Ram Airbreathing Laser Performance

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The theoretical performance characteristics of the ram airbreathing laser (RAL) are evaluated for a wide variety of conditions (M=3-6, altitude=40,000-100,000 ft). The RAL is an adaptation of the airbreathing laser (ABL) and utilizes atmospheric air and the ram effect to produce high-pressure (2-55 atm), high-temperature (600-1700 K) air at the combustion chamber. Benzene (C_6H_6) is used to raise the air temperature from 1400 K to 2500 K. The vibrational nonequilibrium flow in the nozzle and laser cavity is evaluated for the CO_2-N_2-H_2O-O_2 gas mixture to determine the small signal gain and maximum available energy. Significantly high levels of small signal gain ($g_o \approx 0.8$-$1.0\ m^{-1}$) and maximum available energy $e_m/RT_o \approx 0.08$-0.1) are available to provide high levels of specific power output.

Nomenclature

a = acoustic velocity
A = area
A^* = throat area
C = mass fraction
D = diameter
e = available laser energy
f = fuel-air ratio
g_o = small signal gain
h = nozzle throat height
H = blade height
I_s = saturation intensity
$\dot{m}$ = mass-flow rate
M = Mach number
N = number density
p = pressure
P = power
PR = pressure recovery
q = quantum efficiency
Q = partition function
R = gas constant
t = time, throat
T = temperature
u = velocity
W = width
x = axial position
X = mole fraction
ϵ = energy per particle
η_e = power extraction effectiveness
η_f = freezing efficiency
θ = characteristic temperature
λ = wavelength
ν = collision frequency
ρ = density
τ = spontaneous radiative lifetime

Subscripts

AW = aerodynamic window
bl = boundary layer
BP = bypass
D = diffuser
e = exit, effective
E = exit of nozzle
i = combustor inlet, specie
j = specie
max = maximum
N = nozzle
p = products
R = gas constant
t = throat
vib = vibrational
o = combustor outlet
001 = 001 level of CO_2
100 = 100 level of CO_2
∞ = freestream
I = mode I, lower level
II = mode II, upper level

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Introduction

OPEN-cycle gas dynamic lasers (GDL) require large amounts of stored gas for use as the laser working medium. A significant portion of the GDL system weight is associated with the storage of this gas (primarily N_2), which may exceed the weight of all other components for long operating times. A significant reduction in system weight is possible by utilizing the combustion products of atmospheric air and appropriate fuels. This concept, called the airbreathing laser (ABL), utilizes efficient light-weight air supply equipment to deliver the desired mass flow at a given pressure level for optimum laser operation. The required amounts of CO_2 and H_2O for laser action can be provided by the combustion of hydrocarbon fuel with the compressed preheated air. The energy imparted to the air during the compression process minimizes the detrimental effects of excessive amounts of CO_2 and H_2O developed when heating cold air to the final temperature with hydrocarbon fuel.

The feasibility of the ABL concept has been demonstrated.[1] The application of an airbreather utilizing hydrocarbon fuel can significantly improve the specific power of the device based on stored consumables, compared with that of the usual open-cycle GDL. The small signal gain and the low level of soot formation have been shown to be adequate to provide the desired laser operation.

The ram airbreathing laser (RAL) is a unique adaptation of the ABL for advanced aircraft applications, where the ram effect is used to provide high-pressure and high-temperature air to the device. A schematic sketch of the RAL, its essential components, and the various sources of mass flow are shown in Fig. 1.

Inlet Performance

Successful operation of the RAL depends strongly upon adequate performance of the supersonic inlet, which provides the desired mass-flow rate of air at a given pressure and temperature to the combustor inlet. A number of studies have been made[2,3] which have demonstrated the performance and characteristics of inlets over a range of Mach numbers from 2 to 5. Valuable knowledge was obtained about methods capable of optimizing performance as well as attaining flexibility in operation over a range of both Mach number and altitude conditions. To counteract detrimental effects caused by off-design operation (changes of angle of attack, Mach number, and altitude) an adjustable geometry of the inlet configuration is required. Means must also be applied to decrease boundary-layer growth to avoid flow blockage and obtain optimum mass flow and pressure recovery. Since gusts will lead to sudden changes in angle of attack and unstart of flow when the inlet operates close to its maximum pressure recovery, one has to settle for a somewhat lower pressure recovery operation to tolerate such changes, which occur too fast to be corrected by the control mechanism. The previous inlet studies and findings were made in support of airplane propulsion systems with no consideration being given to RAL requirements; however, the results are directly applicable, although additional requirements will have to be incorporated. Special attention has to be given to flow distortion controls to obtain homogeneous flow conditions mandatory for efficient lasing. Due to the stringent requirement of an almost perfect homogeneous flowfield in the lasing zone, coupled with a reasonable amount of flexibility regarding off-design operation, it will be necessary to make many compromises in the design of an optimum supersonic inlet configuration.

The intent of this RAL study was not to design an inlet but to utilize performance characteristics that represent realistic performance over the Mach number range of interest. The performance characteristics of prime interest for assessing the laser potential performance were the total pressure and temperature at the engine face (combustor inlet). The total pressure, based on pressure recovery test data[2,3,4] and standard conditions[5] varies between 2 and 55 atm, and the total temperature varies between 600 and 1700 K, as shown in Fig. 2 for altitudes between 40,000 and 100,000 ft. and Mach numbers between 3 and 6.

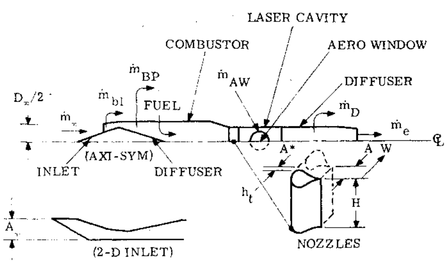

Fig. 1 Typical ram airbreating laser (RAL) geometry.

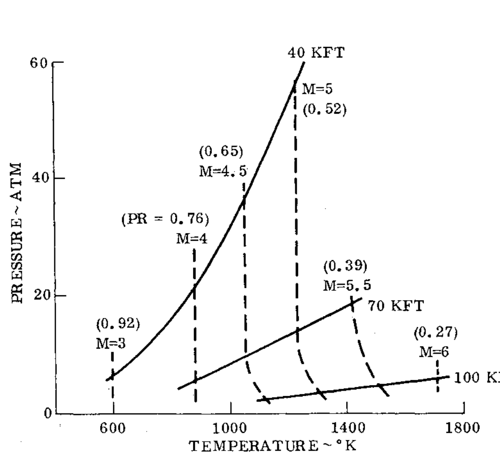

Fig. 2 Combustor inlet conditions (pressure vs temperature for axisymmetric inlet with a given pressure recovery).

Combustion

The airbreathing laser utilizes the combustion of hydrocarbon fuel to raise the air temperature and also provide the required amount of CO_2 and H_2O in the gas mixture to achieve lasing action. It is, therefore, necessary to evaluate the amount of fuel required to raise the temperature to the desired level and to estimate the resulting gas composition. The procedure employed to make this evaluation for known combustor inlet conditions is discussed in this section.

Chemical composition of atmospheric air was assumed constant for all altitudes of this study (40,000-100,000 ft).[5] In analyzing the combustion process, it was assumed that there is always more air present than is required for complete combustion, the reaction proceeds to completion, and the basic constituents in the products of combustion of hydrocarbon fuels in air will be CO_2, H_2O, N_2, and O_2. Validity of this last assumption is confirmed, since the only other species of any significance is NO (less than 0.3%).[6]

The analyses employed permitted calculation of the combustor discharge temperatures (adiabatic flame temperatures) for given fuel-air ratios. Since it was required to determine the amount of fuel necessary to produce a given combustor discharge temperature, an iterative solution was used, employing fuel-air ratio as the independent variable. In this manner the fuel-air ratios corresponding to desired combustor temperatures were determined. Convergence was rapid, since the enthalpies of the species being considered were all nearly linear functions of temperature. The fuel-air ratio and the resulting gas-mixture composition were thus determined for the range of conditions of interest for this RAL study for a range of inlet temperatures (600-1800 K) and combustor outlet temperatures (1400-2500 K). The evaluation was made for benzene (C_6H_6), which was selected as the fuel because it provided a high CO_2/H_2O mole fraction ratio for a common fuel.[1]

The fuel-air ratio required to raise the inlet air to a desired outlet temperature using benzene was determined for a range of fuel-air ratios (0-0.05). As expected, the greater the temperature rise the larger the fuel-air ratio. The fuel-air ratio, for example, is about 0.026 to raise the inlet temperature from 1000 to 1800 K. The gas mixture compositions are shown in Fig. 3 and 4 as functions of inlet and outlet temperatures. For

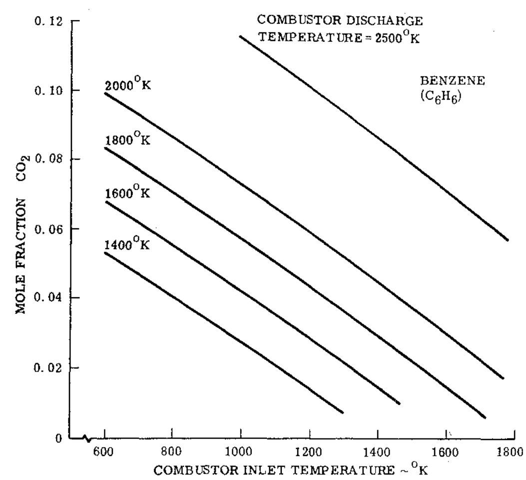

Fig. 3 Mole fraction of Co_2 in combustion products for benzene.

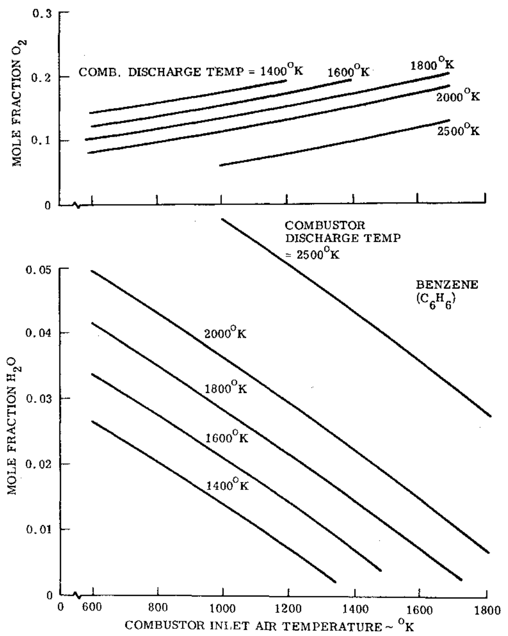

Fig. 4 Mole fraction of H_2O and O_2 in combustion products for benzene.

the condition just cited the gas composition is about $XCO_2 = 0.058$, $XH_2O = 0.029$, and $XO_2 = 0.135$, while the remainder represents N_2 (i.e., $XN_2 = 0.778$). it is noted that the gas composition and fuel-air ratio vary with each inlet and outlet temperature (RAL operating point).

It is evident, that for certain inlet and outlet temperatures (those where the temperature rise is very small) there is little or no fuel required, with the resulting effect that the mole fraction of CO_2 may be too low to provide adequate lasing action. It is, therefore, necessary to match the outlet and inlet temperatures properly to provide sufficient CO_2 to permit efficient RAL operation. It is clear, for example, that, when the RAL operates at Mach 6 and the combustor inlet temperature is about 1710 K, the combustor outlet temperature must be fairly high ($T_o = 2000$ K, or over) to provide efficient laser performance solely from the combustion products.

Laser Performance

The population inversion required to provide the stimulated light emission for the laser is produced by rapidly expanding a suitable gas mixture in an array of nozzle blades. This gas must be in nonequilibrium, where certain constituents due to their different relaxation rates are at effectively different vibrational temperatures. If the number of particles in the upper vibrational level exceeds that in the lower level so that an inversion can exist, the desired laser action can take place. The complex nature of this nonequilibrium flow requires use of sophisticated computer codes to track each constituent properly during its time-dependent reaction as the gas flows through the nozzle and laser cavity.

A bimodal (two vibrational temperature) approach[7,8] has been successfully utilized to reduce the complexity of the vibrational energy transfer process. Full coupling is provided between the finite rate molecular processes and the gas dynamic flow, as required for accurate predictions of the population inversion. Anderson's[7,8] model has been revised to streamline the computations, to include vibrationally active O_2 processes, and to update the kinetic rates as required for an ABL or RAL device.

The kinetics model employs three temperatures in the analysis, namely: 1) translational-rotational temperature (local fluid mechanics temperature); 2) vibrational temperature of N_2 and the asymmetric stretch mode of CO_2 (upper level); and 3) vibrational temperature of the CO_2 bending and symmetric stretch modes (010 and 100, lower level). The 020 and 030 modes of vibration of CO_2 utilize the same vibrational temperature as 3) (the lower level) since the relatively close spacing between these levels of CO_2 are assumed to be depopulate rapidly and dropping to the 010 levels. The vibrational levels of H_2O and O_2 are assumed in equilibrium with the local translational temperature, due to the relatively high reaction rates of these molecules (H_2O and O_2) compared with N_2 and CO_2. Combining all the pertinent kinetic processes into these groups introduces some error into the model, but this error is believed insignificant in light of the uncertainties that exist in the values of the kinetic constants and rates.[9]

Meaningful indicators of laser performance are the streamwise variation of small signal gain and the maximum available optical energy in the cavity. The small signal gain is a direct indication of the ability to extract the available optical energy. The kinetics program[4] computes the fluid mechanics and kinetics of a quasi-one-dimensional nozzle and duct flow for a CO_2-N_2-H_2O-O_2 gas mixture in vibrational nonequilibrium. A time-dependent technique is used so that the governing equations become hyperbolic, regardless of whether the flow is subsonic or supersonic, and thus may be solved as an initial value problem, rather than a boundary value problem for elliptic equations, as would occur in the subsonic portion of the nozzle in steady flow. In solving these equations, an initial solution is assumed, and the computation proceeds until a steady-state solution is attained. The fluid mechanics and kinetics are completely coupled in this scheme.

Modifications to Kinetics

With vibrational energies of O_2 included, for the ABL/RAL gas mixture the total vibrational energy present may be expressed as

$$e_{\text{vib}} = C_{N_2}\, e_{\text{vib}_{N_2}} + C_{CO_2}\, e_{\text{vib}_{CO_2}} + C_{H_2O}\, e_{\text{vib}_{H_2O}} + C_{O_2}\, e_{\text{vib}_{O_2}} \tag{1}$$

where

$$e_{\text{vib}_i} = \sum {}_j g_{ij} \left[R_i \theta_{ij} / \exp(\theta_{ij/T}) - 1 \right] \tag{2}$$

where $\theta_{i,j}$ is the characteristic temperature of vibrational mode j of species $i, g_{i,j}$ is the degeneracy of mode j, and R_i is the gas constant. The energy equation then becomes

$$\frac{\partial T}{\partial t} = \frac{-2}{5(C_{N_2} R_{N_2} + C_{CO_2} R_{CO_2} + C_{O_2} R_{O_2} + 1.2 C_{H_2O} R_{H_2O})} \cdot \left[T \frac{\partial u}{\partial x} + Tu \frac{\partial \ln A}{\partial x} + \frac{1}{R} \left(\frac{\partial e_{\text{vib}}}{\partial t} + u \frac{\partial e_{\text{vib}}}{\partial x} \right) \right] - u \frac{\partial T}{\partial X} \tag{3}$$

As stated previously, the vibrational modes of both H_2O and O_2 relax quickly[10] and, hence, are assumed to be always in equilibrium with the local translational temperature. The effect of including vibrational H_2O energy in a CO_2-N_2-H_2O gas dynamic laser system is that the small signal gain decreases as the mole fraction of H_2O increases. Similar results occur when adding O_2 vibrational energy.

The dominant factor controlling accuracy of this model is the uncertainty associated with parameters governing the kinetic processes in the system.[9] Rates of vibrational relaxation, collisional cross sections, and characteristic temperatures of vibration in the various modes are all, to some extent, uncertain. Originally, the program used values of these parameters as specified by Anderson, who relied heavily on the work of Taylor and Bitterman.[10] A survey of recent literature has indicated that some of the relaxation rate coefficients originally used have changed appreciably, based on more recent measurements.[4]

The overall effect of the new rates on predicted laser performance is to depopulate both the upper and lower laser levels through increased efficiency of H_2O in deactivating vibrational N_2 and increased efficiency of N_2 in deactivating the bending mode (010) of CO_2. These changes lead to a lower maximum small signal gain, with the peak gain occurring closer to the nozzle exit. The lower values of gain obtained with the new rates are a result of the more rapid de-excitation of the upper laser level. The earlier peak in small signal gain is a result of the more rapid depopulation of the lower laser level. A decrease in maximum available laser energy results from the more rapid depopulation of the upper laser level.

General ABL Performance Characteristics

It is essential to characterize the performance of the ABL to obtain an overall understanding of the device. As discussed previously, the ABL has somewhat different characteristics than the GDL since the gas composition is a variable which is dependent on the fuel, the fuel-air ratio, and the combustor inlet and outlet temperatures. The gas composition, in general, then has specific amounts of CO_2-N_2-H_2O-O_2, depending on the fuel and operating conditions, while the usual GDL can fix its gas composition as desired. The analytical models for population inversion which will directly influence the small signal gain and the maximum avilable energy can be evaluated along the nozzle and laser cavity for a wide variety of operating conditions. As we will be discussing the small signal gain and maximum available optical laser energy, these specific quantities are defined[7] as follows

Small signal gain

$$g_o = \frac{\lambda 2}{4\pi\tau_{21}\nu_c}(N_{001}-N_{100})\frac{45.6}{T}e^{-234/T} \quad (4)$$

$(\tau_{21}=5.38$ sec)

$$N_{001}=(N_{CO_2}/Q)\exp(-\epsilon_{100}/KT_{vib_{II}}) \quad (5)$$

$$N_{100}=(N_{CO_2}/Q)\exp(-\epsilon_{100}/KT_{vib_{II}}) \quad (6)$$

Maximum available laser energy

$$e_{max}=[e_{vib_{II}}(T_{vib_{II}})-e_{vib_{II}}(T^o vib_{II})]q \quad (7)$$

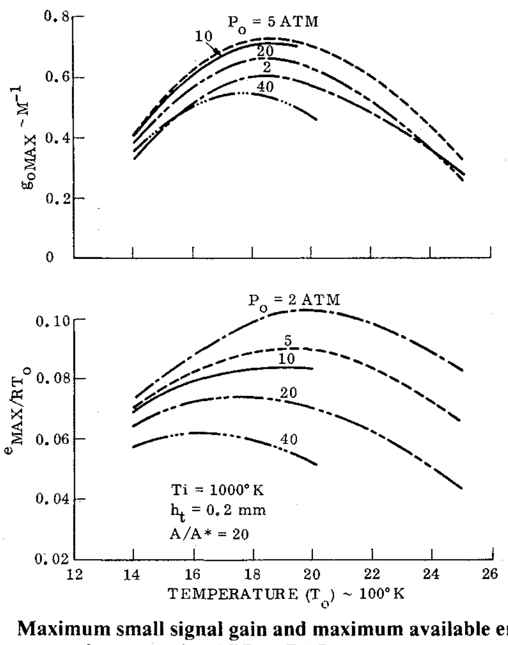

Fig. 5 Maximum small signal gain and maximum available energy vs temperature and pressure for ABL or RAL.

A population inversion exists when

$$N_{001}>N_{100} \quad (8)$$

Laser power can be extracted when

$$T^o vib_{II}>T^o vib_I \quad (9)$$

where

$$T^o vib_{II}=T_{vib_I}(\epsilon_{001}/\epsilon_{100}) \quad (10)$$

The small signal gain and the maximum available energy vary with position along the nozzle and laser cavity. The quantities of particular interest are the maximum value of small signal gain ($g_{o_{max}}$) and the maximum available laser energy (e_{max}) at the location of the maximum small signal gain in the laser cavity. It is noted that the maximum available energy at maximum signal gain location in the laser cavity is not necessarily the maximum value in the duct.[4]

The ABL performance may be described by a number of characteristic curves showing the effect of various input and nozzle conditions on the laser cavity characteristics. The laser performance will be evaluated as a function of nozzle area ratio (A/A^*), nozzle throat height (h_t), nozzle inlet pressure (P_o), combustor inlet temperature (T_i), and combustor outlet temperature (T_o), utilizing benezene (C_6H_6) as fuel. The maximum small signal gain and maximum available laser energy are shown on Fig. 5 as a function of temperature for pressures varying from 2 to 40 atm for a constant set of reference conditions ($A/A^*=20$, $h_t=0.2$ mm, and $T_i=1000$ K). It is evident that optimum laser performance occurs at a specific temperature, and just increasing the temperature does not produce increased performance. It is noted that, for the stated conditions, the optimum laser performance is obtained if the nozzles are operated at between about 1800 and 2000 K, depending on the pressure. The maximum small signal gain reaches a maximum value at a pressure between 5 and 10 atm. There is a desire however, to operate at much higher pressure to reduce the cavity size and to minimize the diffuser requirements. The diffuser is required to provide the transition from local pressure in the laser cavity to ambient pressure. An aerodynamic window is also generally required to provide a noninterference barrier between the cavity flow, the local atmosphere, and the laser beam. The penalty in reduction of small signal gain with increased pressure is generally much smaller than the corresponding advantages obtained for the cavity and diffuser. The maximum available energy (e_{max}/RT_o) increases continuously with decreasing pressure.

The effect of nozzle area ratio (A/A^*) is shown in Fig. 6 at a reference pressure of 10 atm, $T_i=100$ k,and $h_t=0.2$ mm. As the area ratio increases from 20 to 60, both the maximum small signal gain and the maximum available energy increase. These laser performance parameters ($g_{o_{max}}$ and e_{max}/RT_o) at $x\ g_{o_{max}}$ also increase with temperature, except at the lower area ratio ($A/A^*=20$). The effect of nozzle throat height (h_t) on the laser performance is shown on Fig. 7. As expected, the laser performance increases with decreasing throat height. It is noted that the maximum small signal gain and maximum available energy reach a maximum at the lower values of throat height shown. it is also noted that the calculations indicate ideal performance, which doesn't necessarily imply a desire to use the 0.1-mm height shown. Manufacturing structural, thermal, and operational problems may require somewhat larger throat heights.

The gas composition for the ABL results in somewhat different performance characteristics than for the GDL. The ABL produces a lower maximum small signal gain and higher maximum available energy for identical conditions (P_o, T_o, A/A^*, h_t). it is interesting to note that the freezing efficiency ($\eta_F=T_{001}/T_t$) is significantly higher for the ABL, which produces higher maximum available energy, even though there is a diluent, O_2, in the gas mixture. The kinetics of the ABL gas mixture also results in a somewhat slower decay rate in both the small signal gain and the maximum available energy with streamwise distance in the cavity.[12]

The general characteristics noted in Fig. 5-7 have indicated preferred operating conditions for the ABL laser. It is generally desirable to operate the laser for maximum performance at high area ratios, moderate combustor discharge temperature (1800 K), and low values of nozzle throat height, in concert with manufacturing and operating considerations. The pressure should be much higher than required for maximum small signal gain ($P > 5$ atm) to minimize the size of the laser cavity and to ease the requirements of the diffuser.

Ram Airbreathing Laser (RAL) Performance

The RAL performance was evaluated for a wide variety of Mach numbers and altitudes for representative values of nozzle geometry and combustor outlet conditions. The performance characteristics shown previously will be specifically applied to the individual characteristics of the ram inlet, combustor, and transition section located upstream of the nozzle and laser cavity.

The resulting RAL performance is shown on Fig. 8 as a function of Mach number for altitudes of 40,000 70,000 and 100,000 ft, $A/A^* = 20$, and $h_t = 0.2$ mm for specific temperatures (T_o). The maximum small signal gain for 40,000- and 70,000-ft altitudes show the expected increased performance with decreasing pressure as long as the pressures are generally above about 5 atm. The gain obtained at 100,000-ft altitude is substantially lower, due to two effects, namely, low pressure and low values of CO_2 mole fractions. The small amounts of CO_2 are the result of the low fuel-air ratios required for the relatively high inlet temperature produced by the ram inlet at high Mach number operation. It is noted that, for operation at Mach number 6, unless the outlet temperature is sufficiently high, 2000 K or higher, insufficient CO_2 is produced from the combustion of benzene to produce the appreciable population inversion required for adequate small signal gain in the laser cavity. The effect of increasing the laser performance by adding CO_2[4] or the potential application of a mixing laser[13] at the high Mach number condition is indicated. The inlet air temperature to the laser is suf-

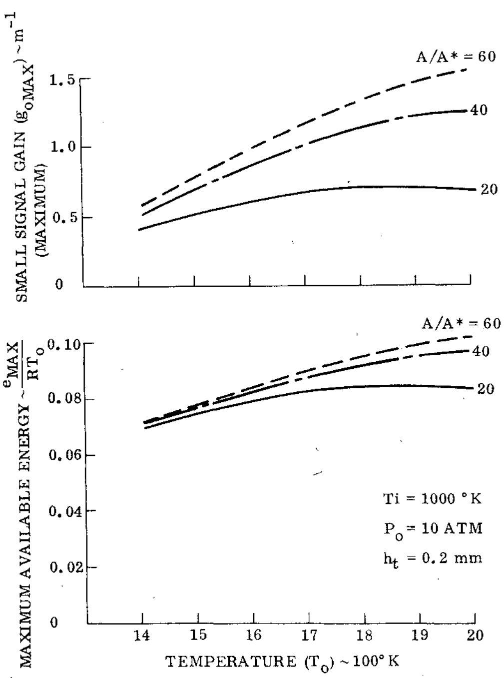

Fig. 6 Maximum small signal gain and maximum available energy vs temperature and area ratio for ABL or RAL.

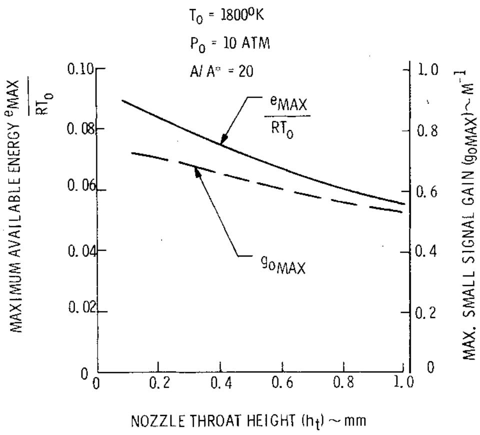

Fig. 7 Effect of nozzle throat height on maximum small signal gain and maximum available energy for ABL or RAL.

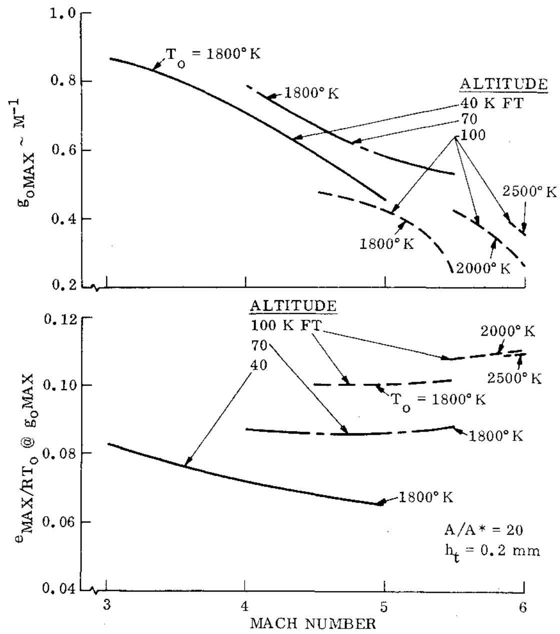

Fig. 8 RAL performance as function of Mach number for various altitudes and nozzle temperatures.

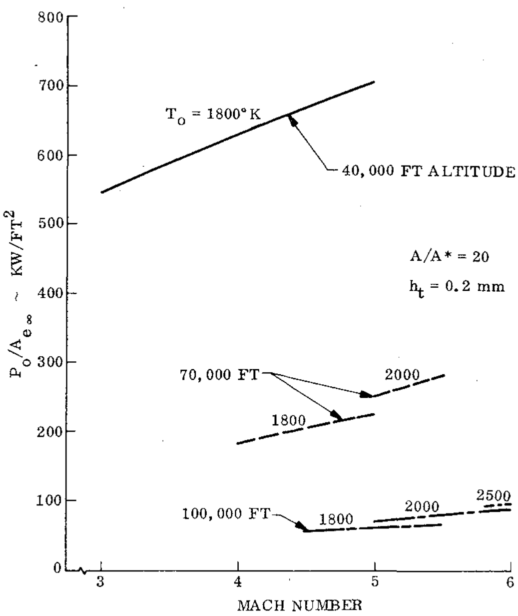

Fig. 9 RAL power output per unit inlet area vs Mach number.

ficiently high so that a combustion chamber is not necessary, but injection of CO_2 is required to obtain the population inversion desired. The maximum available laser energy, however, increases as the altitude increases from 40,000 to 100,000 ft. It is noted that the available energy (e_m/RT_o) is almost the same for 2000 and 2500 K at high Mach number operation.

The precise power output evaluation for the RAL which must be obtained by power extraction calculations[14] for a given specified detailed design is beyond the scope of this paper. It is, however, desired to provide an estimation of potential levels of RAL power over a wide range of conditions. The maximum available energy (e_m) obtained from the kinetic analyses described previously and the saturation intensity[15] (I_s) are both indicators of optical power capability. Saturation is due to the rates at which energy is transferred to and from the lasing species, and to the lasing induced depletion of available power. The maximum available power is dependent on the cavity conditions and the mass-flow rate, while the saturated power is dependent upon the cavity conditions and the transverse beam dimensions for a specific cavity design. The potential RAL power output can be evaluated without resorting to a specific RAL device from e_m and a knowledge of the mass flow which can be expressed in terms of power per unit effective ram inlet area as

$$P_o/A_{e_\infty} = e_m \eta_e M_\infty a_\infty \rho_\infty (1+F) \tag{11}$$

Conservative estimates of the RAL output power[4] can be obtained when the extraction-effectiveness and the area ratio are specified as $\eta_e = 0.5$ and $A/A^* = 20$, respectively.

The RAL power output is shown on Fig. 9 as a function of Mach number for altitudes of 40,000, 70,000 and 100,000 ft. The power output per unit frontal area of the ram inlet (P_o/A_{e_∞}) is given in kw/ft^2. The effective frontal area (A_{e_∞}) represents the flow area necessary to pass the required mass through the nozzles, and does not include the inlet bleed or bypass mass flow; therefore

$$A = A_{e_\infty}[1 + (\dot{m}_{bl} + \dot{m}_{BP})/\dot{m}_\infty] \tag{12}$$

Since boundary-layer bleed and perhaps bypass flow are required for the RAL operation, it is necessary to include this bleed flow in the frontal area requirement. The potential laser power at a 40,000-ft altitude is in excess of 550 kw/ft^2 for a nozzle area ratio of 20, a temperature of 1800 K, and throat height of 0.2 mm. It, of course, is lower at 70,000 and 100,000 ft because of the reduced atmospheric density at these higher altitudes. The unit power at 70,000 and 100,000 ft will be on the order of 200 and 60 kw/ft^2, respectively, at the temperatures and nozzle conditions noted. During operation the RAL device is also capable of producing thrust, although drag may occur for certain combinations of inlet and diffuser bleed.[4] The RAL thrust increases with increasing laser operating temperature and decreasing bleed flow.

Conclusions

The performance characteristics of a ram airbreating laser (RAL) were investigated for a wide range of Mach numbers (3-6) and altitudes (40,000-100,000 ft). The supersonic inlet provided pressure between 2 and 55 atm and temperatures between 600 and 1700 K at the combustor inlet. Benzene (C_6H_6) was used as fuel to raise the gas temperature at the combustor discharge to between 1400 and 2500 K. The population inversion, the small signal gain, and maximum available laser energy were determined for the nonequilibrium flow through the special rapid expansion nozzle and laser cavity section for the unique RAL CO_2-N_2-H_2O-O_2 gas mixture for the current vibrational relaxation rates. A minimum value of fuel addition was shown to be required to obtain the desired amount of CO_2 in the gas for efficient laser action. Significantly high levels of small signal gain ($g_o \simeq 0.8$ and $1.0m^{-1}$) and maximum available energy ($e_m/RT_o \simeq 0.08$-0.1) were shown to be available. The laser performance characteristics were established for a wide variety of pressures, temperatures, and nozzle characteristics. The pressure, temperature, nozzle area ratio, and throat height for maximum laser performance were identified.

Significant laser power output was shown to be available for the RAL device. The laser power output levels per unit inlet area were evaluated as about 620, 200 and 60 kw/ft^2 at altitudes of 40,000, 70,000 and 100,000 ft, and Mach numbers of 4, 4.5, and 5, respectively.

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