_m(T_p)}{\tau_{mp}} - \frac{q_m(T_m)-q_m(T_n)}{\tau_{mn}} - \frac{q_n(T_m)-q_m(T)}{\tau_{mo}} + v\left[\frac{\delta q_m}{\delta x}\right]rad \tag{11}$$

$$v\frac{\partial q_n(T_n)}{\partial x} = -\frac{q_n(T_n)-q_n(T_m)}{\tau_{nm}} - \frac{q_n(T_n)-q_n(T)}{\tau_{no}} + v\left[\frac{\delta q_n}{\delta x}\right]rad \tag{12}$$

In Eqs. (11) and (12) the right-hand terms, $(\delta q_m/\delta x)rad$ and $(\delta q_n/\delta x)rad$, are equal to zero everywhere outside the cavity. Within the resonator region these enthalpy source terms are determined through the populations of upper and lower laser levels (N_m and N_n) by solving, jointly with Eqs. (5-8), the additional six equations, viz., the continuity equations for the respective kinds of particles, including photons:

$$v(\partial N_m/\partial x)rad = (\bar{B}_{nm}N_n - \bar{B}_{mn}N_m)\ (N_f^+ + N_f^-) \tag{13}$$

$$v(\partial N_n/\partial x)rad = -v(\partial N_m/\partial x)rad \tag{14}$$

$$(\partial \ln N_f^+/\partial y) = -c(\partial \ln N_f^-/\partial y) = \bar{B}_{mn}N_m - \bar{B}_{nm}N_n \tag{15}$$

$$N_f^+(x,0) = R(x)N_f^-(x,0);\ N_f^-(x,L_y) = R(x)N_f^+(x,Ly) \tag{16}$$

The population densities N_m, N_n and enthalpies q_p, q_m, q_n are related to the remaining parameters by the formulas:

$$q_p(T_i) = (\omega_v/\rho)N_{N_2}[\exp(\hbar\omega_v/kT_i)-1]^{-1} \tag{17}$$

$$q_m(T_i) = (\omega_{v_3}/\rho)N_{CO_2}[\exp(\hbar\omega_{v_3}/kT_i)-1]^{-1} \tag{18}$$

$$q_n(T_i) = (1/\rho)N_{CO_2}\left[\frac{\omega_{v_1}}{\exp(\hbar\omega_{v_1}/kT_i)-1} + \frac{2\omega_{v_2}}{\exp(\hbar\omega_{v_2}/kT_i)-1}\right] \tag{19}$$

$$N_m = N_{CO_2}\exp(-\hbar\omega_{v_3}/kT_m)[1-\exp(-\hbar\omega_{v_3}/kT_m)]\ [1-\exp(-\hbar\omega_{v_1}/kT_n)]\ [1-\exp(-\hbar\omega_{v_2}/kT_n)]^2 \tag{20}$$

$$N_n = N_m\exp[(\hbar\omega_{v_3}/kT_m)-(\hbar\omega_{v_1}/kT_n)] \tag{21}$$

where[31] $\hbar\omega_v/k = 3353°K$, $\hbar\omega_{v_3}/k = 3380°K$, $\hbar\omega_{v_2}/k = 960°K$, and $\hbar\omega_{v_1}/k = 1998°K$.

The relaxation times, τ_{st} and τ_{ts}, are known functions[23-26] of translational temperature, static pressure, and mixture composition. The modified coefficients of stimulated emission ($\bar{B}_{mn}$) and absorption ($\bar{B}_{nm}$) are related to temperature, pressure, mixture composition, and rotational number, J_{opt}, also by known formulas.[23,27,28] The square of the laser transition dipole momentum $(R_n^m)^2$ has been taken to be equal to 1.255×10^{-52} m^{3}J (spontaneous emission time $A_{mn}^{-1} = 3.13$ sec),[32] and mixed Doppler-Lorentz broadening was taken into account. The gas-wall friction coefficient λ_f as well as the gas-wall heat exchange coefficient λ_h are calculated[33] using semiempirical relations defining them through local values of Reynolds, Nusselt, and Prandtl numbers, respectively.

Some parameters like the kind of fuel and oxidizer, stagnation pressure (p_o), combustion efficiency η_s, the nozzle initial divergence angle (2ϕ), mirrors loss coefficient ($S = 0.02$), and wall temperature (T_s) are assumed; the remaining geometrical and physical parameters are calculated and optimized from the viewpoint of reaching the maximum value of output radiation power per unit mass flow

$$P_g \cong 2\hbar\omega_{rad}c\int_0^{L_x} H(x)N_f^-(x,0)\,[1-S-R(x)]\,dx \tag{22}$$

where $\hbar\omega_{rad}/k = 1382°K$. All of the results described below were obtained under the assumption that the inlet cross section of the cavity is located at a point where the dimensionless gain coefficient attains its maximum value, $\Pi_{v2} = [\Pi_v(x)]_{max}$. The length of the subsonic part of the nozzle, L_p, was taken to be equal to 2.5 H_1, and the velocity v has been assumed to increase along the flow linearly with x up to the critical value v_1 at the nozzle throat. The value $H(x)$ should be understood, in this part of the nozzle, as a length of an arc-section along potential lines rather than as the local height of the GDL channel. The flow outside the nozzle was chosen to be isobaric ($p_1 = \text{const} = p_3$), which gives local height of the channel in the lasing zone, $H(x)$, slightly increasing in the downstream direction.

III. Description of Main Results

With the fuel, oxidizer, combustion efficiency, wall temperature, mirror losses, and nozzle initial divergence angle fixed, the analysis of the cw-GDL working at a stagnation pressure of $p_o = 15$ atm was performed. In every case the mixture composition (X_a), the stagnation temperature (T_o), nozzle throat height (H_1), local value of the channel height calculated along the flow axis [$H(x)$], length of the supersonic part of the nozzle (L_n), length of the resonator mirrors (L_x), distance between the mirrors (L_y), and total mass flow (G) were calculated. The geometrical dimensions, H_1, and L_x, were optimized for reaching maximum value of P_g realizable in a single-nozzle cw-GDL segment filled with the working mixture (combustion products) at the rate corresponding to the mass flow G.

In the course of the optimization procedure, the throat height (H_1), the mirror length (L_x) and the expansion ratio of the nozzle have been considered as free variables whereas the optimum values of the remaining physical and geometrical parameters resulted indirectly from maximizing P_g [see Eq. (22)]. In selecting optimum linear dimensions, an additional condition has been imposed, viz., the distance between the mirrors (optical length L_y) should be selected in such a way that $\Pi_{v2} = [\Pi_v(x)]_{max} = 0.7$. From Eqs. (13-16) the following condition for continuous laser action results: $R(x) = \exp[-\Pi_v(x)]$; therefore the value $\Pi_{v2} = 0.7$ corresponds to $R_o = 0.5$. In the authors' opinion the limiting condition $R(x) \gtrsim 0.5$ [and, correspondingly, $\Pi_v(x) \lesssim 0.7$) ought to be satisfied to avoid losses due to possible generation of parasitic laser oscillations between the sidewalls of the GDL channel upstream from the optical cavity region.

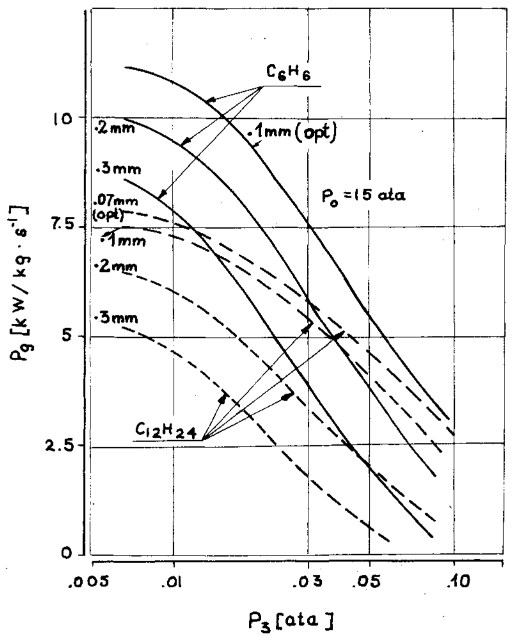

Fig. 2 Net output power per unit mass flow P_g as a function of the cavity outlet pressure p_3 for the optimal and nonoptimal values of the nozzle throat height.

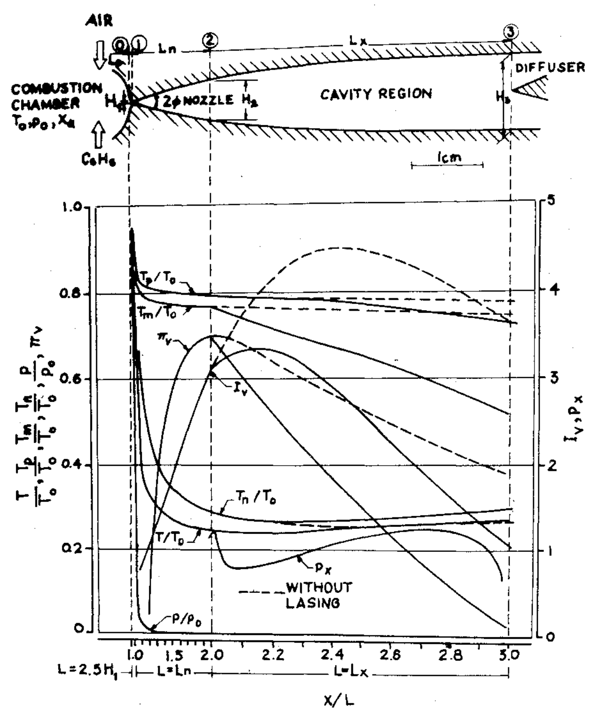

Fig. 3 Example of the distribution of several parameters along the flow axis of an optimal single-nozzle cw-GDL driven by benzene combustion in air at $p_o = 15$ atm.

The calculations were performed for different values of the nozzle expansion ratio, which correspond to different values of the exit pressure p_3. As a measure of the expansion ratio of the nozzle, the quantity M_{2s} has been introduced. M_{2s} stands for the theoretical Mach number at the exit of the nozzle calculated for the mixture flow as an isentropic one.

For every GDL under consideration, together with G, Π_v, L_x, L_y, L_n, and $H(x)$, the five different efficiency coefficients were examined: 1) the excitation efficiency (η_w) defined as a ratio of virtual (theoretically available) radiation power stored in combustion chamber and net heat source power; 2) the expansion efficiency (η_v) measuring the freezing effectiveness and defined as a ratio of virtual radiation power at inlet cross section of the cavity and virtual radiation power stored in the chamber; 3) laser efficiency (η_ι) defined as a ratio of net output radiation power and virtual radiation power at inlet cross section of the cavity; 4) resonator efficiency (η_r) defined as a ratio of net and gross output radiation power; 5) total energetic efficiency, being a product of the previously mentioned coefficients and defined as a ratio of net radiation output power and heat source power ($\eta_e = \eta_w \eta_v \eta_\iota$); and 6) the net output power extracted per unit mass flow P_g [see (22)].

To form an overall picture, examples of the distribution of T_m, T_p, T_n, T, v, H, and p along the flow axis are given (see Figs. 3 and 4). In addition, dimensionless gain $\Pi_v(x)$, dimensionless inversion coefficient $I_v = N_m/N_n$, and output power density per unit length of the mirrors P_x normalized to unity are plotted as functions of x coordinate along the flow axis (Fig. 3 and 4). Some results of the calculations concerning benzene are presented in Figs. 2 and 3. The x/L is a dimensionless distance along the flow axis, being referred to 2.5 H_l in the subsonic part of the nozzle, to L_n in the supersonic part of the nozzle, and to L_x in the optical cavity region. So, $x/L = 0$ in the chamber, $x/L = 1$ at the critical section of the nozzle, $x/L = 2$ at the inlet to the lasing zone, and $x/L = 3$ at the exit from the cavity.

It results from Fig. 2 that in the C_6H_6 case $(H_l)_{opt}$ is near 0.7 mm almost independently from the expansion ratio ($p_o \cdot H_l)_{opt} = 0.15$ atm · cm) and that P_g rises monotonically with the drop of the p_3 value (with increase of the expansion ratio). The problem of proper selection of the M_{2s} value (and, correspondingly, a value of p_3) consequently can be solved easily. It is the maximum value of M_{2s} for which dynamic self-compression of the stream in a diffuser to a given outlet pressure is possible. For example, after fixing the expansion ratio at the value $M_{2s} = 6.9$ and choosing, appropriate for this case, values of $H_l = 0.1$ mm, $L_x = 4.25$ cm, and $G = 0.116$ kg/sec, one can calculate all of the other parameters, as shown in Figs. 2 and 3. The results concern an optimum segment of GDL driven by C_6H_6 burned in cold air ($T = 300°$K) under the pressure of 15 atm, with self-compression of the flow in a diffuser up to the barometric pressure. (Calculations of the diffuser are not discussed in this paper.) This optimum laser gives $P_g = 10.5$ kW/kg·sec^{-1} and $\eta_e = 0.4\%$, which seems to be sufficiently attractive for practical applications.

The calculated value of the output power is $P_c = 1.22$ kW, and this is the power of the single optimum segment of the laser. Consequently, a many-kilowatt GDL should be constructed as a multisegment one, comprising the demanded number of optimum segments.

In C_6H_6-combustion products, there is obviously too large an amount of H_2O. To determine how the output power was affected by H_2O concentration, the calculations were repeated for the same values of $p_o = 15$ atm, $T_o = 2221°$K, $M_{2s} = 6.9$, looking this time for the optimal $CO_2/N_2/H_2O$ mixture composition. As a result, it was established (Table 1) that, in the optimal case, the cw−GDL under consideration ought to be supplied with a mixture $(X_{CO_2}/X_{N_2}/X_{H_2O})_{ideal} = 0.1776/0.8732/0.0092$, consequently being able to produce the amount of radiation output power $P_g = 17.79$ kW/kg·sec^{-1}. The eightfold increase (from lowest ideal level) of H_2O concentration for C_6H_6 caused almost 50% diminution of the power density per unit mass flow. The optimum nozzle-throat height is, in this case, five times larger [$(H_l)_{opt} = 0.5$ mm], and the value $(P_o H_l)_{opt} = 0.76$ atm ·cm has been calculated.[3,33,34,35]

After C_6H_6, the next example of liquid hydrocarbons studied was the technically attractive kerosene ($C_{12}H_{24}$). The calculations were carried out in the same way as previously, and the main data describing the cw-GDL driven by $C_{12}H_{24}$ combustion in air are listed in Figs. 2 and 4. The comparison with benzene shows that the increase of H_2O from $X_{H_2O} = 0.0793$ (for C_6H_6) up to $X_{H_2O} = 0.1291$ (for $C_{12}H_{24}$) was followed by a drop of P_g down to $P_g = 7.69$ kW/kg-sec^{-1}.

Table 1 Main parameters of an ideal-mixture cw-GDL

$T_o = 2221$K	$p_o = 15$ atm	$M_{2s} = 6.9$	$\Pi_{v2} = 0.7$	$T_s = 300$K
$\eta_w = 0.04165$	$P_g = 17.79$ kW/kg-sec^{-1}	$L_n = 8.124$ cm	$T_3 = 548$°K	$X_{CO_2} = 0.1176$
$\eta_v = 0.56654$	$G = 0.6545$ kg/sec	$L_x = 29.451$ cm	$p_3 = 0.0086$ atm	$X_{N_2} = 0.8732$
$\eta_\iota = 0.29246$	$H_I = 0.5048$	$L_y = 1.0681$ m	$M_3 = 4.26$	$X_{H_2O} = 0.0092$
$\eta_r = 0.82030$	$H_2 = 3.2808$ cm	$H_3 = 5.6220$ cm	$Re_I = 19{,}503$	$Re_3 = 42{,}992$

The energetic efficiency dropped to $\eta_e = 0.29\%$, and total output power extracted from the one-segment cavity was equal to only $P_c = 0.67$ kW. Following the increase of the effective velocity of the vibrational energy relaxation,[3] the parameter $p_o H_{I\,\mathrm{opt}}$ diminished again, reaching for $C_{12}H_{24}$ the value of 0.09 atm. cm.

In the cases of both benzene and kerosene the stagnation temperature T_o is almost the same and equals approximately 2200°K, but this value could be changed easily. Therefore, additional calculations have been performed to examine the influence of T_o on laser performance and to check whether this value is very different from an optimum one. Some results obtained for the case of an ideal-mixture laser (as previously for: $p_o = 15$ atm, $M_{2s} = 6.9$, $S = 0.02$, $2\phi = 30°$ and $\Pi_{v2} = 0.7$) are presented in Fig. 5. It is evident from the figure that, for $p_o = 15$ atm, $(T_o)_{\mathrm{opt}} \cong 2000$°K. It is therefore reasonable to assume combustion with air/fuel ratio α_s slightly greater than stoichiometric, which results in lowering the stagnation temperature and avoiding insufficient combustion and creation of smoke. The amount of O_2 in the working gas which will appear in this case causes only a relatively small drop of the laser performance. Calculations for the case of the C_6H_6 laser show that $T_o = 2000$°K results from the combustion with the coefficient $\alpha_s = 1.2$, and for the value $\alpha_s \cong 1.1$ there is an insignificant optimum with $T_o \cong 2100$°K, $X_{O_2} \cong 0.02$, and $(P_g)_{\alpha_s = 1.1}/(P_g)_{\alpha_s = 1.0} \cong 1.015$.

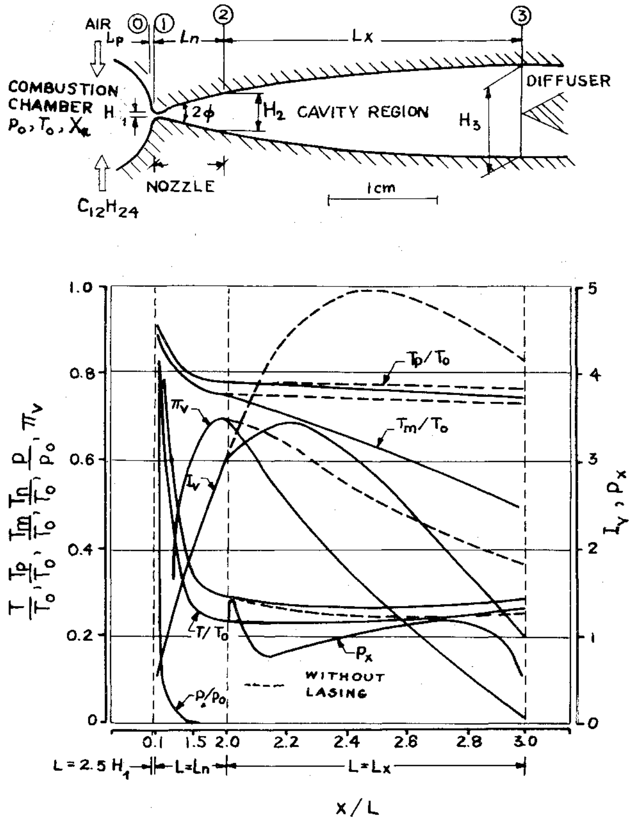

Fig. 4 Example of the distribution of several parameters along the flow axis in a single-nozzle channel of the cw-GDL driven by $C_{12}H_{24}$ combustion in air at $p_o = 15$ atm.

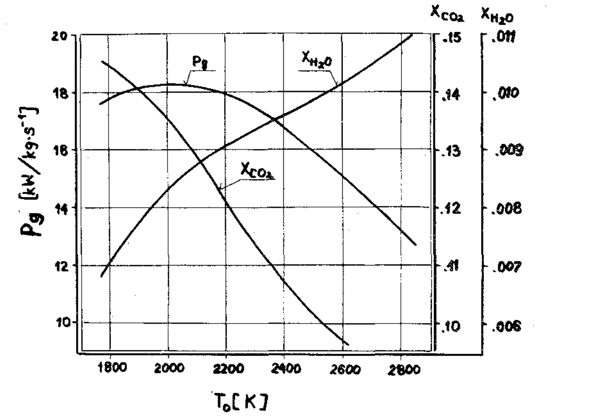

Fig. 5 Dependence of the output power per unit mass flow P_g and optimum water and carbon dioxide concentrations X_{H_2O} and X_{CO_2} on stagnation temperature T_o for an ideal-mixture cw-GDL working at stagnation pressure $p_o = 15$ atm and $M_{2s} = 6.9$.

Criteria for selection of the proper value of the stagnation pressure p_o are very flexible, because the influence of p_o on P_g and η_e of the GDL is but slight. Calculations for the case of C_6H_6 and $p_o = 50$ atm show that P_g and η_e are almost identical as for $p_o = 15$ atm. This is expected because T_o was kept approximately constant. All dimensions of the channel are approximately three times smaller, and the exit pressure p_3, approximately proportional to p_o, is greater. Therefore, increasing p_o makes the problem of exit diffuser for high values of M_{2s} easier to cope with but also causes proportional increase of the power needed for compression of air supplied to the combustion chamber and makes manufacturing of the nozzle system more difficult.

IV. Conclusions

The performance of both benzene (C_6H_6) and kerosene ($C_{12}H_{24}$) for use as fuels in air-combustion-driven cw-GDL's was calculated. The predicted output power per unit mass flow was about 11 kW/kg-sec^{-1} (for C_6H_6) and 7.6 kW/kg-sec^{-1} (for $C_{12}H_{24}$). This means about 39% and 58% deterioration if compared with output power produced by low H_2O-concentration ideal mixture ($P_g = 18$ kW/kg-sec^{-1}). The essential geometric and physical conditions necessary for realization of efficient cw-GDL were identified for both fuels.

The obtained results are in satisfactory agreement with those presented elsewhere. Somewhat higher values given in Ref. 3, e.g., for combustion of benzene, can be explained by differences in kinetic rates assumed.[36] The rates utilized in the present paper have been chosen so as to obtain rather pessimistic values of P_g. One also should remember that the presented calculations are based on the assumption of the resonator model that is somewhat abstract and may differ from an actual optical system chosen for the laser.

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