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Performance Potential of Advanced GDL Concepts

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Gasdynamic lasers (GDLs) have been recognized for the last decade as prime candidates for very high-power cw infrared laser systems, but in general have been considered to have very limited performance potential. Recent analytical and experimental work indicates that considerable improvement in the specific power of GDLs can be achieved. Performance analyses have been carried out for three advanced GDL concepts: the bipropellant GDL (BDGL), the advanced fuel-rich GDL (AGDL), and the screen mixing GDL (SMGDL). The results of these projections have been corroborated by small-scale experiments in the MSNW shock-tube GDL simulator. Small signal gains of 1%/cm and available energy of 20 kJ/lb have been measured in typical BGDL mixtures. Excess oxygen produced in the BGDL has been shown to interact vibrationally in a manner detrimental to performance. A BGDL should be able to deliver 12-13 kJ/lb from a well-designed optical cavity. The excess oxygen is eliminated in the advanced fuel-rich GDL; however, a large fraction of the available energy is carried by CO. Available energies near 40 kJ/lb and small signal gains of 0.6%/cm have been measured in typical AGDL mixtures. The storage of available energy in CO was found to be particularly sensitive to the amount of H_2O in the mixture. Performance calculations show that an AGDL device should be able to produce a specific output power of 18 to 20 kJ/lb. The screen mixing GDL relieves the limitations on stagnation temperature and pressure, inherent to the premixed GDL, allowing greater efficiency and specific power and, at the same time, demonstrates beam quality potential equivalent to that of the existing GDL. This concept has been experimentally demonstrated in a small-scale device. A preliminary fuels identification and characterization program has been completed. Performance calculations now predict that extracted specific powers of 30 kJ/lb should be possible from a well-designed screen mixing GDL. These advanced GDL concepts indicate that substantially improved performance is possible while retaining the inherent simplicity and reliability of conventional GDLs.

Introduction

RECENT developments in fuels technology together with the potential performance gains achievable with higher temperature operation have resulted in a reevaluation of the premixed, CO_2, gasdynamic laser. Conventional GDL technology was characterized by stagnation temperatures of 1500 to 1800 K, area ratios of 50 to 60, and stagnation pressures on the order of 50 atm.[1,2] Relatively large CO_2 concentrations (10-15%) provided gain in excess of 1%/cm. Operation at these conditions falls far short of realizing the potential of the gasdynamic laser principle. For instance, the energy available for lasing in N_2 at 1500 K is only about 20 kJ/lb, as compared to approximately 80 kJ/lb at 3000 K.[3] Available energy is defined as the net vibrational energy stored in all of the molecular species that is potentially available as laser output.

GDL operating conditions are dictated largely by gas kinetic limitations, existing fuels, and hardware technology. Deactivation of excited N_2 proceeds at a rapidly increasing rate with increasing temperature. Thus, as stagnation temperature is raised, the rate of N_2 deactivation at the nozzle throats increases rapidly until the increased vibrational N_2 energy is more than offset by deactivation loss and increased cavity static temperature. GDL fuels have been incapable of simultaneously providing higher temperatures and the mixtures necessary for higher temperature operation. Hardware technology has limited gasdynamic expansions and chamber pressures, thus restricting efficient high temperature operation.

Within these constraints, the optimum reservoir temperature for GDL operation was found to be 1700 to 1800 K. However, other fuels can be considered which offer considerable flexibility in mixtures and temperatures up to 2800 K.[3] Use of these fuels in nozzles with smaller throats and larger area ratios results in significantly shorter particle dwell time in the nozzle throat and increased energy available for lasing. The performance of GDLs was investigated[4,5] with area ratio 100 nozzles operating at stagnation temperatures of 2300 K. The large area ratio was required to expand the gas from the higher stagnation temperature to a cavity static temperature low enough to insure high gain and available energy. In order to allow atmospheric recovery through a passive diffuser, a stagnation pressure of 100 atm was utilized. The nozzles had throat heights of 0.089 mm to maintain the kinetics in the throat region.

Experiments conducted with the above configuration simulated a combustion-driven bireactant GDL utilizing N_2O and JP-4 combustion. This oxidizer-rich operation results in laser mixtures containing substantial amounts of O_2. Predictions indicated that operation under these conditions would exhibit significant improvements over previously attained levels. These predictions were verified by experiment[5] with available energy on the order of 20 kJ/lb being measured for 2300 K operation with O_2 concentrations on the order of 20%. It was found that the effect of the large O_2 concentration was more deleterious than previously realized. The oxygen acted not only as an inert diluent, but had significant effect in deactivating N_2 vibrational energy, thus decreasing the reservoir of available energy and raising the static temperature.

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Further search for fuels that could provide higher temperature without producing excess O_2 revealed fuels which, when burned fuel-rich, could give high temperatures and produce excess CO rather than excess O_2. The effect of CO in GDLs had already been investigated at lower temperatures: It had been found to be a useful energy storage medium, though not as effective as N_2 (Refs. 6 and 7). Several questions remained, however, concerning the high temperature kinetic deactivation of CO and the kinetics of energy transfer and loss from the CO in the laser cavity. Thus the effects of variation of the mixture concentrations at these high stagnation temperatures and pressures when appreciable CO was present were investigated, theoretically and experimentally.[8-10]

The experimental results agreed well with theoretical predictions showing available energies as high as 40 kJ/lb at small signal gain levels near 0.7%/cm. The collisional loss of energy from the large CO fraction in the presence of the required low catalyst concentration was found to be a prominent kinetic loss mechanism. This situation, coupled with the low gain levels, necessitates large optical cavities for these advanced fuel-rich GDLs. Performance optimizations indicate as much as 32.5 kJ/lb of saturated extraction energy from a cavity 60-cm long in the flow direction. The saturated extraction energy is the amount of energy that can be delivered by a fully saturated laser medium in the specified cavity flow length; it differs from available energy because of finite energy transfer rates and collisional energy losses. A good optical design should allow extraction of 70% of this energy.

As a further improvement, the mixing laser concept has been proposed[3] as a method of minimizing the collisional loss of vibrational energy during the gasdynamic expansion. Early experiments achieved 30 kJ/lb available energy and showed small signal gains of 1.5%/cm. An analytical model, verified by these results, was used to predict that specific energy of 25 kJ/lb could be extracted from a 20-cm flow length. More recent performance calculations based on gas mixtures which could be supplied from solid fuel combustors have shown that a saturated extraction energy of as much as 48 kJ/lb with a small signal gain of 1.3%/cm are possible.[9]

Some of the important results and implications that were developed during these investigations are discussed in the following sections. The conclusions that were drawn from these studies are presented in the final section.

The Bipropellant GDL

Bipropellant combustors buring JP-4 fuel and N_2O oxidizer have demonstrated stagnation temperatures greater than 2000 K at pressures greater than 100 atm. A kinetics and extraction code was modified to provide an assessment of the performance potential of this concept.[4] It was ncessary to compile and critically assess the kinetic rate data for temperatures up to 3000 K for species including CO_2, N_2, H_2O, O_2, N_2O, and NO, together with their reaction and decomposition products. A major area of uncertainty was identified in the rate constants for high temperatures and for processes involving water.

Laser performance calculations revealed that the high O_2 concentration in the bipropellant gas mixture implied a significant fraction of vibrational energy stored in the O_2. Vibrational deactivation of the O_2 during the expansion process led to a substantial increase in the static temperature and a reduction in small signal gain. The dominant path for this deactivation at high temperature was identified as the VT reaction with water. The results of a sensitivity study on this rate constant are shown in Fig. 1.

Since N_2O undergoes a near resonant VV exchange with N_2, any concentration of unreacted oxidizer (in excess of 1%) that may survive in the boundary layer could lead to an important loss of vibrational energy in the expansion process.

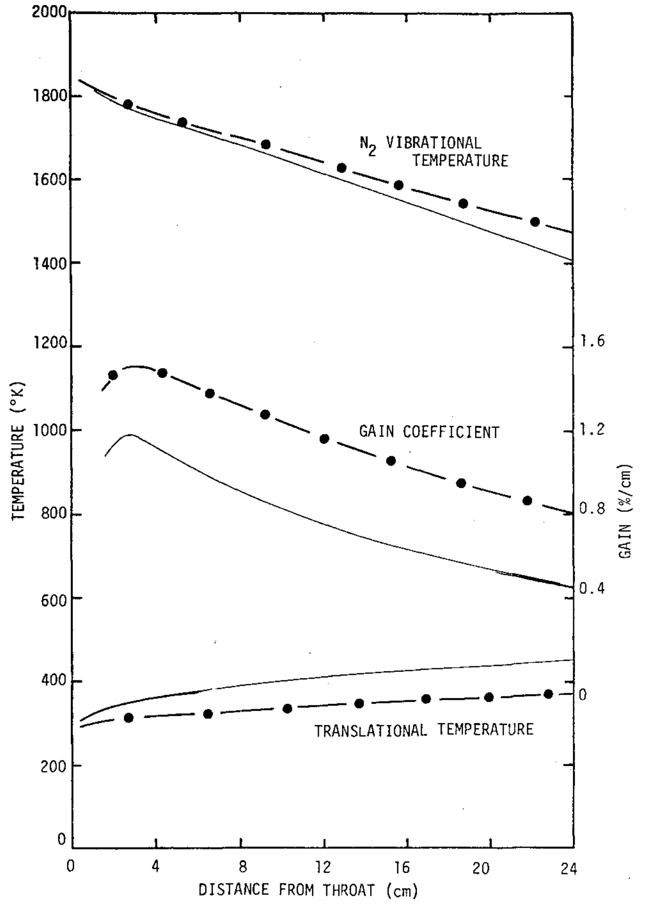

Fig. 1 Predicted variation in N_2 vibrational temperature, small signal gain, and translational temperature with distance from the throat of BGDL. -•-•-• O_2 frozen, —— O_2 permitted to V-V exchange with H_2O, 63 N_2/24 O_2/8CO_2/5 H_2O, 2300 K. 100 atm, area ratio 100, $h^* = 0.01$ cm.

The need for careful design of the combustor to maximize the thermal decomposition of N_2O, particularly for gas mixtures with a high H_2O content, was clearly indicated. The presence of NO, the largest of the minor reaction products from a bipropellant fuel, was shown to play a minor role in the loss of vibrational energy.

Calculations showed potential laser performance was most sensitive to variations in the kinetic rates for high-temperature VT relaxation with water. In particular, the major uncertainty affecting performance was found to be in the rate for the high-temperature VT deactivation of nitrogen by water. Existing data for this rate varied by an order of magnitude.[11,12] The results of calculations using the upper and lower bounds on this rate are shown in Fig. 2. The assumption of the faster of the two rates is seen to result in a large decrease in nitrogen vibrational temperature and a reduction in small signal gain. The energy extractable from a typical cavity varies by at least 20% due to this uncertainty in the VT deactivation rate of N_2 by water.

As a result of this uncertainty, measurements were made behind the incident shock in a shock tube to confirm the rate for the VT deactivation of N_2 by water between 1500 K and 3000 K.[4] Both infrared diagnostics using a CO tracer and interferometric measurements of N_2 density variations were used to infer the temperature dependence of the VT kinetic rate. The results from this investigation are shown in Fig. 3; they corroborated the earlier measurements showing a slower relaxation rate for this process.[11]

An investigation was carried out to demonstrate the performance capabilities of the bipropellant GDL concept and to verify the kinetics code.[5] A shock tunnel was fitted with an

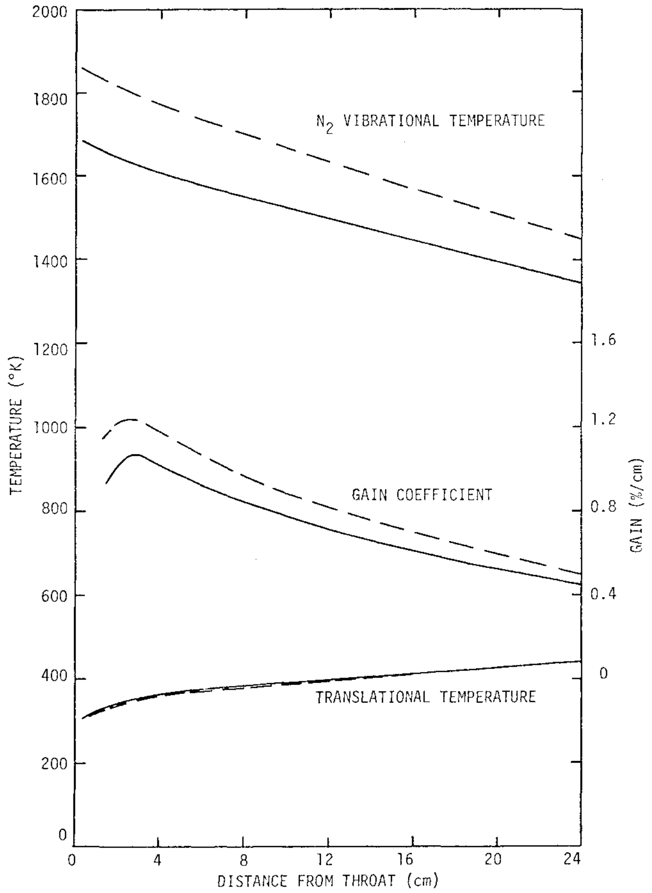

Fig. 2 Predicted variation in N_2 vibrational temperature, small signal gain and translational temperature with distance from the throat of BGDL. —— Fast deactivation of N_2 by H_2O - - - - slow deactivation of N_2 by H_2O. 63 N_2/24 O_2/8 CO_2/5 H_2O, 2300 K, 100 atm, area ratio 100, $h^* = 0.01$ cm.

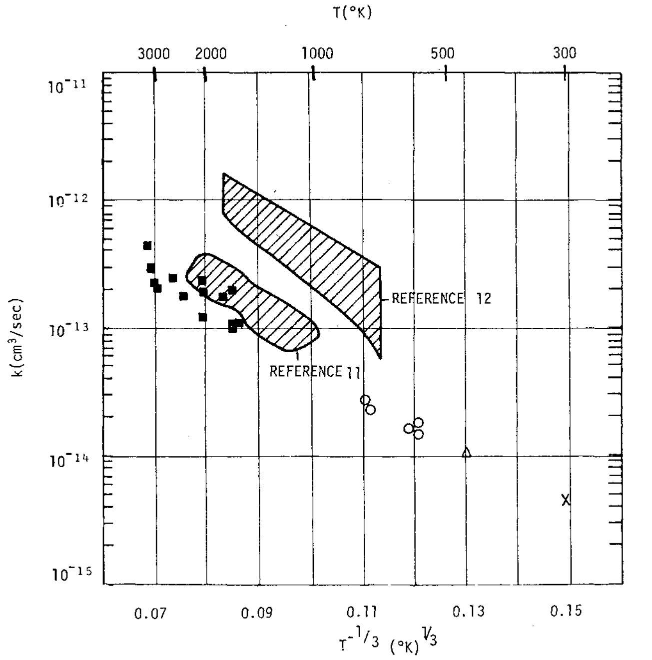

Fig. 3 Nitrogen vibrational relaxation by water, comparison of present high temperature measurements (■) with previous shock-tube measurements (hatched regions) and with low temperature data.[4]

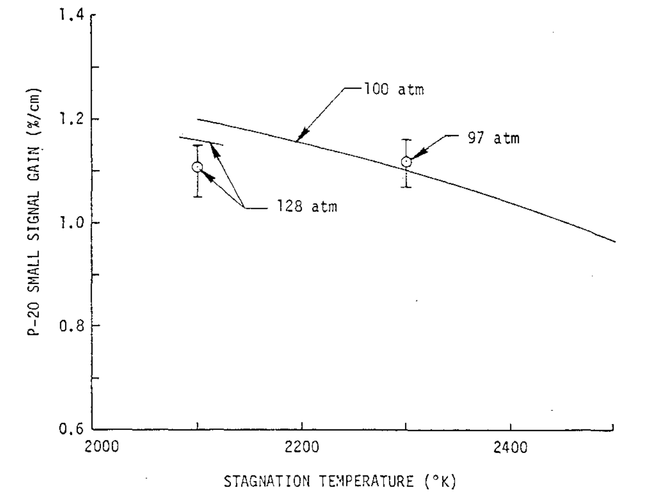

Fig. 4 Effect of stagnation temperature on BGDL small signal gain for 0.68 N_2/0.08 CO_2/0.04 H_2O/0.20 O_2 mixture. 6.7 cm downstream of area ratio 100 nozzle throat, $h^* = 0.0089$ cm,—analytical model, ○ data.

array of area-ratio-100 grid nozzles with throat heights of 0.0089 cm. An investigation of the effects of stagnation temperature and gas composition on laser performance (as characterized by small signal gain and available energy) was performed utilizing the gain scan technique[5] at a point in the laser cavity 6.7 cm downstream of the nozzle throat plane.

The effect of stagnation temperature on small signal gain is shown in Fig. 4. The results show a decrease in gain with increasing stagnation temperature as the lower level becomes more populated for the same nozzle geometry. A decrease in gain is also associated with increased stagnation pressure due to increased collisional deactivation. However, it is apparent that small signal gains of the order of 1%/cm are possible from bipropellant mixtures expanded from temperatures as high as 2500 K in area ratio 100 nozzles with $p_0 d^* = 0.9$ atm cm. Available energy was found to increase almost linearly with stagnation temperature, as shown in Fig. 5. A higher stagnation pressure results in a drop in available energy due to increased throat deactivation.

Small signal gain decreases as the oxygen concentration increases, as shown in Fig. 6. This occurs because the upper level temperature is depressed and the lower level temperature is increased by the collisional deactivation of vibrationally excited oxygen. The available energy also decreases rapidly with increasing oxygen fraction, as seen in Fig. 7. The presence of oxygen has been shown to be more detrimental than an inert diluent because it supplies a channel for the loss of vibrational energy stored in the N_2 through the thermalization of its vibrational excitation. This causes an increase in static temperature which enhances other collision loss rates as well as depressing the small signal gain.

Figures 4-7 show that the bipropellant GDL, with an area-ratio-100 nozzle operating at 2300 K and at $p_0 d^* = 0.9$ atm cm, is capable of providing more than 20 kJ/lb of energy available and more than 1%/cm small signal gain if the oxygen fraction is kept below 25%. Lower oxygen fractions allow better performance, but realistic bipropellent combustor effluents contain at least 20% oxygen.

Further investigations showed that 7% CO_2 concentration was required to provide 1%/cm small signal gain at 2300 K operation. Higher CO_2 fractions are necessary at higher stagnation temperatures to maintain this gain level; however, larger collisional losses would then be incurred. The available energy decreases monatonically with increased CO_2 concentration because of increased collisional deactivation.

An increase in H_2O concentration was found to cause a decrease in gain due to increased collisional deactivation and decreased upper level temperatures. H_2O concentrations of less than 4% were necessary to assure a 1%/cm small signal

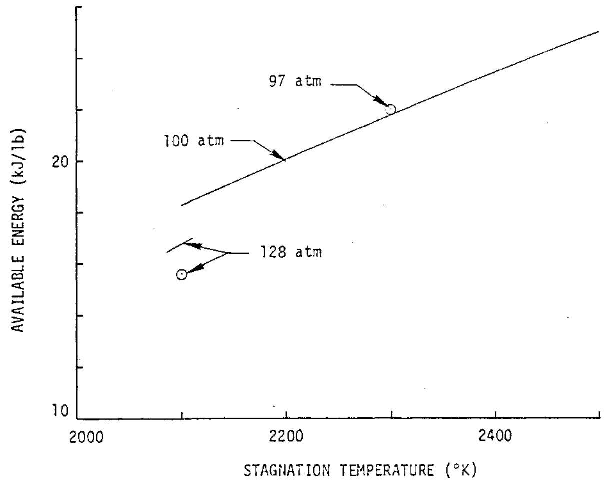

Fig. 5 Effect of stagnation temperature on BGDL available energy for 0.68 N_2/0.08 CO_2/0.04 H_2O/0.20 O_2 mixture. 6.7 cm downstream of area ratio 100 nozzle throat, $h^* = 0.0089$ cm,—analytical model, ○ data.

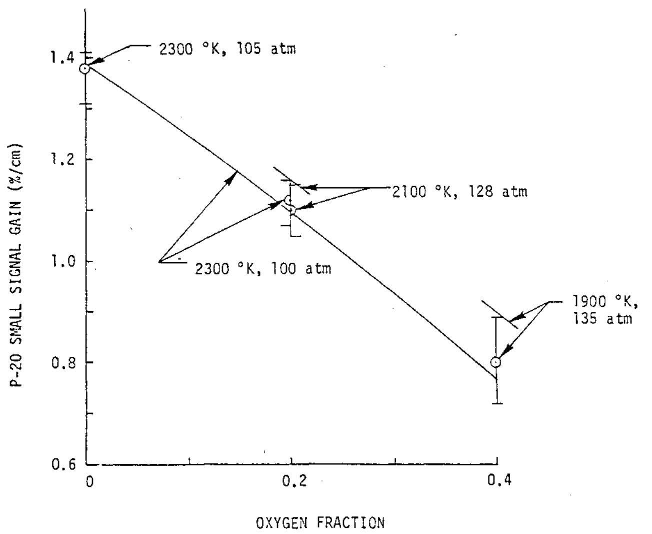

Fig. 6 Effect of oxygen concentration on BGDL small signal gain for 0.08 CO_2/0.04 H_2O/balance N_2 mixture. 6.7 cm downstream of area ratio 100 nozzle throat, $h^* = 0.0089$ cm,—analytical model, ○ data.

gain level for 2300 K operation. The available energy also decreased at the larger H_2O concentrations, due to increased collisional deactivation of the nitrogen. The results showed that available energy of 23 kJ/lb is possible from area ratio 100 bipropellant devices operating at 2300 K, if the H_2O fraction is kept below 3%. No optimum was seen in accompanying calculations, but enough H_2O is required during power extraction to allow the rapid depopulation of the lower level as it is filled by stimulated emission.

Since the rate of deactivation of vibrational energy is roughly proportional to the total concentration of CO_2 and water which act together to depopulate the nitrogen, a simple linear scaling law can be developed to relate the available energy to the sum of the CO_2 and H_2O concentrations.[5]

Power extraction calculations were performed for a practical bipropellant GDL mixture (65.7 N_2/4.4CO_2/1.6H_2O/28.3 O_2) at stagnation conditions of 2034 K and 130 atm expanded through the same area-ratio-100 nozzle with 0.009-cm throats. The saturated extraction energy is shown as a function of cavity length in the flow direction in Fig. 8. A well-designed optical cavity should be capable of extracting 70% of this saturated energy. Consequently, it appears that a

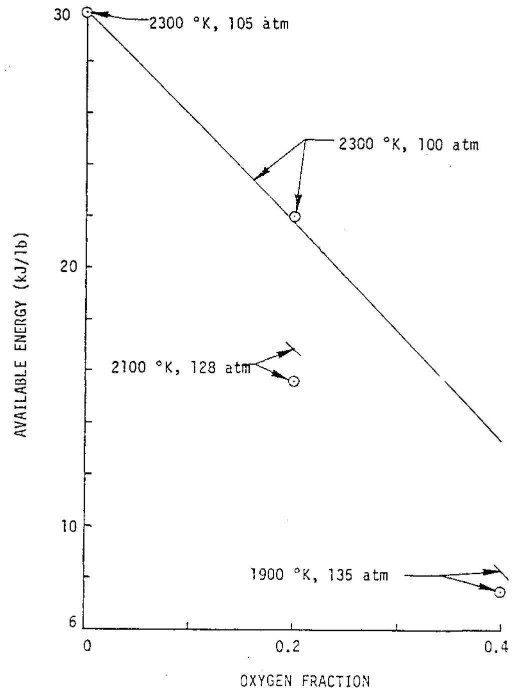

Fig. 7 Effect of oxygen concentration on BGDL available energy for 0.08 CO_2/0.04 H_2O/balance N_2 mixture. 6.7 downstream of area ratio 100 nozzle throat, $h^* = 0.0089$ cm,—analytical model, ○ data.

cavity 40-cm long in the flow direction should be capable of delivering performance of 12-13 kJ/lb ($K_{sat} = 18$ kJ/lb) specific energy. The long extraction length is a consequence of the low CO_2 concentration in this mixture.

The Advanced Fuel-Rich Gasdynamic Laser

Efforts to eliminate the detrimental effects of excess oxygen in the bireactant GDL led to an investigation of the fuel-rich operation of advanced GDLs, at stagnation temperatures up to 2800 K and pressures up to 200 atm. The amount of oxygen present in fuel-rich combustion will be negligible, but there will be large amounts of CO formed (up to 50%) and significant concentrations of H_2 (up to 10%). A kinetics rate survey was performed to gather and critically assess all available kinetic data pertinent to the molecular systems present in AGDL mixtures. Energy extraction was investigated to predict optimum operational conditions for AGDL performance. An experimental verification of AGDL performance was carried out in a shock tunnel to demonstrate the potential of the concept and to confirm the kinetics code.

The performance study for AGDLs[8] utilized the kinetics code of the previous study[4] with the addition of rate data for the species CO, H_2, HCl, H, Cl, and OH. The primary new kinetics in the AGDL involved the presence of H_2 and CO.

Available measurements of the rate of VT deactivation of vibrationally excited N_2 show that H_2 will be almost as effective as H_2O at high temperatures. The catalytic efficiency of H_2 as measured by its rate of VT deactivation of the lower laser level at cavity temperatures was found to be less than 20% that of H_2O. These rates suggest that both gain and power extraction will be affected by the presence of H_2 in the mixture, dependent upon the concentration of H_2O present.

The rates for the VT deactivation of vibrationally excited CO are an order of magnitude faster than those of N_2 by similar catalysts, as shown in Fig. 9. Since the concentration of CO will be high in AGDL mixtures, a considerable fraction of the vibrational energy imparted to the mixture in the combustion process will be transported into the laser cavity by the CO. Increased collisional losses will significantly lower the system performance. The performance will be particularly

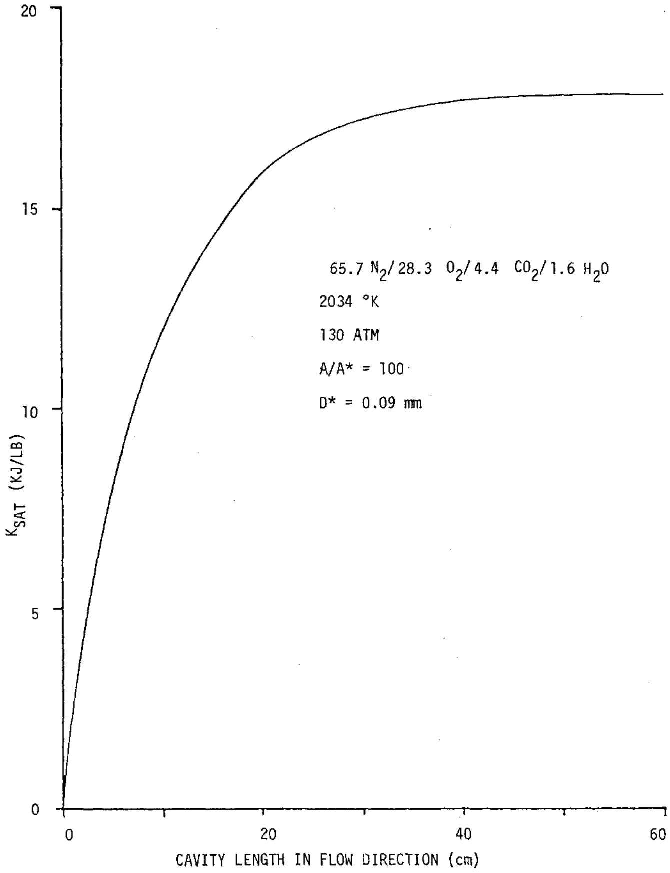

Fig. 8 K_{sat} **as a function of cavity length for bireactant GDL.**

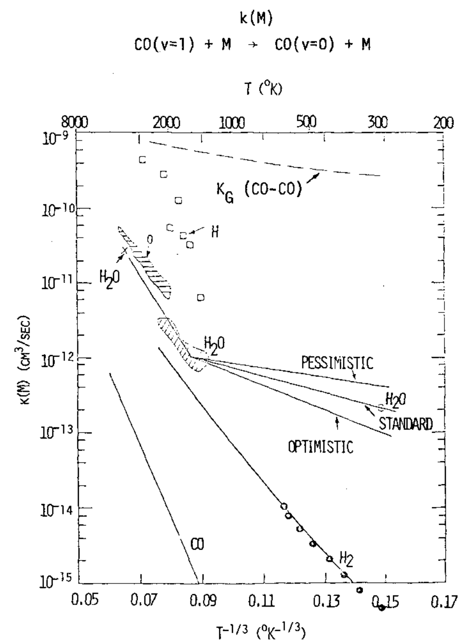

Fig. 9 Experimentally derived rate constants for VT deactivation of CO by various collision partners, M. The dashed line represents the gas kinetic rate constant.

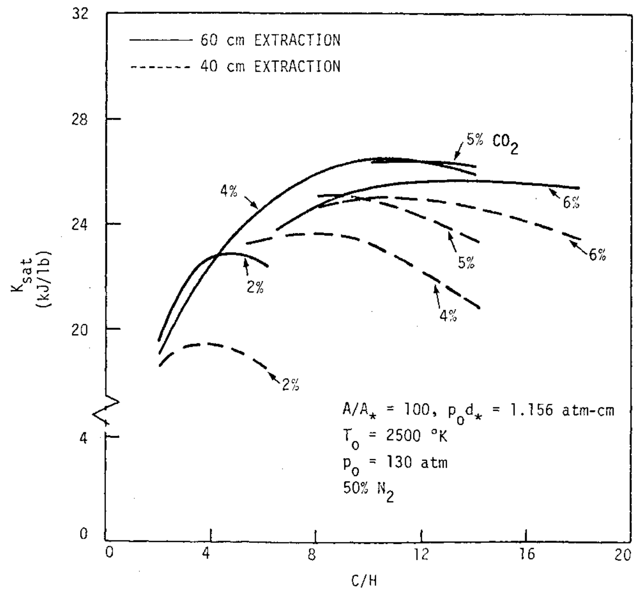

Fig. 10 Effect of fuel C/H on AGDL energy extraction for various CO_2 fractions.

sensitive to the deactivation rate of CO by H_2O at cavity temperatures. The kinetic rate survey also showed that CO was not as efficient as N_2 in pumping CO_2 and that, consequently, longer extraction lengths in the flow direction would be required.

An investigation of performance of fuel-rich AGDLs was done to quantitatively evaluate these various kinetic effects.[9] The expansion was nominally fixed as area ratio 100 from a throat height of 0.009 cm, and nominal stagnation conditions of 2500 K and 130 atm were used. Performance was evaluated by the saturated energy extraction over 60 cm in the flow direction.

The gasdynamic expansions of GDLs can exhibit considerable vibrational freezing upstream of the sonic throat, with a beneficial effect on performance. Since the high-temperature relaxation rates of CO are an order of magnitude faster than those of N_2 for similar catalysts, the degree of subsonic freezing is expected to be less in the AGDL. The subsonic freezing of a typical AGDL mixture ($50N_2/43.6CO/4CO_2/1.5H_2/0.9H_2O$) provided an increase of 2.6% in peak gain, an increase of 3% in peak available energy and an increase of only 1.5% in saturated power extraction from 60 cm of flow length when compared to operation with complete equilibrium assumed up to the throat.

The effect of the C/H ratio of the fuel and the CO_2 concentration with a fixed N_2 fraction (50%) was examined for the nominal conditions. An equilibrium water gas shift reaction in the combustion chamber was used to determine the concentrations of CO, H_2 and H_2O. The saturated energy extraction in 40 and 60 cm of flow length are shown in Fig. 10. An optimum saturated extraction energy of 27 kJ/lb in 60 cm of flow length is indicated at a C/H of 10. This mixture was utilized as a nominal mixture for the succeeding parametric variations. A higher CO_2 concentration is needed to extract the energy in the shorter flow length (40 cm), but the attendant increase in collisional loss gives lower peak performance.

The kinetic rate survey indicated that the collisional energy loss processes of CO would have a great influence on AGDL performance, since a substantial amount of laser energy is transported by the CO in fuel-rich mixtures. A sensitivity study was performed with the VT deactivation rate of CO by H_2O increased and decreased by a factor of two at 300 K, coupled with a linear extrapolation to the 1200 K data, as shown in Fig. 9. Figure 11 shows the effect of this variation on the saturated extraction energy. Most of the variation of extracted energy was found to occur in the cavity during the extraction process rather than during the expansion process in the nozzle.

Since the CO provides the major vibrational energy loss mechanism, the effect of raising the N_2 fraction at the expense of the CO was studied. For the nominal flow conditions there

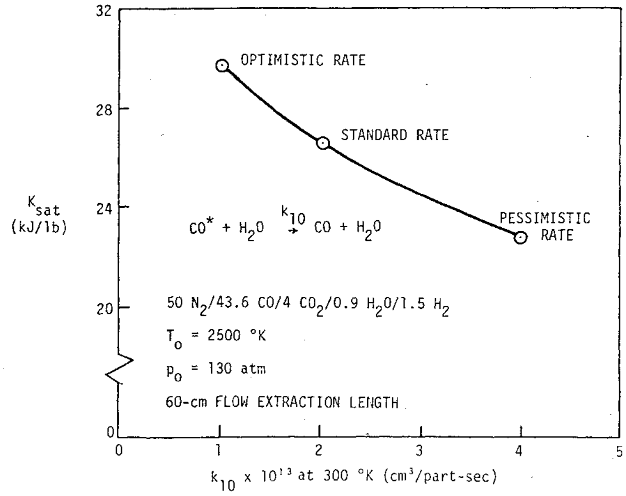

Fig. 11 Sensitivity of AGDL power extraction to CO VT relaxation by H_2O.

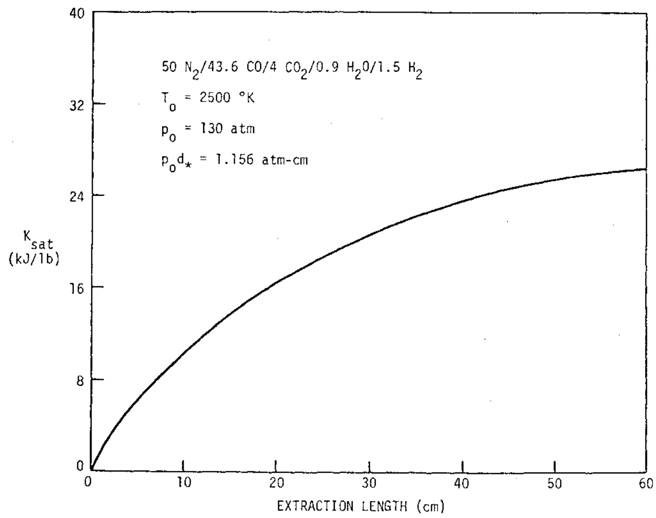

Fig. 13 Saturated extracted power as a function of extraction length in the flow direction for the AGDL.

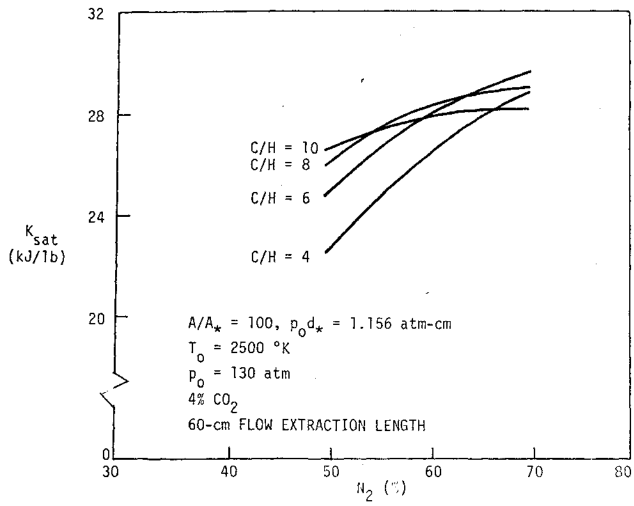

Fig. 12 Effect of N_2 concentration and C/H ratio on AGDL extracted energy.

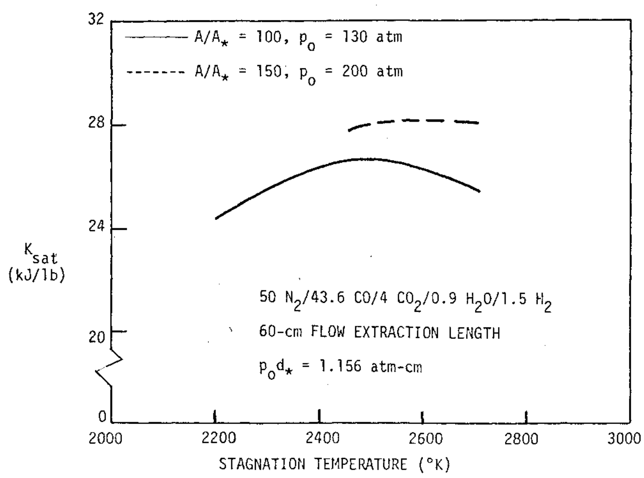

Fig. 14 Optimum total temperature for the AGDL.

was 12% improvement in saturated extraction energy when the N_2 fraction was raised from 50 to 70%, as shown in Fig. 12. As the CO fraction decreases, the optimum C/H ratio also decreases to maintain the necessary catalyst concentration.

Since the catalytic efficiency of H_2 on the CO_2 vibrational modes was found to be nearly an order of magnitude lower than the efficiency of H_2O and the concentration of the two catalysts was comparable in AGDL mixtures, AGDL performance was thought to be sensitive to the VT decay rates of CO_2 by H_2. Sensitivity studies varying the H_2 rates by factors of two (for the nominal mixture under nominal flow conditions) found performance to be relatively insensitive to variations in the upper level deactivation rate by H_2. An increase or decrease in the lower level deactivation rate by a factor of two caused an increase or decrease, respectively, of 5% in the saturated extraction energy. The performance was sensitive to this rate process because of the low concentration (0.9%) of H_2O in the nominal mixture.

Fuel-rich AGDL mixtures with low CO_2 concentrations and substantial CO concentrations require fairly long extraction lengths in the flow direction for efficient energy extraction, primarily due to the slow VV exchange rate between CO and CO_2. The effect of length in the flow direction on the saturated extraction energy is shown in Fig. 13. The essentially complete extraction afforded by a 60 cm long cavity is reduced by 23% if the cavity is shortened to 30 cm.

Although the stored vibrational energy increases with increasing stagnation temperature, the vibrational loss rates increase and consequently the available energy decreases with increasing static temperature. An optimum temperature was thus found to be 2500 K for the nominal AGDL mixture expanded through an area ratio 100 nozzle, as shown in Fig. 14. The loss of available energy may be alleviated somewhat by expanding to a higher area ratio; however, the stagnation pressure must also be increased to achieve recovery to atmospheric pressure. To maintain a similar kinetic freezing parameter, p_0d^*, the nozzle will require a smaller throat height. Increasing the area ratio to 150 broadens the optimum and moves it upward, as shown in Fig. 14.

Finally, a combined optimization was done to find the best performance within the range of parameters investigated. A maximum saturated extraction energy of 32.5 kJ/lb can be obtained from a mixture of $0.7N_2/0.04CO_2$ with C/H = 6 expanded from 2500 K and 200 atm through an area ratio 150 nozzle with a 0.0058 cm throat. The optimum is rather broad with respect to CO_2 fraction, decreasing to 32 kJ/lb at both 3% CO_2 (C/H = 4) and 5% CO_2 (C/H = 7).

An experimental program was carried out to demonstrate the performance potential of these high-C/H-ratio fuels burned fuel-rich in an area ratio 100 nozzle.[10] Three mixtures were examined: a low-C/H (4) mixture and a high-C/H (10) mixture (each with 4% CO_2 and 50% N_2), and a high-N_2 (70%) mixture with 4% CO_2 and optimum C/H (6). Static and vibrational temperatures and available energy were in-

Table 1 Advanced fuel-rich GDL—shock tube simulator results[10]
p_0 = 130 atm, h^* = 0.0089 cm, 6.7 cm downstream of area ratio 100 nozzle throats

	P-18 gain, %/cm	Temperatures K: Static	Lower level	Upper level	N_2	CO	Available energy, kJ/lb
	Low-C/H mixture: $48N_2/42CO/3.9H_2/4CO_2/2.1H_2O$, 2400 K, 130 atm						
Predictions	0.63	313	343	1561	1749	1921	34.0
Results	0.54	327	357	1509	1697	1868	31.8
	High-C/H mixture: $50N_2/43.6CO/1.5H_2/4CO_2/0.9H_2O$, 2500 K, 130 atm						
Predictions	0.61	321	415	1670	1849	2165	40.0
Results	0.58	317	411	1626	1805	2121	38.2
	High-N_2 mixture: $70N_2/23.7CO/1.1H_2/4CO_2/1.2H_2O$, 2500 K, 130 atm						
Predictions	0.76	320	398	1789	1937	2223	40.6
Results	0.69	357	435	1841	1989	2275	42.0

ferred from gain scan measurements taken 6.7 cm downstream of the nozzle throat.[10] In Table 1, results of these measurements are compared with the predictions of the kinetics code.

These mixtures exhibit low values of small signal gain, due to the low CO_2 concentration and low catalyst concentrations that are necessary to minimize collisional energy loss and to the high concentration of CO in the mixtures. The effect of the low catalyst concentration can be seen in the high degree of lower level nonequilibrium that existed. Vibrational energy was found to be frozen in the N_2 at well above its equilibrium level with respect to the CO_2 upper level temperature. The vibrational energy stored in the CO is seen to be far below the equilibrium level with respect to the upper level temperature, signifying the serious energy-loss path provided by VT deactivation of CO by H_2O.

This investigation demonstrated that significant improvement in premixed GDL performance is possible through the use of fuel-rich operation at high stagnation temperature and pressure (2500 K, 130 atm). Saturated extraction energies above 30 kJ/lb and small signal gains of 0.6%/cm appear to be achievable if the proper fuel/oxidizer/diluent combination is available. Fuels providing high values of C/H (10) produce better performance. This improvement is primarily due to the decreased vibrational deactivation of CO in this environment with lower catalyst concentration. An increase in the N_2 fraction (70%) will also provide higher performance. This investigation has also demonstrated accurate predictions of advanced GDL performance by the kinetics code used in these studies.

The Screen Mixing Gasdynamic Laser

The mixing laser concept has been proposed as a method to minimize the collisional loss, during the gasdynamic expansion, of the energy that was thermally invested in the nitrogen in the plenum region, and thus to extend the performance of a GDL. This goal is accomplished by mixing the lasing gas and catalyst with the nitrogen (donor gas) downstream of the expansion, where kinetic deactivation rates are considerably lower. Although this concept promised flexibility of operation and improved performance, previous attempts were unable to simultaneously achieve high specific power, good medium quality and recovery to atmospheric pressure, the primary requirements of a good GDL system.

A new approach[3] was suggested by our work with small-scale axisymmetric screen nozzles.[13] Theoretical and experimental studies of the flowfield disturbances caused by individual, miniaturized nozzle wakes and waves showed rapid decay of shock and boundary-layer mixing, and good medium quality was obtained prior to appreciable kinetic decay 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 GDL (SMGDL) to extend the performance of the GDL by a large factor.

A mixing GDL based on this screen nozzle concept was analyzed, built, and tested in a shock tunnel.[3] 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 were measured in the laser cavity. Time-resolved interferometric measurements have shown that the mixing process and turbulence decay occur rapidly, before appreciable loss of stored energy, as a result of 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 specific power output of up to 11.8 kJ/lb was extracted from a small device, gain length 27 cm, with a multimode resonator. The results agreed with calculations that predict approximately 20 kJ/lb extractable from a larger device under equivalent conditions. The effects of impurities, such as hydrogen and carbon monoxide, that may appear in the combustion products of typical fuels have been determined. An increase in CO fraction was seen to decrease the small signal gain but had no discernable effect on available energy E_A. An increased H_2 fraction adversely affected both gain and E_A. Small signal gains of 1.25%/cm and available energies of 27 kJ/lb were measured from a typical mixture ($75N_2/22CO/3H_2$) and 2300 K mixed with 10% CO_2/1% H_2O in the laser cavity.

Some performance calculations done for a specific class of liquid fuels are shown in Fig. 15. The saturated extraction is calculated for a donor gas ($66N_2/31CO/3H_2$) expanded from 2804 K, 161 atm through an area ratio 140 nozzle, and mixed with various fractions of CO_2 and H_2O. The output power corresponds approximately to 70% of the saturated extraction energy K_{sat} for a well-designed optical cavity. These results range from 25 to 35 kJ/lb and demonstrate the high performance that is possible through the wide choice of operational parameters afforded by the SMGDL. In particular the CO_2 and H_2O fractions are now quite independent of the fuel and can be regulated in such a way as to optimize performance. An excess of either leads to excessive decay and loss in performance, yet a sufficient amount of each is necessary to depress the lower level temperature and also enhance the extraction of N_2 vibrational energy in a given flow length. For a 10 cm cavity length, 17% CO_2 and 2% H_2O are necessary to provide a saturated extraction energy of 30.6 kJ/lb.

When the cavity length is increased to 20 cm, the performance of this mixture is unimproved because very little energy is left after 10 cm of flow. Several mixtures with a

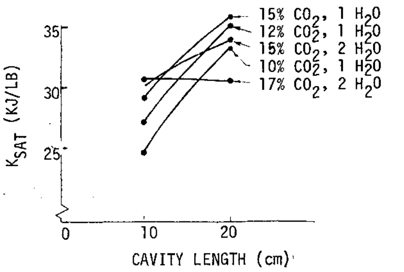

Fig. 15 Screen mixing GDL, calculations of K_{sat} as a function of cavity length for 66 N_2/31 CO/3 H_2 at 2804 K, 161 atm, expanded through an area ratio 140 nozzle with 0.15 mm throat diameter. CO_2 at 2000 K, $M = 6.5$.

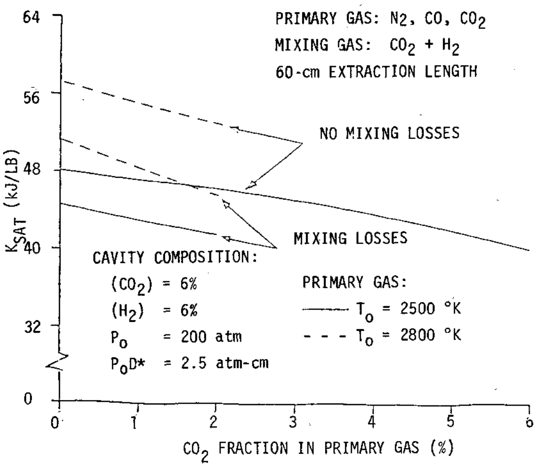

Fig. 16 Mixing GDL performance potential, equal parts CO and N_2 in primary gas.

lower mixed gas fraction allow up to 36 kJ/lb saturated extraction from 20-cm-long cavities, because they experience less kinetic decay. The operational flexibility of the SMGDL allows the variation of the mixed gas fraction without alteration of the primary fuel composition.

Recently, analyses have been performed[9] for a solid fuel producing equal parts of CO and N_2, with the possibility of a small amount of CO_2 included. The mixing gas consisted of the lasing gas, CO_2, and the catalyst, H_2.

Figure 16 shows the results of the energy extraction calculations from a gas mixture consisting of 6% CO_2 and 6% H_2, with equal amounts of N_2 and CO forming the remainder of the composition. The extraction length is 60 cm in the flow direction. With the primary gas at 2500 K and containing less than 2% CO_2, a saturated extraction energy of 42-45 kJ/lb is indicated, as compared with 26 kJ/lb from a premixed two-dimensional expansion under similar conditions. The small signal gain was 1.3%/cm, as compared to the 0.6%/cm achieved in the premixed case. The saturated extraction energy can be increased to 45-51 kJ/lb if the stagnation temperature of the mixing laser is increased to 2800 K. A similar increase in stagnation temperature in the two-dimensional premixed GDL produced approximately 28 kJ/lb of saturated extraction energy.

These analyses show that the SMGDL is capable of producing an improvement of 60-80% in saturated extraction energy over that of a premixed two-dimensional expansion of gases with similar total temperature and composition. The screen mixing laser also is capable of much greater small signal gains allowing a smaller device with equivalent extraction efficiency. These calculations by no means comprise an optimum design, but show the significant performance improvements that are possible from the SMGDL concept.

Conclusions

Several years of investigations into the improvements in performance possible for three advanced GDL concepts—the bipropellant GDL, the fuel-rich advanced GDL, and the screen mixing GDL—have been summarized. The results from extensive kinetic code calculations have been corroborated by experimental demonstrations of performance in a shock-tube GDL simulator.

A bireactant GDL operating at a stagnation temperature of 2100 K (area-ratio-100 nozzle, 0.01 cm throat height) should be capable of delivering a specific power of 12 to 13 kJ/lb from a well-designed optical cavity. There appear to be no major uncertainties in the kinetics pertaining to the operation of the BGDL. Because of the low gains exhibited in such a system, it will be difficult to demonstrate this performance potential in a small experiment.

A fuel-rich advanced GDL operating at a stagnation temperature of 2500 K (200 atm, area ratio 150 nozzle) should be capable of producing a specific power output of 18 to 20 kJ/lb from a well-designed optical cavity. There are several unanswered technology questions associated with such operation. Considerable development is needed in the area of fuels having a high-C/H ratio (6) that produce a high nitrogen concentration (70%). Stagnation temperatues above 2500 K do not appear to increase performance appreciably.

Some questions remain with respect to the kinetics of the AGDL, particularly concerning the effect of water on CO deactivation in the cavity and concerning the substitution of hydrogen for water as the lower level catalyst. The role of CO during power extraction has not been verified experimentally.

The high-pressure and high-heat-flux environment and the maintenance of the very small throat dimensions required of a 2-D nozzle present difficulties. Consequently, the use of a screen nozzle may be well suited to this application. However, such a screen nozzle should be analyzed, optimized, and designed for the AGDL to minimize the performance penalty observed in previous screen nozzle studies.[13]

The SMGDL offers the greatest potential for improving the performance of the GDL while retaining its simplicity. A well-designed mixing GDL should be capable of delivering 30 kJ/lb output specific energy and a small signal gain of 1.3%/cm or higher. However, fuels development is needed to achieve this performance. A hybrid combustion scheme using a solid fuel appears to be a promising possibility.

Although small-scale power extraction experiments have demonstrated the potential of the concept, a verification of performance in a larger experiment is high desirable. Engineering demonstration of continuous operation with nozzle cooling and diffuser operation is also needed. Finally, a detailed optimization of the SMGDL is yet to be performed to define the ultimate performance potential of the SMGDL concept.

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