A New Mixing Gasdynamic Laser

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A mixing gasdynamic laser (MGDL) incorporating a screen nozzle has been developed and demonstrated in a shock tube simulator. This concept has been shown to extend the specific power and efficiency of the conventional gasdynamic laser by a large factor and, at the same time, avoid the persistent, large-scale flow nonuniformities exhibited in earlier mixing laser concepts. Through the mixing of supersonic streams of N_2 (2000 K and 66 atm), with adjacent supersonic streams providing CO_2 and H_2O from very small orifices, gains of 1.5%/cm and 30 kJ/lb of stored energy have been measured in the laser cavity. Time-resolved interferometric measurements have shown the mixing process and decay of turbulence to occur rapidly, before appreciable loss of stored energy, due to the small characteristic scale of the mixing. Essentially complete mixing and flow homogeneity (2% $\Delta\rho/\rho$) were achieved 15 cm downstream of the nozzle exit plane. Measured output specific powers of up to 11.8 kJ/lb were extracted with a multimode resonator. The results obeyed scaling laws that predict 15-20 kJ/lb extractable from a larger device. The effects of impurities such as hydrogen and carbon monoxide that may appear in the combustion products of fuels have been determined. Small signal gains of 1.25%/cm and available energies of 27 kJ/lb were measured from a typical mixture of 75 N_2/22 CO/3 H_2 at 2300 K mixed with 10% CO_2/1% H_2O in the laser cavity. Based on the agreement of these measurements with an analytic model, an extractable specific power of greater than 20 kJ/lb can be predicted for a well-designed, large-scale laser device.

I. Introduction

ONE of the performance limitations of conventional gasdynamic lasers (GDLs) has been caused by the loss, through collisional processes in the early portion of the nozzle expansion, of the vibrational energy that was thermally invested in the hot nitrogen donor gas. Vibrational energy is lost from the nitrogen in this region through collisions with both the carbon dioxide and water whose presence is necessary further downstream in the optical cavity to allow the efficient extraction of infrared power. The existence of these loss processes has restricted the operation of premixed GDLs to relatively low stagnation temperatures and pressures with limited amounts of carbon dioxide and water catalyst. Nitrogen is capable of storing much more energy in molecular vibration than these throat loss limits will allow to be transferred to the laser cavity.

Several authors[1-3] have suggested that the mixing of the vibrationally excited nitrogen with the carbon dioxide and catalyst after expansion to low static temperature and pressure (where the collisional loss rates are considerably reduced) would allow much greater flexibility in the choice of operating conditions and, consequently, improved performance. Although the resulting mixing GDL has been considered since the earliest days of the development of the N_2/CO_2 laser, it has not replaced the conventional premixed GDL, since it has not been possible to simultaneously achieve high specific power, good medium quality, and recovery to atmospheric pressure.

An alternative approach to the achievement of a successful mixing GDL was suggested by the results of a recent program at Mathematical Sciences Northwest, Inc. (MSNW) in which the potential of screen nozzles for premixed GDLs was investigated.[4] It was theoretically predicted and experimentally verified that a screen nozzle array consisting of many very small scale conical nozzles could be built and operated with acceptable shock and boundary-layer mixing losses and a rate of disturbance decay sufficiently rapid that good medium quality could be obtained prior to appreciable kinetic deactivation in the cavity. Calculations revealed that such rapid mixing and decay of disturbances could also be accomplished between two dissimilar gas streams with correspondingly small mixing losses. In this manner, the high available energy and gain afforded by the mixing concept could be combined with the good medium homogeneity provided by the screen nozzle in the screen mixing gasdynamic laser to extend the performance of the gasdynamic laser by a large factor and still retain the simplicity of the GDL system. A mixing GDL based on this screen nozzle concept has been analyzed, built, and tested in a shock tunnel at MSNW.[5]

II. Analysis and Nozzle Design

An analytical program was developed to predict the performance of the screen-mixing GDL, in order to allow an evaluation of the concept and the design of a meaningful experiment. The analytical effort involved the calculation of the axisymmetric nozzle flowfield, the evaluation of losses caused by the boundary layers and the turning shocks at the exits of individual nozzles, the assessment of the losses inherent to the turbulent mixing of two dissimilar supersonic gas streams, the tracing of the chemical (vibrational energy transfer) kinetics through the nozzle and laser cavity, and the decay of flow disturbances generated by the waves and wakes from the individual nozzles with distance along the cavity.

The performance of a screen nozzle involves a balance between the growth of the wall boundary layer in the nozzle and the shock losses in the merging flows, as described in Ref. 4. Axisymmetric contoured nozzles were shown to exhibit large boundary-layer losses, as calculated by the Cohen-Reshotko integral technique.[6] For the same area ratio, shorter conical nozzles were shown to exhibit less boundary-layer growth but require stronger shocks to turn the individual flows into the merged flow. The composite losses were shown to be characterized by two parameters for a specified area ratio: the contour (wall angle), and the product

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of stagnation pressure and throat diameter ($p_0 d^*$). It was concluded in Ref. 4 that a conical nozzle with a 10-deg half-angle performed as well as a three-dimensional contoured nozzle. Consequently, design analyses were performed for an area ratio 60 conical nozzle with a 10-deg wall angle. This same design was chosen for the donor (N_2) nozzles in the screen-mixing GDL. The stagnation pressure, chosen to be 66 atm to assure good pressure recovery potential, combined with a 0.4-mm throat size for the donor (N_2) nozzles, resulted in a $p_0 d^*$ of 2.6 atm-cm, which afforded good throat freezing even in the presence of contaminants, as well as low shock and boundary-layer mixing losses.[4]

The screen-mixing nozzle incurs additional mixing losses, because of the entropy rise associated with the mixing of two different gas streams. The turbulence generated by the velocity difference between the two streams is necessary to insure the mixing and transfer of vibrational energy between the donor gas and the lasing gas; however, it engenders losses. An efficient design must incorporate a compromise between vigorous mixing and reduced mixing losses. An analytical technique has been developed to calculate the final mixed state of two different gas streams with different flow properties, utilizing an integral formulation of the conservation equations. One of the critical parameters by means of which losses may be assessed is the static temperature, an increase which adversely affects both gain and available energy in the cavity. The results of calculations of the rise in static temperature resulting from the mixing of Mach 6 nitrogen at a stagnation temperature of 2000 K with CO_2 injected at Mach numbers between 1 and 5 as a function of the mole fraction of CO_2 in the mixed gas are shown in Fig. 1. The static pressures of the two streams at the nozzle exit plane were assumed equal, and the CO_2 stagnation temperature was chosen to match the static temperatures at the nozzle exit plane in each case. Sonic injection of the CO_2 produces very large heating, and only small mole fractions of CO_2 could be used without large performance degradation. However, the injection of a 10% mole fraction of CO_2 at Mach 5 incurs less than 20% rise in static temperature, a loss comparable with the shock and boundary-layer loss associated with the Mach 6, 10-deg conical donor nozzle operating at $p_0 d^* = 2.6$ atm-cm.[4]

The MSNW chemical kinetics code[7] was used to calculate molecular and flow properties in the nozzle expansion, giving conditions at the nozzle exit. The screen nozzle shock and boundary-layer losses were then calculated and applied as jump conditions in the flow properties immediately at the

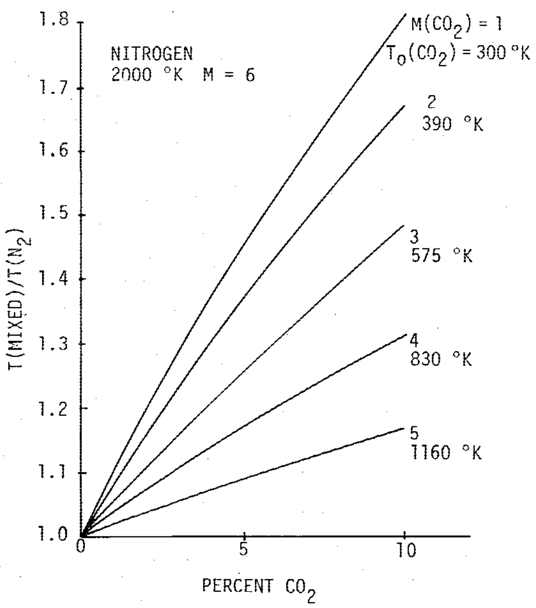

Fig. 1 Dissimilar gas mixing losses—static temperature rise in the cavity as a function of CO_2 concentration and Mach number.

nozzle exit. The validity of this assumption has been supported by gain measurements with a premixed screen nozzle reported in Ref. 4. The dissimilar gas mixing losses were calculated and also applied as jump conditions immediately at the nozzle exit plane. The validity of this assumption will be discussed with the data in Sec. IV. The chemical kinetics were then calculated through the laser cavity to generate profiles of gain, static and vibrational temperature, and available energy, against which the experimental data are compared. A power extraction option was incorporated into the chemical kinetics code, which allowed the prediction of extracted power for a given optical cavity, specified by its gain length and output coupling.

These calculations were used to design the screen-mixing GDL experiment. The results showed that it was possible to obtain 30 kJ/lb available energy at gain levels of 1.5%/cm from a screen-mixing GDL with pure nitrogen supplied at 2000 K and Mach 6 mixed with 10% CO_2 and 1% H_2O supplied at Mach 4.5.

Finally, a calculation was made of the flow quality existing in the laser cavity. Following the analysis presented in Ref. 4, predictions were made of the maximum density perturbation caused by the waves and wakes of the individual nozzles as the flow proceeded downstream. These calculations showed that the maximum density disturbances downstream from a 10-deg half-angle conical screen nozzle of area ratio 60 having an exit diameter of 3.5 mm would decay to the order of 1% at or before a point 30 cm downstream of the nozzle exit plane, as shown in Sec. VI.

The donor (N_2) gas nozzles were designed as area ratio 60 conical nozzles with a 10-deg half-angle and a 3.5-mm exit diam (including boundary-layer corrections), as described in Ref. 4. The subsonic portion consisted of a 42-deg half-angle conical entrance followed by a 0.13-mm long throat of 0.4-mm diam. The screen-mixing nozzle block was arranged (Fig. 2) in a close-packed hexagonal array with two donor (N_2) nozzles for each CO_2/H_2O nozzle, which was thus surrounded by six donor (N_2) nozzles. This configuration allowed symmetric and rapid mixing because each donor nozzle was only half an exit diameter away from a source of CO_2/H_2O.

The CO_2/H_2O nozzles were designed to achieve several goals. The desired 10% CO_2/1% H_2O mole fraction was to be obtained with the same exit pressure as the donor nozzle and an exit Mach number as near 5 as possible. The total temperature, which affects the turbulent mixing losses through the gas stream velocity ratio, was limited to 1000 K by heater design limitations. For reasons of ease of manufacture, the CO_2/H_2O nozzle Mach number was chosen to be 4.5. The loss in gain associated with the decrease in Mach number from a value of 5 was calculated to amount to only 4%. The resulting design for the CO_2/H_2O nozzle consisted of an 8-deg half-angle cone with a 0.37-mm throat and a 2.11-mm exit diam (including boundary-layer corrections).

The screen-mixing nozzle block was manufactured by conventional drilling, reaming, and machining methods from 2024-T4 aluminum alloy. It was 28 cm wide × 2-cm high to fit the existing shock tunnel facility and had 318 donor gas nozzles and 159 CO_2/H_2O nozzles.

The CO_2/H_2O nozzles were fed through vertical feed tubes connecting each bank to a horizontally drilled manifold across the top of the nozzle block. This gallery was fed at two equally spaced points from a resistance heated oven. Turbulent heat transfer calculations predicted a 20% loss in total temperature in these manifolds, and the heater was operated above the nominal temperature to allow for these losses.

III. Experimental Facility

The experiments were performed in a GDL simulator shock tunnel, consisting of a stainless steel shock tube with a 7.62-

cm i.d., 8.5-m long driven section equipped with a downstream diaphragm, followed by a transition section changing the cross section from 7.62-cm i.d. to a 2-cm × 28-cm rectangle to supply donor (N_2) gas to the stagnation region in front of the screen nozzle. The shock tube was operated in the double-diaphragm mode in order to time the arrival of the shock wave in the donor gas with the flow of the CO_2/H_2O mixture.

The laser flow cavity was 2 cm high, 28 cm wide, and 35 cm long in the flow direction, with top and bottom walls diverged downstream at an angle of 1/2 deg to compensate for the calculated turbulent boundary-layer displacement thickness growth. For the gain measurements, opposing salt windows 1.5 cm in diameter were located in the cavity sidewalls at stations 11 and 21 cm downstream of the nozzle exit plane. Windows that extended 10 cm in the flow direction and the full 2-cm cavity height were used in the power extraction and flow quality investigations. These windows were located either between 6.5 and 16.5 cm or between 14 and 24 cm downstream of the nozzle exit plane. The flow subsequently passed through a diffuser and into a dump tank.

The total donor (N_2) nozzle throat cross-sectional area amounted to about 1% of the total shock tube cross-sectional area, so that the donor nozzles were fed from approximately closed end wall reflected shock conditions. The shock speed in the shock tube and stagnation pressure just upstream of the nozzle block were measured during each run, and a real gas Rankine-Hugoniot calculation was used to determine the nominal stagnation temperature. Line reversal measurements showed an overshoot in the stagnation temperature, measured just upstream of the nozzle block, followed by a temporal decay presumably caused by the filling process in the transition section. Examination of the measured stagnation temperature time histories showed nominal conditions to occur about 3 ms after flow start, a time at which data were collected during all of the subsequent investigations.

IV. Gain and Available Energy

An expression for small signal optical gain in the 10-6-μ band of CO_2 in a mixture of gases may be written in the form[8]

$$\ln\left[\left(\frac{\lambda_0}{\lambda_j}\right)^2 \frac{\alpha}{2j+1}\right] = \ln(A\lambda_0^2/T^{3/2}) - j(j+1)0.565/T \qquad (1)$$

where α is the gain, λ_0 is the reference wavelength of 10.60 μ, λ_j the wavelength of the transition being studied, j refers to the upper-state rotational level of that transition, T is the static (rotational) temperature, and A is defined by

$$A = \psi_c\left(e^{-3380/T_v} - e^{-1997/T_\ell}\right)\left(1 - e^{-1920/T_\ell}\right)\left(1 - e^{-960/T_\ell}\right)^2$$

$$\times\left(1 - e^{-3380/T_v}\right)\left(8.704\times 10^5 \sum_i \psi_i \sigma_{ci}/\sqrt{W_{ci}}\right)^{-1} \qquad (2)$$

In Eq. (2), ψ_c is the mole fraction of CO_2, ψ_i the mole fraction of the remaining constituents, σ_{ci} and W_{ci} the cross sections for pressure broadening and reduced molecular weight for these molecules and CO_2, and T_v and T_ℓ are the upper (asymmetric stretch) and lower (coupled symmetric stretch and bending) level vibrational temperatures in the CO_2 molecule. Gain data, experimentally taken as a function of wavelength and cast in the form of the left-hand side of Eq. (1), will be linearly related to the variable $j(j+1)$ with a slope inversely proportional to the static temperature and an intercept at $j=0$ determined by the static temperature and the vibrational temperatures. The analytical model described in Sec. II was used to supply the remaining relationship between the static and lower level vibrational temperatures in the cavity and enable the determination of the upper level vibrational temperature from line-by-line measurements of optical gain using Eqs. (1) and (2). A least-squares fit to the gain data provided the required slope and intercept values. Confidence limits of 75% were placed on variations in these slope and intercept values that were caused by scatter in the gain data, in order to generate the scatter intervals shown in the figures for the derived properties of static temperature, vibrational temperature, and available energy. The available energy is defined as the difference between the energy stored in the vibrational modes of CO_2, N_2, and CO in the mixture at the measured conditions, and the energy stored in these vibrational modes at conditions corresponding to zero gain, divided by the total mass flow rate.

The gain measurements were taken at two positions in the cavity—11 cm and 21 cm downstream of the nozzle exit plane—utilizing a tunable single-mode CO_2 probe laser modified by the use of an original grating to allow selection of the proper rotational lines. A spectrum analyzer was used to adjust operation to the desired line prior to each test. The 5-mm diam output beam was chopped at a frequency of 500 cps and passed across the flow cavity through salt windows. Just beyond the test section, the beam was uniformly diffused by a salt-scattering cell, which was viewed by a gold doped germanium detector protected from background radiation by an interference filter. The detector output was amplified by a high-gain, low-noise amplifier and displayed on an oscillogram. Comparison of the detector signal before and after flow initiation in the cavity provided the data from which gain was calculated.

The first set of gain measurements was performed to provide an experimental evaluation of the screen-mixing GDL concept and verification of the proposed analytical model. The donor gas was pure nitrogen supplied at 2000 K and 66 atm from the reflected shock region. The CO_2/H_2O nozzles were operated at 870 K and 15 atm stagnation conditions to provide a final mixture ratio of 89 N_2/10 CO_2/1 H_2O. The gain data are shown in Fig. 3. Six data points were taken at each station—three on the P-12 transition and three on the P-30 transition. The measured gains were adjusted to the equivalent gain on the P-20 transition (the optimum gain calculated by the analytical model) using the measured static temperature. The data matched the analytical prediction quite well, with an average value of 1.5%/cm at the 11-cm station

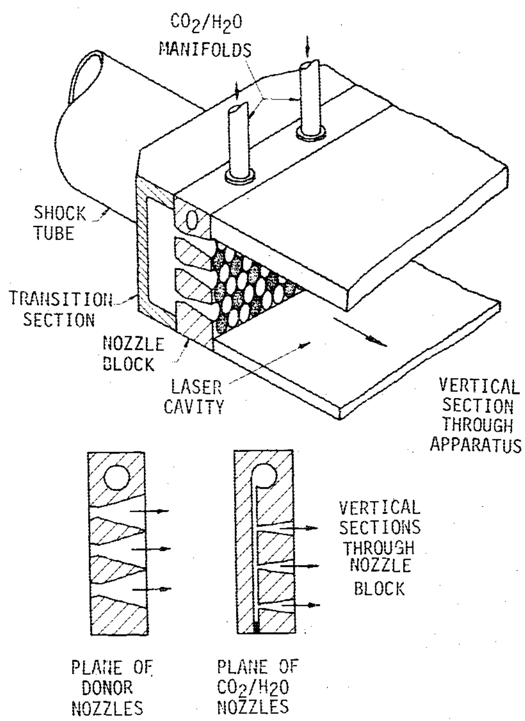

Fig. 2 Screen-mixing GDL schematic. The donor nozzles are for N_2.

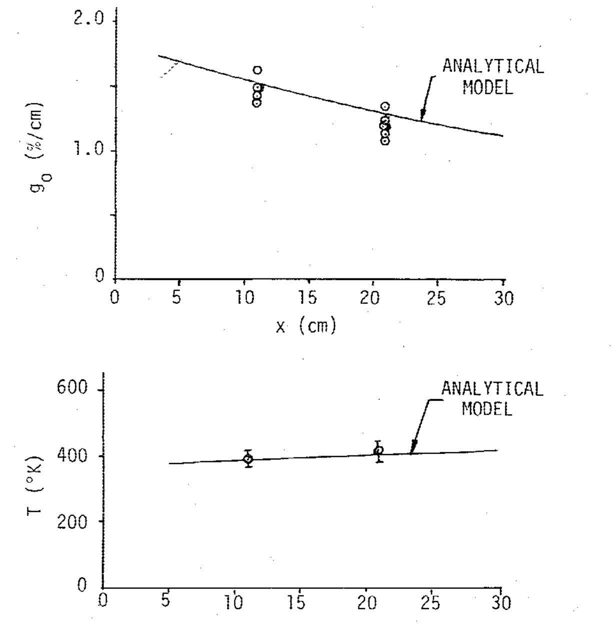

Fig. 3 Small signal gain (P-20) and static temperature as a function of distance from the nozzle exit plane for pure N_2 at 2000 K mixed with 10% CO_2 + 1% H_2O.

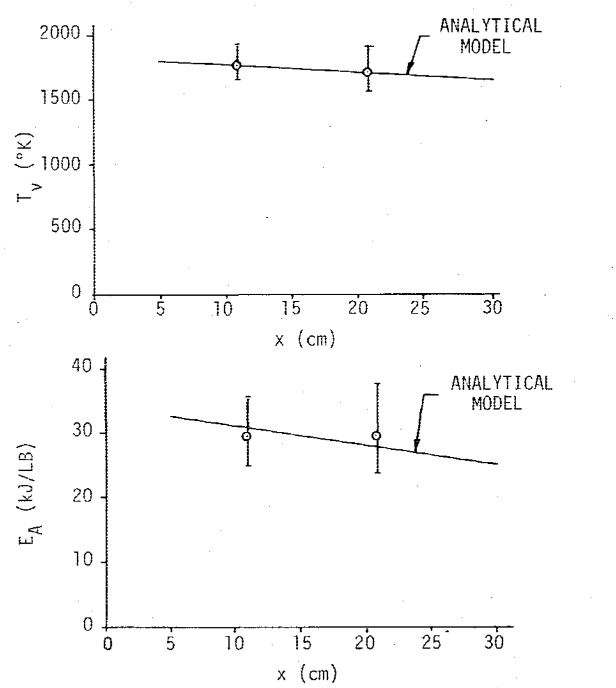

Fig. 4 Vibrational temperature and available energy as a function of distance from the nozzle exit plane for pure N_2 at 2000 K mixed with 10% CO_2 + 1% H_2O.

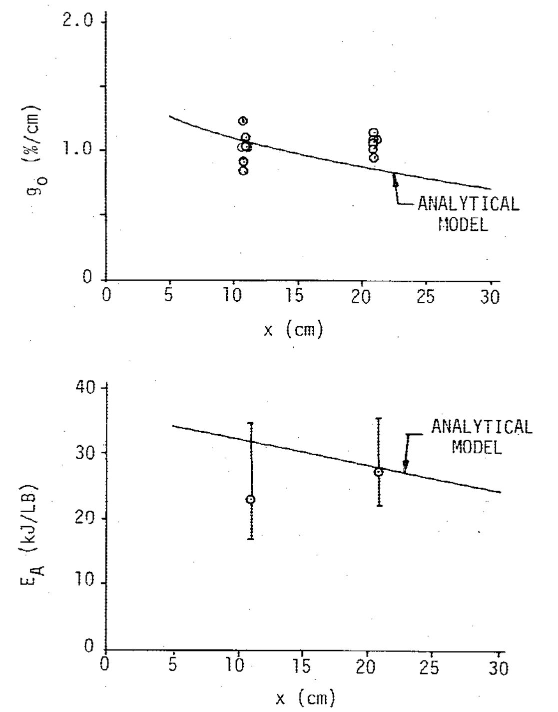

Fig. 5 Small signal gain and available energy as a function of distance from the nozzle exit plane for 75 N_2/22 CO/3 H_2 at 2300 K mixed with 10% CO_2 + 1% H_2O. P-20 gain derived from P-12 and P-30 measurements.

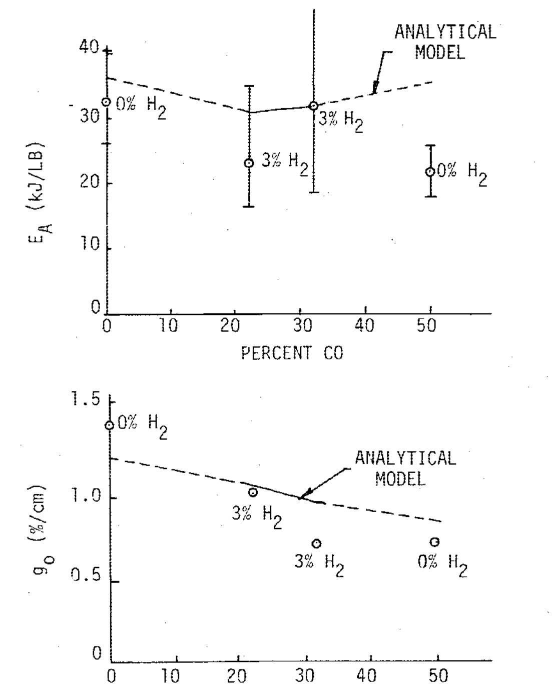

Fig. 6 The effect of CO fraction on the gain and available energy 11 cm downstream of the nozzle exit plane, 10% CO_2, 1% H_2O, balance N_2. P-20 gain derived from P-12 and P-30 measurements.

and 1.2%/cm at the 21-cm station. The static temperatures derived from these data are also shown in Fig. 3. The predicted level of 395 K in the cavity was very closely matched by the measurements. The vibrational temperatures deduced from the data are shown in Fig. 4, and can be seen to follow the analytical predictions; however, the scatter intervals were much larger, because both the variation in slope and the variation in intercept of the gain data are reflected. The measured value of 1770 K at the first station represents nearly 90% of the stagnation temperature, indicating substantial freezing upstream of the nozzle throat. The available energy deduced from the gain data is also shown in Fig. 4. The least-squares fit to the data closely approximated the analytical predictions of nearly 30 kJ/lb. These results indicate that the analytical model is quite capable of predicting the gain, static, and vibrational temperature and available energy in the cavity.

A similar set of experiments was performed with pure nitrogen at 2300 K, as the donor gas and the CO_2/H_2O at 1000 K with all other conditions held constant. The gain 11 cm

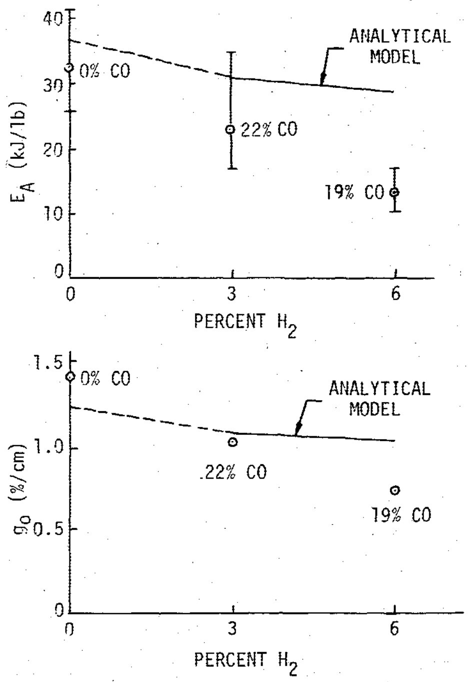

Fig. 7 The effect of H_2 fraction on the gain and available energy 11 cm downstream of the nozzle plane, 10% CO_2, 1% H_2O, balance N_2. P-20 gain derived from P-12 and P-30 measurements.

downstream of the nozzle exit plane was measured to be 1.5%/cm and the available energy 33 kJ/lb.

An investigation of practical fuels capable of supplying a donor gas in the range of 2000-2500 K to power a MGDL showed that the combustion products could include some carbon monoxide and hydrogen in addition to nitrogen. An examination of the effects of the presence of these contaminants, at realistic concentration levels, on the laser performance was carried out in the shock tube simulator using the line-by-line gain measurement technique. The results of these measurements of gain and the deduced values of available energy for a 75 N_2/22 CO/3 H_2 donor gas at 2300 K and 66 atm mixed with 10% CO_2 and 1% H_2O in the cavity are shown in Fig. 5. The vibrational energy stored in the CO that is available for lasing was included in the calculated available energy. The measured gain remained relatively constant along the cavity at an average value of nearly 1.1%/cm, and measured available energy rose from 23 kJ/lb at the first station to 27 kJ/lb at the second station, in contrast to the decay predicted in this quantity. This effect could be caused by the finite rate of mixing between the donor and CO_2/H_2O gas streams that was assumed to be instantaneous in the anlytical model. The value of vibrational temperature in the cavity represented only 71% of the stagnation temperature, showing the disruptive effect of the hydrogen on throat freezing.

Gains were measured for several different mixtures of $N_2/CO/H_2$ at 2300 K and 66 atm stagnation conditions, mixed with 10% CO_2 and 1% H_2O in the cavity. Figure 6 shows the effect of an increased CO fraction on the gain and available energy 11 cm downstream of the nozzle exit plane. The hydrogen content was not the same for all the mixtures; however, the gain and energy values were calculated for the correct experimental mixtures. It can be seen that the predicted variation of available energy showed no definite trend with increased CO fraction. Although these data exhibit considerable scatter, they support the same conclusion, except possibly for the 50/50 N_2/CO case with no H_2. An increase in CO fraction did, however, cause a definite theoretical decrease in small signal gain. The experimental data followed this predicted decrease in gain.

The effect of the hydrogen content on the gain and available energy is shown in Fig. 7, where it is seen that an increase in hydrogen content caused a definite decrease in both gain and available energy. The measured values of these properties were lower than the predicted ones, showing that the hydrogen was possibly more detrimental in the kinetic deactivation of vibrational energy than was predicted by the analytical model.

V. Power Extraction

Power was extracted from the flow in an optical cavity through windows 10 cm in length and 2 cm in height attached to the sides of the flow cavity at two positions: either between 6.5 and 16.5 cm downstream of the nozzle exit plane or between 14 and 24 cm downstream of the nozzle exit plane. A multimode optical cavity was used consisting of a flat 15% output coupler and a 244-cm radius-of-curvature total reflector, each 10 cm in diameter and separated by 125 cm. The output beam was focused into a calorimeter by an 11-cm diam mirror with a 61-cm radius-of-curvature placed 50 cm from the output coupler. An array of five small vertical wires was placed in the near field 15 cm from the output coupler to reflect a small fraction of the output power into a gold doped germanium detector and provide a time history of the output pulse. The apparatus was also arranged so that gain measurements on the P-20 line of CO_2 could be made at the center of the windows.

Zinc selenide windows were used on the cavity sides. Absorption measurements with a CO_2 probe laser gave a 2% loss per pass through these windows. However, during the course of the experimental program, a crack developed in one of these windows that introduced an additional loss in the cavity that was measured to be 10%. The intracavity losses introduced by windows are very detrimental to the extraction of power from lasers with such short gain path lengths (28 cm), because the cavity gain necessary to reach threshold becomes very high, making it difficult to sufficiently saturate the medium. An early series of experiments showed that the gain was not sufficiently above threshold to allow reliable and meaningful extraction of laser power. The cavity gain could normally be raised by expanding the gases to a higher Mach number through a more optimally designed nozzle. However, for the purposes of this investigation, the same effect was produced by adding 25% argon as an inert diluent to the donor gas (nitrogen) to lower the cavity static temperature without changing the kinetic processes occurring in the flow cavity.

Power extraction experiments were performed using this 75 N_2/25 Ar donor gas at 2000 K at 50 atm stagnation conditions. The mole fraction of water was held at 1% and the mole fraction of CO_2 was varied from 7% to 10, 12, and 15%, in order to vary the gain of the medium without changing other parameters.

A simplified analytical model of the extraction of power from a multimode GDL cavity was formulated in order to allow evaluation and interpretation of the experimental data. The expressions for small signal gain g_0 and available energy E_A may be utilized when steady-state conditions exist in an optical cavity with total output coupling η to yield an expression for the output energy

$$E_{out} = KE_A\,[I + \ln(1-\eta)/2g_0 L] \tag{3}$$

where L is the cavity width in the direction of the optic axis and K the kinetic factor that relates the cavity length in the flow direction to the flow length necessary to transfer and extract the vibrational energy from the nitrogen and the CO_2 at the conditions existing in the cavity. To evaluate this factor quantitatively, the power extraction option of the kinetics code was used to calculate output power from the flow of 75 N_2/25 Ar at 50 atm and 2000 K mixed with 10% CO_2 and 1%

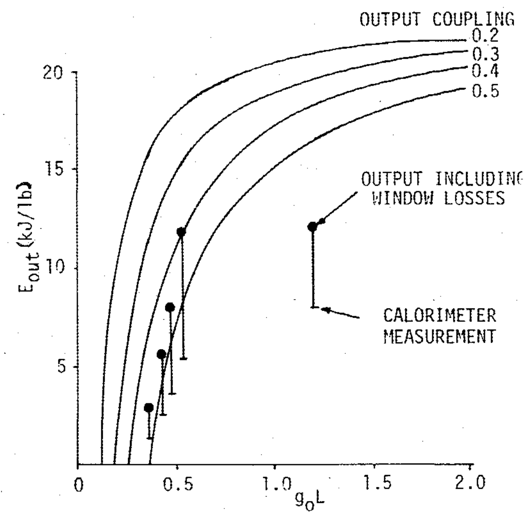

Fig. 8 Output power through zinc selenide windows 10 cm long with leading edge located 6.5 cm from nozzle exit plane.

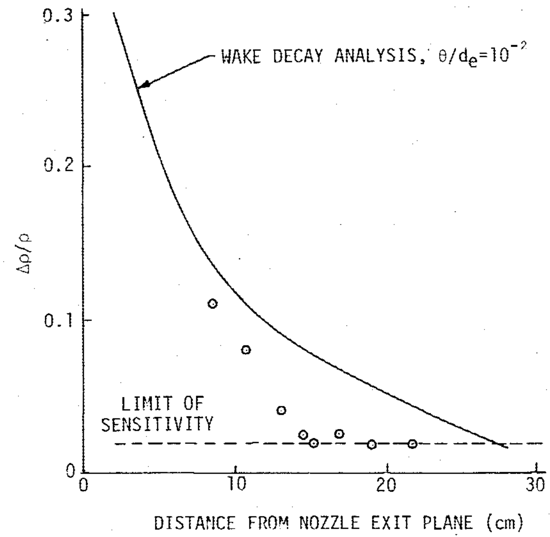

Fig. 9 Damping of maximum density fluctuations.

H_2O in a 10-cm long cavity for various values of output coupling. The computed results agreed very well with values calculated from Eq. (3), with a value of 0.75 for K. Equation (3) was thus used with the calculated value of E_A (31 kJ/lb at the first position) as the analytical model for the power extraction experiments.

The results from power extraction experiments performed with the windows located in the first position (6.5-16.5 cm) are presented in Fig. 8. The product of the small signal gain, as measured for the 7, 10, 12, and 15% CO_2 mixtures, and the cavity width (28 cm) appears as the horizontal coordinate, and the power measured by the calorimeter divided by the nitrogen and CO_2 mass flow rate appears as the lower value on each data bar. This experimentally recorded output does not correspond to the total output energy of the system to be compared with the analytical model, since power lost to the windows cannot be extracted out of the cavity and recorded on the calorimeter. Since these losses are specific to the current experimental cavity and correspond to power that could be extracted from a more efficient cavity, the output power recorded on the calorimeter was multiplied by a factor representing the calculated total cavity losses divided by the useful output coupling (33/15). This corrected value of total output specific power appears as the solid data point at the top of the data bar for each measurement. The maximum total specific output power obtained with the mixing GDL was 11.8 kJ/lb at the highest value of g_0L that was experimentally accessible.

For the values of g_0L obtainable with the experimental device, the output power is seen to be very sensitive to the g_0L product. The data generally fell below the values predicted for the total output coupling of 33%. The highest laser output measurements fall on theoretical curves that correspond to an output coupling 7-12% higher than the corrected output coupling of the experiment. This difference may be caused by several effects: The channel being only 2 cm high contains a large fraction of boundary-layer gas which does not carry the full freestream available energy. The mixing of the CO_2/H_2O and donor gas may not be complete at the upstream cavity location, thereby reducing the extractable power. The available energy in the cavity may not be quite as high as the 31 kJ/lb used in the analytical model. The measurements presented in Fig. 4 show 29± 5 kJ/lb available 10 cm downstream of the nozzle exit plane.

Another difference is the presence of walkoff losses in the optical cavity which are not included in the total intracavity loss values. The theoretical curves show the output power from the device if all of the energy lost from the cavity is usefully coupled out, a value which would thus differ from the data by the effect of these walkoff losses. The walkoff losses were not included in the window loss correction, because these losses, as contrasted to the window losses, would not be recoverable through changes in the optical design. The magnitude of the walkoff loss is not readily amenable to quantitative determination; however, the walkoff loss has been estimated to contribute from 3-4% loss per round trip for output couplings between 30 and 40%. This effect alone would make up a large portion of the difference between experiment and analysis.

Within the capabilities of the experimental apparatus, the ability of the mixing GDL to deliver specific output power far in excess of existing GDLs has been demonstrated in this investigation. The precise level of performance that is possible with the device is still uncertain, but the data give confidence that larger devices with specific output powers of more than 20 kW/lb/s can be expected.

VI. Flow Quality

The mixing process that takes place in the laser cavity of the screen-mixing GDL exhibits both ordered and random density disturbances that affect the flow quality in the cavity. The ordered array of waves and wakes from the individual nozzles in the screen-mixing array produce ordered density disturbances that decay in the flow direction in the manner reported in Ref. 4. Superimposed upon these ordered density perturbations are random turbulent fluctuations in density that arise from the turbulent mixing of gas streams in the laser cavity. Holographic interferometry was utilized to study the flow quality in the cavity of the screen-mixing GDL. The decay of the ordered perturbations to the density can be investigated through the examination of fringe shapes recorded on an interferogram spanning the flow area of interest at any one given instant of time during an experimental run. In order to investigate the flow unsteadiness during an experimental run, it was necessary to measure the time history of density fluctuations in the flow cavity which can be deduced from the temporal variation of fringe displacements. By means of the live-fringe holographic technique,[9] it was possible to record interferograms sequentially every 100 μs during an experiment, with an exposure time of 1 μs to minimize fringe blurring. A description of the apparatus is given in Ref. 10.

By the measurement of fringe displacement caused by the wakes and waves in the center of the flowfield, a calculation was made of the ordered density disturbance at several positions along the cavity. In Fig. 9, these data are compared with the wake model of the decay with distance downstream that was shown to apply to screen nozzles in Ref. 4. It can be seen that the ordered density disturbances in the flowfield of a

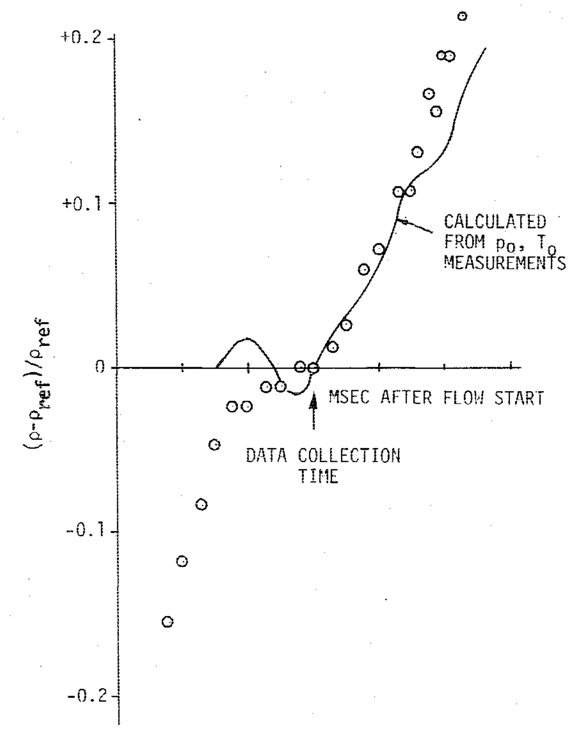

Fig. 10 Density time history in cavity 11 cm downstream of nozzle exit plane.

mixing nozzle decay with distance in the flow direction even more rapidly than those from a screen nozzle reaching the level of sensitivity of the measurement (2% peak-to-peak) by 15 cm (43 nozzle exit diam) downstream of the nozzle exit plane. This improved decay in disturbances may be caused by the finite velocity difference that exists between adjacent jets in the mixing nozzle. However, this velocity difference also gives rise to turbulence and flow unsteadiness.

As a measure of flow unsteadiness, fringe displacements, as a function of time (frame-to-frame), were measured at several positions downstream in the cavity on the centerline of the flow channel. Figure 10 shows these displacements converted to density disturbances as a function of time after flow start for a positon 10.9 cm downstream of the nozzle exit plane. The reference time was 3.0 ms after donor gas flow start, and the solid line represents the calculated shift in overall density in the flow cavity during the experiment, caused by the decay in total temperature (from previous line reversal measurements) and the measured variation in total pressure (shock tube operation was not tailored). A smoothed line through the data points would follow these calculations closely. It can also be seen that the flow unsteadiness at the center of the channel, which causes the density fluctuations above and below such a smoothed line, is not more than ±1% during the experimental time. The accuracy is at the level of sensitivity of these measurements. No increases in unsteadiness were measured at any of the other flow stations.

The results presented here show that the density disturbances present in the cavity flow of a screen-mixing GDL decay to a level that does not seriously affect beam quality at a downstream station where measurements of both gain and available energy remain high. Measurements of density fluctuations caused by the turbulent mixing taking place in the cavity of the screen-mixing GDL have shown that these disturbances are small enough to have a negligible effect on the optical quality of the flowing medium.

VII. Conclusions

The results of this investigation have demonstrated the feasibility of the screen-mixing GDL and shown its potential for high performance. The mixing laser concept was originally suggested as a means of transcending kinetic limitations inherent to conventional premixed GDLs, and allowing more efficient transformation of the energy thermally invested in the donor gas to useful output power. The screen-mixing GDL has provided a solution to the flow uniformity problems inherent to earlier embodiments of the mixing concept. In this investigation, no attempt was made to optimize the design of the screen-mixing GDL; however, realistic GDL conditions were utilized, and the experiment was designed to facilitate nozzle fabrication while allowing a meaningful examination of the concept. Within these limitations, the present research has demonstrated:

1) Rapid mixing. Measurements of high gain and available energy 11 cm downstream of the nozzle exit plane indicate that vibrational energy is rapidly transferred from the donor gas to the lasing gas.

2) Good freezing efficiency. Measurements of vibrational temperature in the cavity have recorded nearly 90% of the stagnation temperature level, indicating substantial freezing upstream of the nozzle throat when pure nitrogen was used as a donor gas. When the donor gas consisted of the combustion products of a realistic fuel, the efficiency was over 70%.

3) Good performance with realistic donor gas. Measurements made with a donor gas whose constituents represented the combustion products of a potential fuel showed values of gain between 1.0 and 1.3%/cm and values of available energy of 20-30 kJ/lb in the optical cavity.

4) High output power. Within the limits of the experimental apparatus, the ability of the screen-mixing GDL to deliver specific output power far in excess of that from existing GDLs has been clearly demonstrated.

5) Good flow quality. Both the ordered density disturbances caused by the individual nozzle wakes and waves and the turbulent disturbances caused by the mixing processes were shown to be small enough to assure good beam quality in the far field.

6) Good agreement between data and model. The experimental data have been shown to be in general agreement with the predictions of the analytical model of the mixing GDL process, allowing the conclusion that this analytical model can be used to predict performance results and trends in the operational parameter space outside current experimental capabilities. Some preliminary parametric studies have projected an extracted specific power of 25 kW/lb/s from a screen-mixing GDL powered by realistic fuels.

The promise of the screen-mixing GDL is to provide substantially improved performance, while retaining the inherent simplicity of conventional GDLs, particularly in the use of a simple liquid or solid fuel combustor to power the device, and operation at a high enough cavity pressure to allow direct recovery to the atmosphere. The screen-mixing GDL relieves the limitations on stagnation temperature and pressure inherent in the premixed GDL, allowing greater efficiency and specific power and, at the same time, demonstrating beam quality potential equivalent to that of the existing GDL.

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