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R. J. De Young
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R. J. De Young
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Langley Research Center
Hampton, Virginia

Introduction

Future space missions may require large amounts of power, which may someday be beamed from a central solar- or nuclear-driven laser to a multitude of receiver spacecraft, each with a relatively simple laser-to-electric converter system providing useful onboard power for electric or propulsive requirements. Such a visionary concept demands that efficient high-power lasers be developed. A system study (ref. 1) which defined some critical system elements has shown that there could be an economic payoff over solar photovoltaic power if solar-pumped lasers can achieve efficiencies (laser output divided by solar energy collected) greater than 1 percent.

One laser concept that may achieve such efficiencies is the blackbody-pumped CO_2 transfer laser. Such a system is called a fluid-mixing or transfer gas-dynamic laser and is shown in conceptual form in figure 1. In this system a blackbody cavity is heated by collected sunlight to a temperature of approximately 2000 K. Nitrogen gas passing through the cavity is heated to the blackbody temperature. The vibrationally excited N_2 then passes through a nozzle into a low-pressure laser cavity. Here CO_2 and He are mixed with the vibrationally excited N_2. A coincidence between $N_2(\nu = 1)$ and the $00°1$ asymmetric longitudinal mode of CO_2 allows rapid transfer of the $N_2(\nu = 1)$ vibrational energy into the CO_2 $00°1$ upper laser level. Lasing commences between the $00°1$ and the $10°0$ levels at 10.6 μm. Helium is added to help depopulate the lower laser level and increase diffusion of heat to the cool laser cell walls.

The gases are pumped from the laser cavity through a heat exchanger-radiator to extract excess heat. The gases are then passed through a gas separator where the N_2 is separated from the CO_2 and $He(H_2O)$. The N_2 is recompressed and then sent to the blackbody cavity while the CO_2 and $He(H_2O)$ are sent back to the mixing nozzles. Methods for separating the gases are discussed in reference 2.

Four laser cavities are shown in figure 1. Laser outputs would be combined and transmission optics would then beam energy to distant receivers for onboard electrical and propulsion requirements.

An advantage of the blackbody laser system is the inherent energy storage capability of the blackbody cavity. This could be an important advantage when sunlight is unavailable during certain orbit periods. The system also uses readily available low-cost lasant materials, which can be recycled. This system does not require any major technology breakthroughs; the major issue is the most economic means of scaling to high powers.

There are two disadvantages of the blackbody system. Probable lasing wavelengths near 10 μm will result in larger transmission optics than shorter wavelength laser systems. Also, because blackbody cavity materials will probably limit temperatures to about 2000 K, the N_2-CO_2 intrinsic efficiency will be limited to 5 percent; consequently the total system efficiency will be less than 5 percent.

Improvements in system efficiency may be possible if N_2 is replaced by CO, which can optically absorb solar radiation to create vibrationally excited CO. Such a system has been evaluated and efficiencies on the order of 10 percent have been predicted (ref. 3). Conversely, the calculations of McInville and Hassan (ref. 4) indicate that the N_2-CO_2 system should be more efficient than the CO-CO_2 system. Further research is in progress to resolve this issue.

The results reported here are an extension of the work of Fein et al. (ref. 5). We have extended their parameter studies to include system complexities and configurations for potential use in space. Parameters such as total pressure, blackbody temperature, laser mirror reflectivity, nozzle characteristics, and laser cell coolant temperature were systematically studied. Finally, the near optimum power for this experimental configuration and intrinsic efficiency were measured. The intrinsic efficiency is defined as the total power absorbed in N_2 within the blackbody cavity divided into the measured laser power output.

Experimental Setup

Figure 2 is a diagram of the experimental setup. Standard purity N_2 flowed through a quartz tube within an electrically heated oven (with a heating volume 30 cm long by 2-cm i.d.), which in the present experiment simulates a solar-heated blackbody cavity. The oven temperature and pressure were monitored. The gas velocity was slow enough (226 cm/sec) to allow the N_2 temperature to come into equilibrium with the oven temperature. Once outside the oven, the N_2 gas and vibrational temperature drop. The lifetime of $N_2(\nu = 1)$ is approximately 50 msec (1000 K, 450 torr N_2) (ref. 6); thus within one lifetime the N_2 travels 11 cm. The distance from the oven exit to the nozzle throat was varied to observe the effect of N_2 vibrational loss. The N_2 gas passed through a water-cooled nozzle into the low-pressure laser cell (2.2-cm diameter). At the exit of the nozzle throat the gas temperature rapidly dropped, but the N_2 vibrational temperature remained high. CO_2 and He were then mixed with the vibrationally excited N_2 to cause a transfer of energy from the $N_2(\nu = 1)$ to the CO_2 upper laser level. Lasing at 10.6 μm was then established between the laser cavity mirrors (with radius of curvature of 1 m), which were mounted directly on the laser cell (no windows) with the back cavity mirror having maximum reflectivity and the output mirror

having either 99-, 97.5-, or 95-percent reflectivity. The laser cavity mirror separation was 80 cm and the gain length was approximately 60 cm. The laser cell was water cooled to help prevent excitation of the lower laser level by keeping the CO_2 gas as cool as possible. The pressure in the laser cell, monitored near the cell exit, was typically about 10 torr, whereas the pressure in the oven was typically 500 torr.

The laser beam was multimode, filling the output mirror aperture. The beam diameter was approximately 1.5 cm at the output mirror.

Results

A number of system parameters were varied to study their effect on CO_2 laser output. The objective was to determine the critical scaling parameters which will enable higher power operation and efficiencies. The results of the parameter scaling studies are now discussed in detail.

In figure 3, laser output is shown as a function of CO_2 and He partial pressures at a fixed N_2 partial pressure of 2.4 torr for an oven temperature of 1430 K. Peak lasing occurred in a pressure range around 0.4 torr CO_2 and 3 torr He. The optimum laser mixture was approximately $1CO_2/7.5He/6N_2$.

In figure 4, the laser output is shown as a function of the reflectivity of the output laser cavity mirror. The 97.5-percent mirror gave a higher output than either the 99- or 95-percent mirror.

In figure 5, the effect of water temperature in the laser cell cooling jacket on laser output is shown. As the water temperature decreases, the laser output increases. There is a 33-percent decrease in laser output when the cooling water temperature increases from 5° to 40°C. Gas heating, as a consequence of lasing, is an important consideration in the CO_2 laser since excitation of the lower laser level can occur at gas temperatures slightly higher than room temperature. Helium helps conduct heat to the cool cavity walls and thus contributes to improved laser output.

The distance from the oven to the nozzle throat was varied and its effect on laser output noted. As shown in figure 6, as the distance increases, laser output decreases. The minimum separation distance possible was approximately 30 mm. As the distance increases, the $N_2(\nu = 1)$ suffers more collisional deactivation with the quartz tube wall and the laser output correspondingly decreases. Such systems should be designed with the oven-to-nozzle distance less than a few centimeters. Laser output decreased at a rate of 0.7 percent per mm of separation. At the exit of the nozzle, the N_2 gas is supersonic and thus experiences little deactivation before mixing with injected CO_2.

To assess the effect on laser output of different nozzle throat areas, three water-cooled nozzles were constructed having nozzle throat diameters of 1.07, 1.5, and 1.8 mm. The results are shown in figure 7 where the laser output is plotted as a function of N_2 oven pressure for each nozzle. The optimum nozzle diameter is 1.5 mm (1.76 mm^2). If the 1.5-mm nozzle is replaced by the 1.07-mm nozzle at a fixed N_2 pressure, for example, 400 torr, the laser output decreases since the N_2 partial pressure in the laser cell is now below the optimum of 4 torr. In figure 8, the laser cavity N_2 pressure is plotted as a function of oven pressure for each nozzle. To achieve optimum lasing conditions, the oven pressure must be increased to approximately 650 torr so that the laser cell N_2 partial pressure is again at the optimum of 4 torr. The laser output (fig. 7) of the 1.07-mm nozzle at 650 torr is less than that of the 1.5-mm nozzle at 400 torr, probably because of the increased collisional deactivation of $N_2(\nu = 1)$ at the higher pressure. Alternatively, if the 1.5-mm nozzle is replaced by the 1.8-mm nozzle, the laser output again decreases (at a fixed N_2 pressure of 400 torr) because the laser cell N_2 pressure is now higher than the 4 torr optimum pressure (see fig. 8). To achieve optimum lasing conditions, the oven pressure must now be decreased to approximately 250 torr. The optimum laser output of the 1.8-mm nozzle is less than that of the 1.5-mm nozzle, probably because of the increased N_2 velocity in the oven. Increasing the velocity does not allow sufficient time for the N_2 temperature to come to equilibrium with the oven temperature resulting in less excitation of the N_2 gas.

Probably the most important parameter of any laser system is efficiency. The experimental intrinsic efficiency is defined as the measured laser power output divided by the calculated enthalpy of the N_2 at the oven temperature. This efficiency is then compared with the calculated maximum intrinsic efficiency. The maximum intrinsic efficiency is defined as

$$\eta = (QE)(TE) \tag{1}$$

where QE is 0.41, the quantum efficiency of the CO_2 laser transition, and TE is the thermal efficiency, or the energy in the vibrational modes of N_2 divided by the N_2 gas enthalpy. Thus,

$$TE = E_{N_2}(T)/H(T) \tag{2}$$

where

$$E_{N_2}(T) = \frac{\theta R}{\exp(\theta/T) - 1} \tag{3}$$

where R is the specific gas constant, $\theta = 3357$ K, the characteristic vibrational temperature, and T is the N_2 gas temperature (ref. 7). The N_2 gas enthalpy $H(T)$ is given in J/g-mole by (ref. 8)

$$H(T) = 29.0(T_2 - T_1) + (0.11 \times 10^{-2}(T_2^2 - T_1^2)$$
$$+ (0.19 \times 10^{-5})(T_2^3 - T_1^3)$$
$$- (0.72 \times 10^{-9})(T_2^4 - T_1^4) \tag{4}$$

where T_2 and T_1 are the final and initial N_2 gas temperatures (°C).

Equation (1), the maximum intrinsic efficiency, is plotted in figure 9 as a function of N_2 gas oven temperature. As the N_2 temperature increases, the maximum efficiency also increases and is a maximum of 2.9 percent at 1500 K. The experimental intrinsic efficiency shown in figure 9 was defined as the measured CO_2 laser power divided by the total power absorbed in the N_2 gas. The power absorbed in N_2 at an oven temperature T is given by

$$P_{N_2} = H(T)(\text{SCCM})/(1.34 \times 10^6) \qquad (5)$$

where $H(T)$ is given in equation (4) and SCCM is the flow gauge reading in standard cm^3/min. The experimental intrinsic efficiency also increases with temperature and is approximately a factor of 4 lower than the maximum efficiency at 1500 K. Laser output is also plotted in figure 9 and increases with temperature to 1 watt at 1473 K, the oven limitation. The N_2 oven pressure was fixed at 440 torr.

In figure 10, the laser power and intrinsic efficiency are plotted as a function of N_2 oven pressure. The experimental intrinsic efficiency is seen to be constant at approximately 0.7 percent. If the coolant temperature is decreased to 5°C, experimental intrinsic efficiency increases to 0.93 percent. Both laser power and energy absorbed in N_2 are directly proportional to the N_2 oven pressure; thus the efficiency (laser power divided by N_2 power absorbed) is constant as shown by the maximum intrinsic efficiency curve.

With the system parameters optimized (laser cell coolant temperature 30° C), laser power increased with pressure to 1.4 watts at 700 torr N_2. The maximum oven temperature was 1473 K and flow rate of 1.17×10^{-4} kg/sec. Thus specific power was 1.2×10^4 J/kg. This is about a factor of 2 lower than predicted from a gasdynamic N_2-CO_2 laser system (ref. 9). Higher laser outputs could be achieved with higher oven temperatures and pressures.

Conclusions

Blackbody-pumped transfer laser systems, which are relatively simple to construct, will convert broadband solar radiation into narrow-band laser light. Continuous lasing of N_2-pumped CO_2 at 10.6 μm has been achieved for periods of hours with simulated solar pumping. The major laser parameters were investigated and optimized for maximum intrinsic efficiency and laser power. An intrinsic efficiency of 0.7 percent (0.93 percent with laser cell coolant at 5°C) was achieved at a laser power output of 1.4 watts. The specific power at 1.4 watts was found to be 1.2×10^4 J/kg. The maximum intrinsic efficiency was calculated to be 2.9 percent. Further improvements in efficiency can be achieved by increasing the blackbody temperature, lowering the laser cell gas temperature, and decreasing the collisional losses near the N_2 nozzle, but maximum intrinsic efficiencies will be limited to 5 percent for the N_2-CO_2 transfer laser system. To overcome this efficiency limitation, other systems must be investigated such as the CO-N_2O or CO-CO_2 transfer laser systems. With these systems, intrinsic efficiencies of greater than 10 percent have been predicted.

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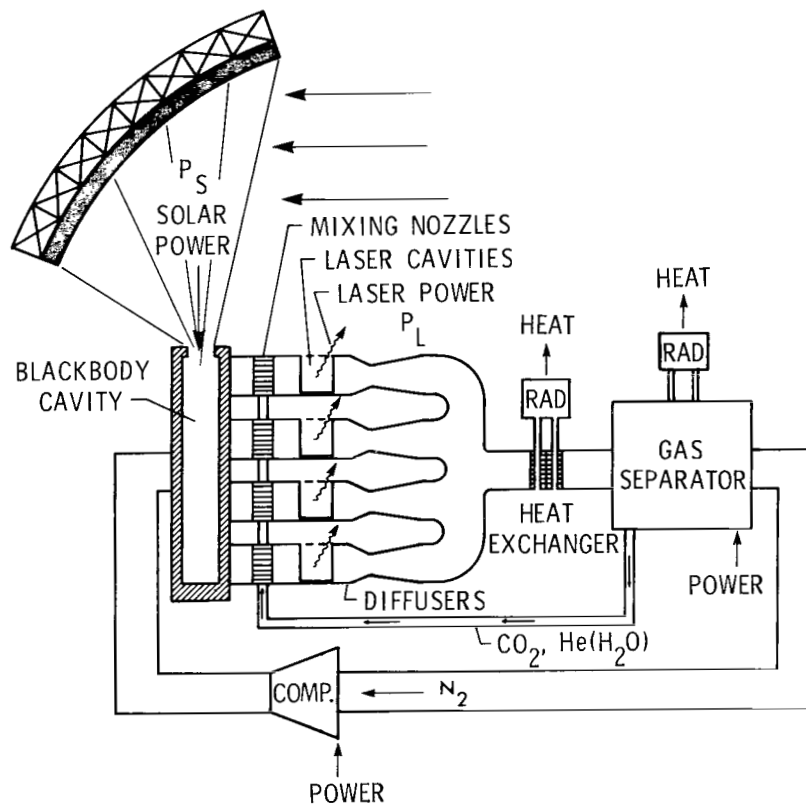
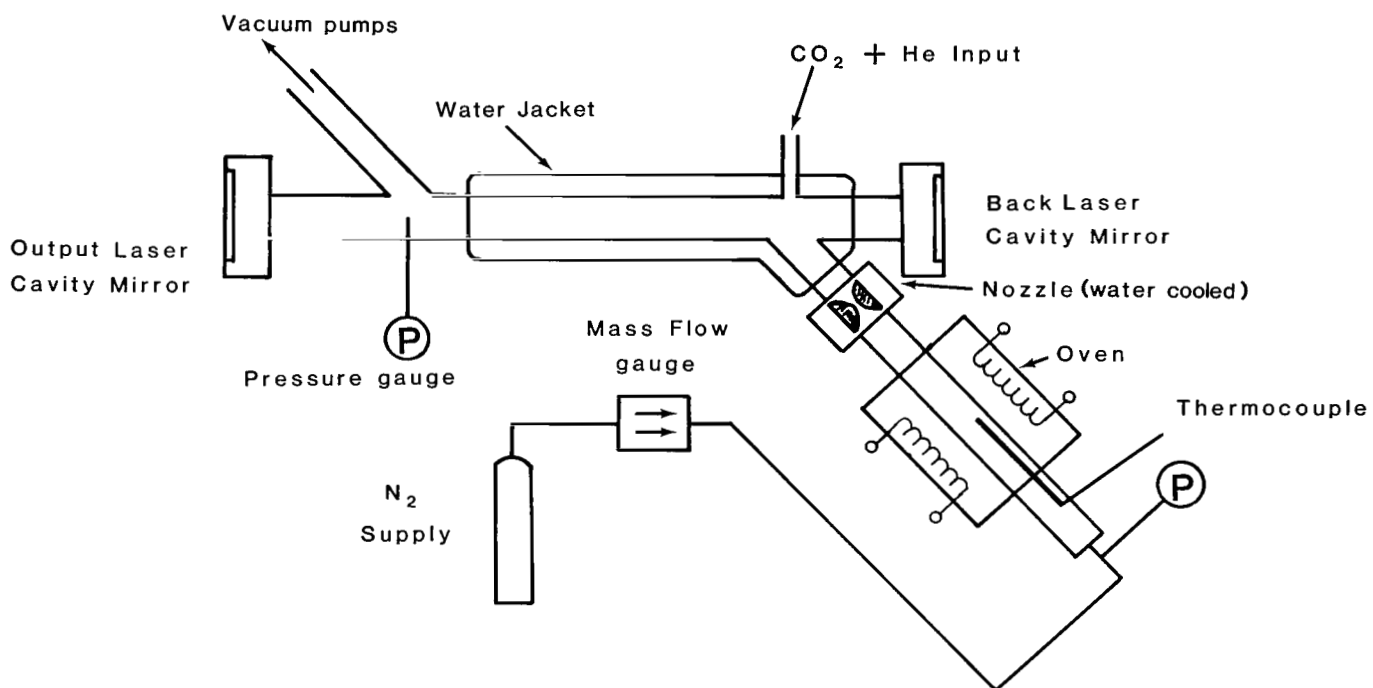Figure 1. A conceptual design of a space-based blackbody N_2-CO_2 transfer laser.

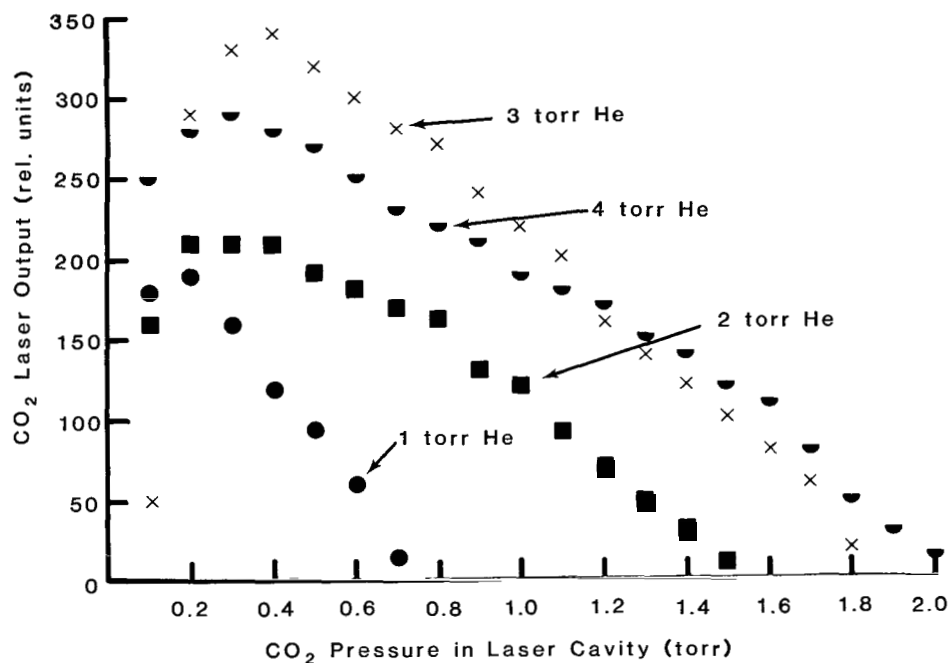Figure 2. Experimental setup of blackbody-pumped N_2-CO_2 transfer laser.

Figure 3. Laser output as a function of CO_2 and He partial pressures at a fixed N_2 pressure of 2.4 torr. The optimum partial pressure ratio was $1CO_2/7.5He/6N_2$.
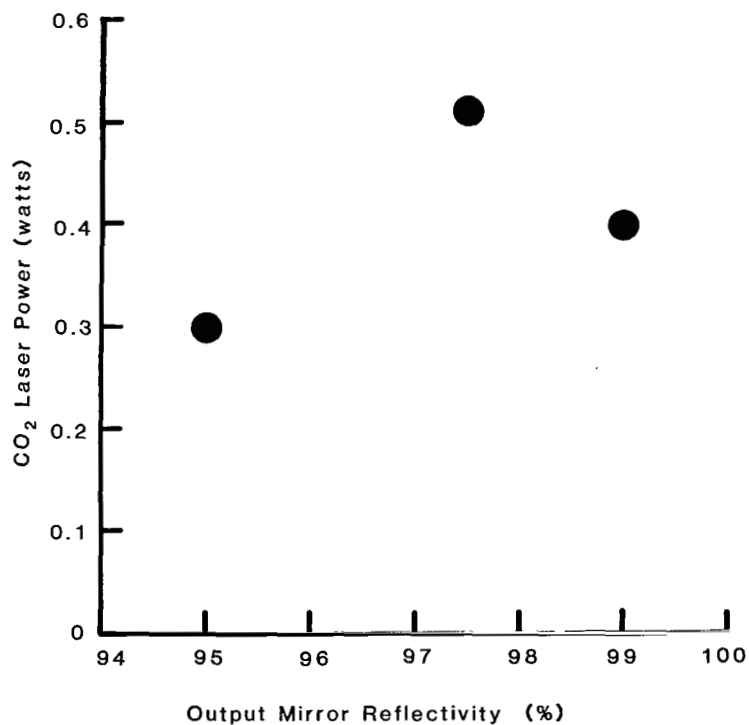

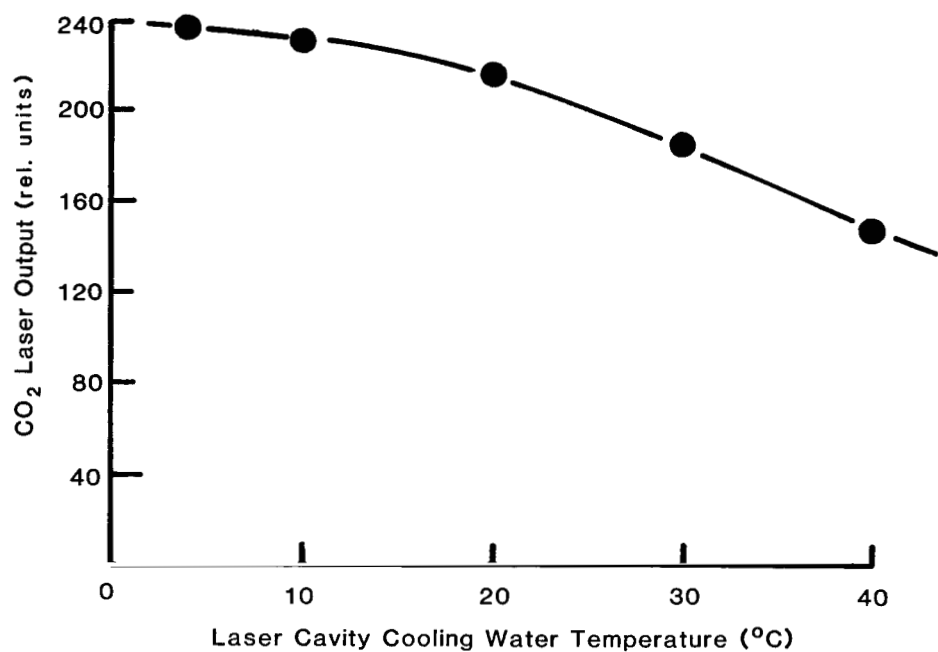Figure 4. Laser output as a function of output cavity mirror reflectivity.

Figure 5. Laser output as a function of water temperature in laser cell cooling jacket.
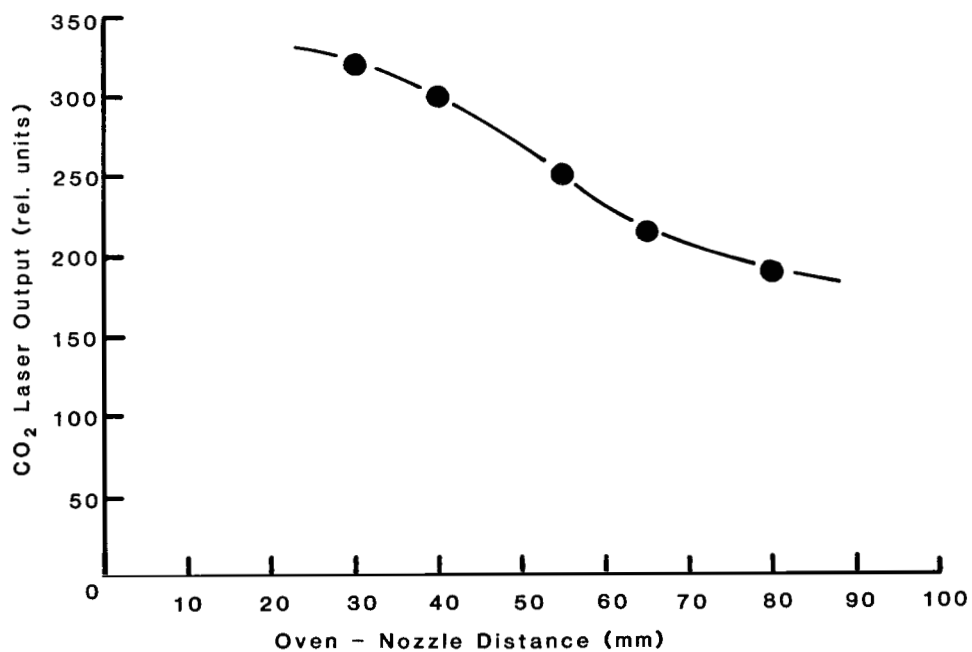

Figure 6. CO_2 laser output as a function of oven-to-nozzle distance.
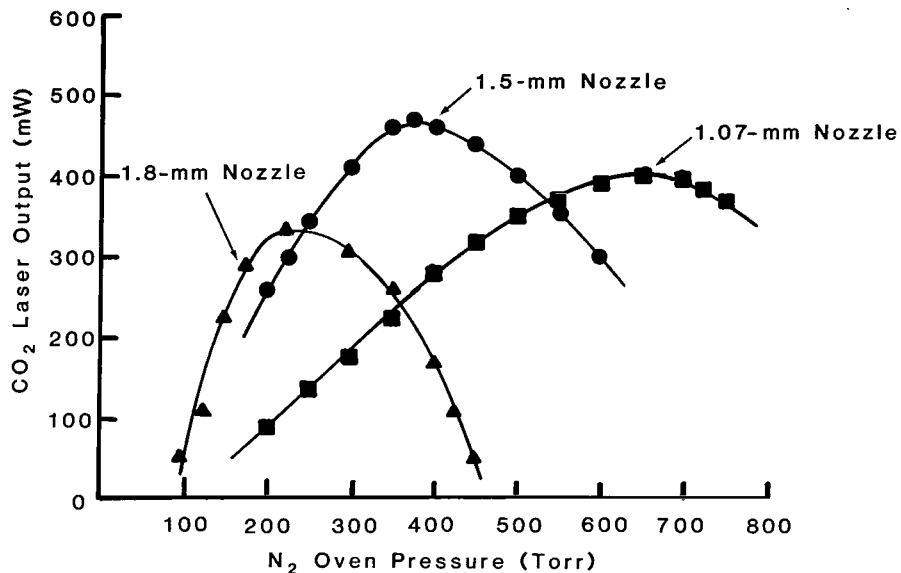
Figure 7. The effect on laser output of various nozzle throat diameters. He pressure was 4.5 torr, CO_2 pressure was 0.7 torr, and oven temperature was 1160°C.
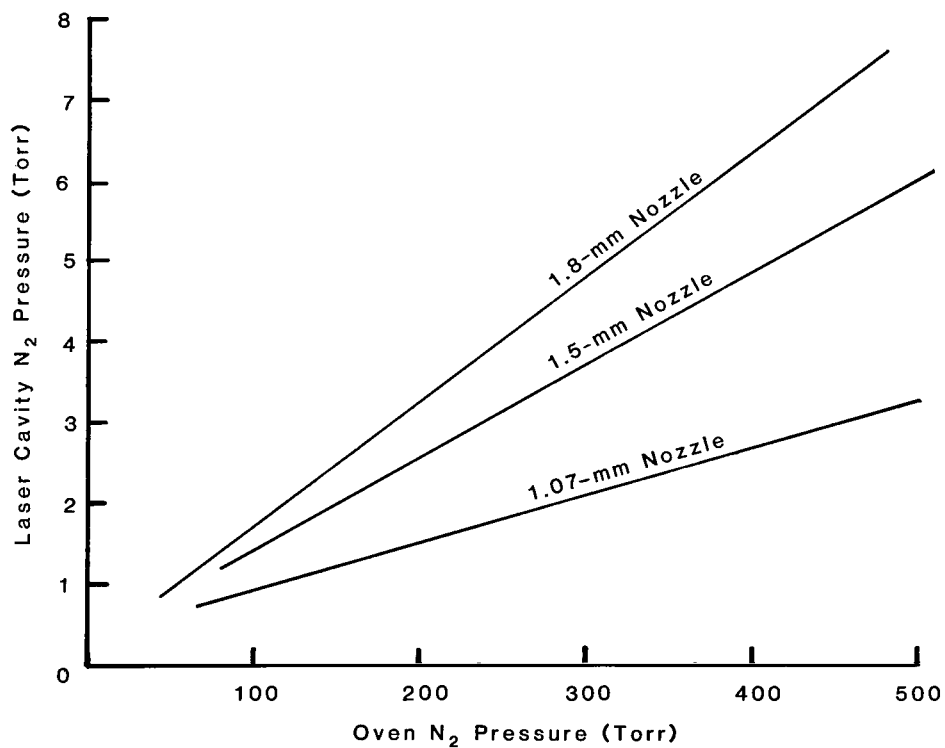

Figure 8. The relationship of N_2 pressure in the oven to the pressure in the laser cell for each nozzle diameter at a fixed oven temperature of 1160°C.
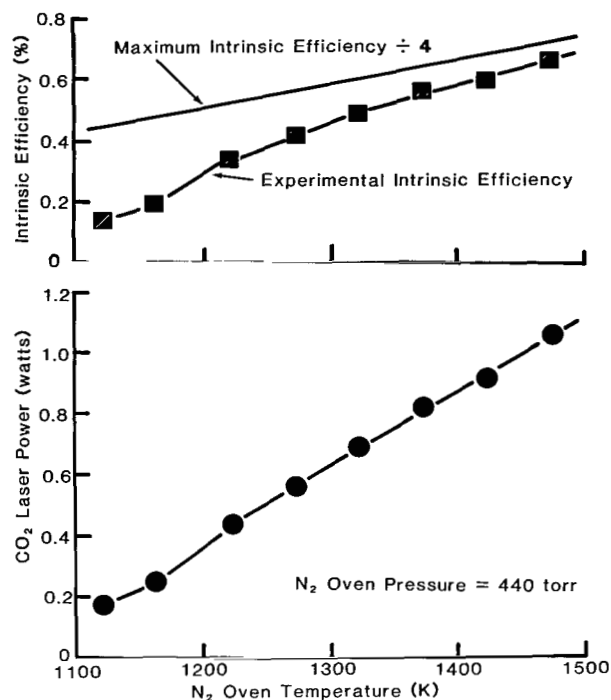
Figure 9. Laser output and experimental intrinsic efficiency as a function of oven temperature for a partial pressure ratio of $1CO_2/7He/5N_2$. The maximum intrinsic efficiency (eq. (1)) is also shown.
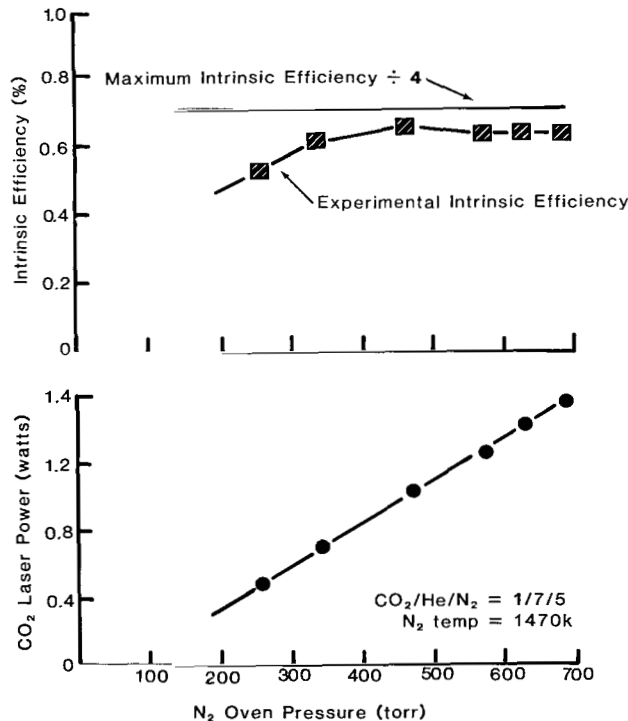
Figure 10. Laser output power and experimental intrinsic efficiency as a function of N_2 oven pressure for a fixed oven temperature of 1473 K and a partial pressure ratio of $1CO_2/7He/5N_2$. The maximum intrinsic efficiency (eq. (1)) is also shown.

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15. Supplementary Notes

16. Abstract

A compact blackbody-pumped CO_2-N_2 transfer laser was constructed and the significant operating parameters were investigated. Lasing was achieved at 10.6 μm by passing preheated N_2 through a 1.5-mm-diameter nozzle to a laser cavity where the N_2 was mixed with CO_2 and He. An intrinsic efficiency of 0.7 percent was achieved for an oven temperature of 1473 K and N_2 oven pressure of 440 torr. The optimum laser cavity consisted of a back mirror with maximum reflectivity and an output mirror with 97.5-percent reflectivity. The optimum gas mixture was $1CO_2$/$7.5He$/$6N_2$. The variation of laser output was measured as a function of oven temperature, nozzle diameter, N_2 oven pressure, He and CO_2 partial pressures, nozzle-to-oven separation, laser cell temperature, and output laser mirror reflectivity. With these parameters optimized, outputs approaching 1.4 watts were achieved.

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