Potential Efficiencies of Open- and Closed-Cycle CO, Supersonic, Electric-Discharge Lasers

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Computed open- and closed-cycle system efficiencies (laser power output divided by electrical power input) are presented for a cw carbon monoxide, supersonic, electric-discharge laser. Closed-system results include the compressor power required to overcome stagnation pressure losses due to supersonic heat addition and a supersonic diffuser. The paper shows the effect on the system efficiencies of varying several important parameters. These parameters include: gas mixture, gas temperature, gas total temperature, gas density, total discharge energy loading, discharge efficiency, saturated gain coefficient, optical cavity size and location with respect to the discharge, and supersonic diffuser efficiency. Maximum open-cycle efficiency of 80-90% is predicted; the best closed-cycle result is 60-70%.

I. Introduction

THE gas laser is being proposed for an ever-increasing number of important uses, such as cutting and welding, large-batch chemical processing, bedrock tunneling, long-range radar, and power transmission,[1] to name but a few. Many of the applications will require high-power lasers of reasonable efficiency. For example, Hansen and Lee[2] have discussed laser power stations in Earth orbit. Good efficiency will be especially important here because of the great expense of delivering the power source into orbit. For the same reason, a closed-cycle system will be required to conserve the laser gas. The requirements of high efficiency and high power in a closed-cycle system put exacting limits on the types of lasers that will satisfy them. As pointed out by Hansen,[1] the electric-discharge gas lasers are now the most efficient, whereas the purely gasdynamic type is the most powerful. He, therefore, suggests combining these two types into a hybrid laser, in which the electric discharge efficiently creates a population inversion, and a supersonic expansion is used to cool the gas, enhance the inversion, and convect the waste energy away. Such a laser can also conceptually be made into a closed-cycle system.

Burns[3] has performed an extensive thermodynamic analysis of such a gas laser operating in space (as well as a purely gasdynamic type). In that study he predicts the effect of laser performance on closed-cycle thermal efficiencies and heat rejection radiator sizes, but does not predict actual laser performance because he treats the properties of the laser as parameters that are varied over a certain range. If actual laser performance characteristics become available, however, then his report can be used to predict detailed system properties.

Perhaps the most efficient laser to date is the carbon monoxide, electric-discharge laser. Electrical-to-laser radiation conversion efficiencies exceeding 60% have been both predicted and measured for cryogenically cooled CO lasers.[4] More recently, hybrid CO, supersonic, electric-discharge lasers (CO SEDL's) have been proposed and developed. Plummer and Glowacki,[5] in a theoretical study, show that such a device may be capable of efficiencies exceeding 50% at high power. However, actual hybrid devices tested to date have not exceeded 20% efficiency.[4] This low efficiency is not too surprising in view of the small size of the devices thus far developed and the fact that the technology is very recent. The survey article by Mann[4] gives an excellent review of the many theoretical and experimental papers published to date on this laser. Overall, the CO SEDL appears an excellent candidate for a high-power laser system of reasonable efficiency that can be used in either an open or closed cycle.

Although the many theoretical studies just referred to predict a high efficiency for the CO SEDL, none of them varied the parameters for the laser over a wide enough range to show systematically how its efficiency depends on these parameters and what its ultimate efficiency might be. Also, no study, to the author's knowledge, has yet investigated the potential closed-cycle efficiency of the CO SEDL. There, the pressure losses associated with supersonic flow become critical, and the conditions that produce high, open-cycle laser efficiency will not necessarily give good closed-cycle efficiency. Accordingly, the purpose here is to predict the potential efficiencies of open- and closed-cycle CO SEDL systems by varying, over a wide range, many of the important parameters that describe the laser. System efficiency is defined here as the laser radiation power output divided by the electrical discharge power input plus, for closed cycle, the compressor power required. (Optimizing other laser characteristics such as wavelength may be important for some applications, but these are not considered in this study.) Variables examined include gas mixture, gas temperature, gas total temperature (or Mach number), gas density (or pressure), total discharge energy loading, discharge efficiency (or average electron energy), saturated gain coefficient (or average cavity loss coefficient), and optical cavity size and location with respect to the discharge. An additional variable examined for closed-cycle system is supersonic diffuser efficiency.

In Sec. II, the theory and assumptions are discussed. In Sec. III, the calculated results are discussed. Finally, in Sec. IV, the conclusions of this study are summarized.

II. Theory and Assumptions

The CO SEDL configuration is shown schematically in Fig. 1. The laser gas mixture is expanded from stagnation conditions, through a nozzle, to a supersonic Mach number. There, a cw glow discharge of a chosen downstream length is established across the flow. The discharge is assumed to be of a type that allows independent control of voltage gradient (or average electron energy) and current density (or electron density). The discharge thus consists of a sustainer electric field below that required for avalanche ionization (to maintain the desired electron energy), coupled with an auxiliary ionization source (to maintain the desired electron density). This last could conceivably be an electron beam,[6] an ultraviolet photoionization source,[7] a high repetition rate series of controlled avalanche ionization pulses,[8] or an auxiliary cw discharge covering the cathode.[9] As the gas flows through the

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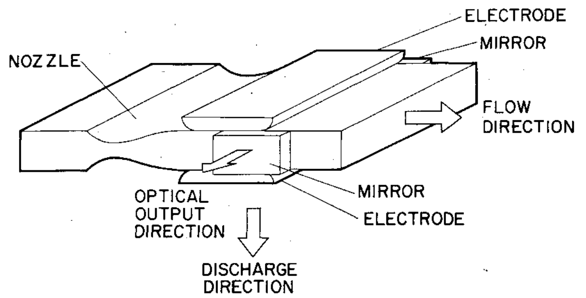

Fig. 1 CO supersonic electric discharge laser (CO SEDL).

discharge, it is excited vibrationally by the hot electrons, and many of the CO vibration-rotation lines become inverted. Finally, an optical cavity of chosen length is placed coincident with, or downstream of, the discharge to extract power in a laser beam.

Other configurations are possible. For example, the discharge can be located in the plenum,[10] or it can be repetitively pulsed.[11] Such schemes are not considered here, however.

The computer program used for this study was obtained from W.J. Glowacki of the Naval Ordnance Laboratory and is described by Plummer and Glowacki.[5] The program treats mixtures of CO with Ar or He. Briefly, the program integrates the differential rate equations describing the vibrational populations of CO along with the continuity, momentum, and energy equations. The integration provides the temperature and density of the gas and the vibrational populations as a function of position along the flow axis. The kinetics incorporated into the rate equations for the vibrational populations include all the major processes: excitation by electrons, V-V energy transfer, V-T energy transfer, and spontaneous and stimulated emission of radiation. The gain of each line is calculated from the known population densities and temperature and includes the combined effects of Doppler and pressure broadening. When the gain of a line reaches the optical cavity threshold loss, it is allowed to lase. Lasing is restricted to the single rotational line in each vibrational band which has the maximum small-signal gain at the gas conditions (although many bands may lase simultaneously). The intensity on each lasing line is adjusted to keep the gain saturated at the cavity loss value. Further details of the program may be found in Plummer and Glowacki.[5] For the present study, the program was run on a CDC 7600 computer. Running times varied from 3 sec to 3 min.

In this study, three changes were made in the computer program just described. The first change modified the CO V-V transition probabilities. In the original program, because of the first-order perturbation theory used for these collisions, the probabilities along and near the diagonal of the V-V matrix exceeded unity for only modest values of the vibrational quantum number. Because the first Born approximation used in the V-V theory assumes that the probabilities are small compared with unity,[12] the probabilities were truncated at 0.5 for this study. Other studies have followed a similar procedure.[13,14]

A second change in the program was to use different e-V rates. In the original paper, Plummer and Glowacki[5] used rates computed with a Boltzmann electron energy distribution. Here, the forward e-V rates were obtained from Proctor[15] at AFWL and are from exact solutions of the electron energy distribution function using the method described by Rockwood et al.,[16] but including updated electron excitation cross sections.

A final change introduced a discharge efficiency expression into the program. Plummer and Glowacki let all of the discharge energy go into the vibrational mode of CO. Thus, the only gas heating they predicted was due to molecular collision processes. Here, a heat source term was introduced into the energy equation in the manner described by Lordi et al.[10] The term contains all the discharge energy predicted to go into ionization plus electronic, rotational, and elastic excitation. The assumption was made that these energies immediately went into gas heating by neutral collision processes. A discharge efficiency was introduced and defined as the ratio of discharge energy added to vibration by forward processes, to the sum total added to all energy modes. The fractional energy transfer into ionization and electronic excitation was obtained from the previously described solutions of Proctor.[15] The fraction into rotational and elastic excitation was obtained from Eckbreth et al.[17]

It should be emphasized here that the computer program just described includes many reasonable but still speculative assumptions and approximations which may or may not be verified by future work. For example, the various V-V rates and optical-broadening cross sections are not well known at low temperatures.[10] Also, some electron excitation cross sections are poorly known; and the model neglects changes in the initial gas composition resulting from electron-excited-state interactions, electron pumping from excited CO states, and coupling of the discharge with the flow equations, all of which could result in changing plasma properties in the discharge.[19] Other approximations include neglecting multiquantum rotational transitions,[21] resonance self-absorption,[4] and several "realistic" optical cavity effects, such as the influence of curved mirrors, diffraction, mode structure, and multiple rotational line lasing within each vibrational band. Following presentation of the results, their sensitivity to many of these factors will be discussed.

A schematic of the closed-cycle CO SEDL system considered here is shown in Fig. 2. Beginning the cycle at the laser stagnation conditions, the gas is accelerated to supersonic speeds in the laser channel, after which the discharge and other collisional processes add heat to it. The heat addition raises the gas temperature, lowers the Mach number, and causes a loss of total pressure. The pressure loss due to heat addition is computed by standard methods.[10]

The laser channel is followed by a supersonic diffuser of chosen design, which causes additional total pressure losses. Most results given here are for the simplest (and least efficient) type possible, i.e., a normal shock at the laser exit conditions followed by a subsonic diffuser. A few results are also shown for a very efficient diffuser to determine the importance of diffuser design to closed-cycle system efficiency. This last type is a variable-throat diffuser with a wedge-shaped entrance. The gas thus flows through two oblique shocks, followed by a normal shock and a subsonic diffuser.[18] The wedge angle is always adjusted to give maximum pressure recovery from the laser exit conditions. The pressure loss for either type of diffuser is computed by standard methods.[18]

Following the diffuser, the rest of the cycle simply returns the gas to the original stagnation conditions. The first heat exchanger cools the gas to the original stagnation temperature

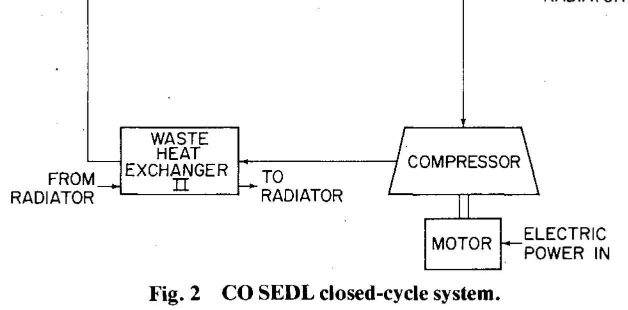

Fig. 2 CO SEDL closed-cycle system.

Table 1 Reference case conditions[a]

1)	CO mole fraction = 0.1
2)	Ar mole fraction = 0.9
3)	Gas total temperature = 300 K
4)	Gas freestream temperature = 65 K
5)	Gas freestream number density = 4.4×10^{18} cm $^{-3}$
6)	Average electron energy = 0.5 eV
7)	Electron number density = 5×10^{12} cm $^{-3}$ (produces a discharge energy loading of 1.32 eV/CO molecule for this case)
8)	Discharge efficiency = 0.96
9)	Length of discharge region = 15 cm
10)	Length of optical cavity = 20 cm (measured from start of discharge)
11)	Saturated gain coefficient = 0.0025 cm $^{-1}$ (also average cavity loss coefficient)

[a]Unless otherwise stated, the above conditions apply to all cases in this study.

(this reduces the required compressor power), then the compressor isentropically compresses the gas to the original stagnation pressure. (The work done by the compressor is simply the total enthalpy change occurring in this process. Further details may be found in Ref. 3.) Finally, the second heat exchanger once again cools the gas to the original stagnation temperature. (Other heat exchanger arrangements are possible, but Burns[3] shows that they produce only minor changes in system efficiency.) In this study, no compressor inefficiencies or other pressure losses due to friction, flow in the heat exchanger, etc., are included in the closed-cycle results. Such losses would be quite small compared to the losses that are associated with supersonic heat addition and the diffuser, but they should be considered in more detailed system studies. If he so desires, the reader can include these other losses as a fraction of the compressor power in the results to be shown for closed-cycle systems. Also, results using actual measured supersonic diffuser pressure-recovery ratios are not included, since they would be somewhere between the extremes considered here.

III. Results and Discussion

CO SEDL open- and closed-cycle system efficiencies (laser output power divided by electrical input power) have been computed using the methods described in Sec. II. Reference conditions chosen for the calculations are given in Table 1. Exceptions to the stated conditions are noted in each particular figure. Most of the conditions are separately varied over a certain range to show how they affect efficiency. For example, pure CO and mixtures of CO-He and CO-Ar are examined. Gas total temperature is checked at 300 and 650 K. Gas freestream temperature is set at 30, 65, and 100 K. (Of course, to operate much below 65 K would require a supersaturated gas. This possibility will be discussed later.) Gas freestream number density is varied from 0 to 30×10^{18} cm $^{-3}$. The average electron energy is set at 0.5 eV. This energy produces the highest discharge efficiency (96%) possible. (Lower energies produce too much elastic and rotational excitation, whereas higher values cause too much ionization and electronic excitation.) The discharge efficiency is also varied from 65 to 100%. The length of the discharge is set at 15 cm. The electron number density is varied from 0 to 4×10^{13} cm $^{-3}$. (Together with the stated electron energy and discharge length, this range of electron density produces discharge energy loadings between 0 and 3.3 eV/CO molecule, depending on the gas mixture.) For most results, the optical cavity is set at a length of 20 cm, beginning at the discharge leading edge. A few results are shown for different lengths and positioning with respect to the discharge. Finally, the saturated gain coefficient is varied from 0.001 to 0.1 cm $^{-1}$.

The effect on system efficiency of different gas mixtures and gas temperatures is shown in Figs. 3-7. The format is the same for all figures: system efficiency is plotted versus

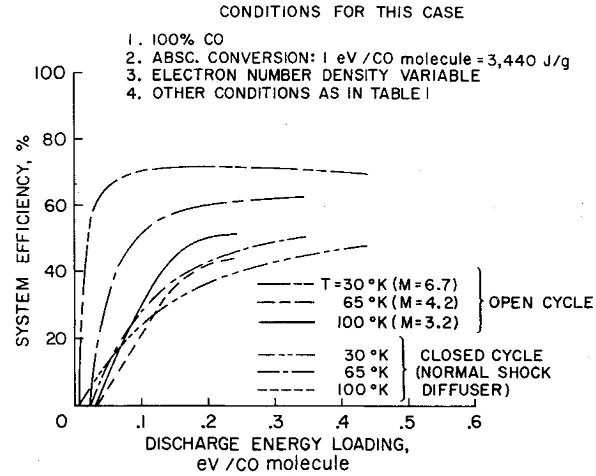

Fig. 3 Open- and closed-cycle system efficiency for CO SEDL with 100% CO.

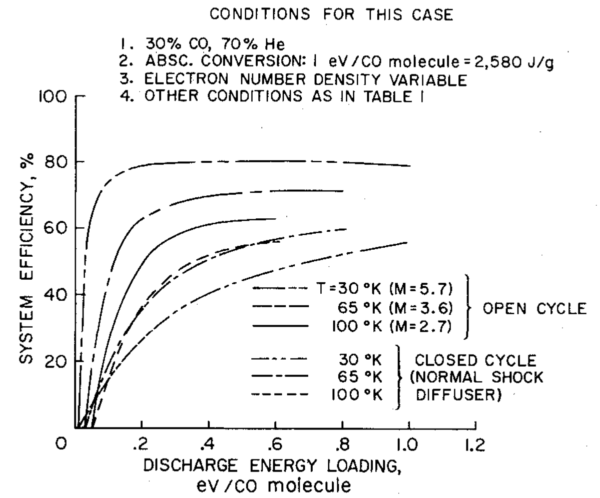

Fig. 4 Open- and closed-cycle system efficiency for CO SEDL with 30% CO, 70% He.

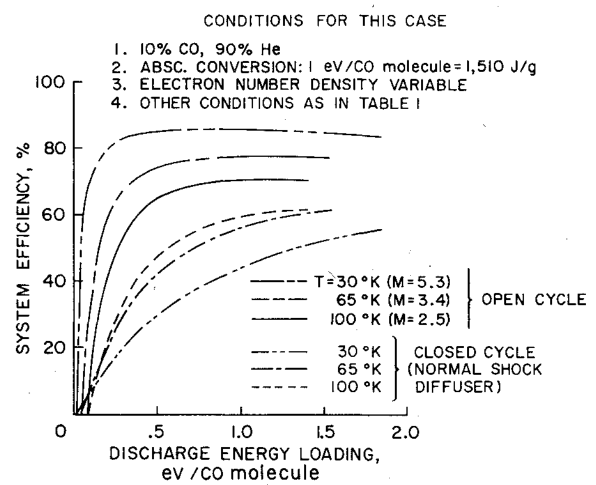

Fig. 5 Open- and closed-cycle system efficiency for CO SEDL with 10% CO, 90% He.

discharge energy loading. (The energy loading is varied by changing electron number density.) Curves are given for open- and closed-cycle systems. The closed-cycle results are for a normal-shock diffuser. Results are given for initial freestream gas temperatures T of 30, 65, and 100 K. Corresponding Mach numbers M are given in parentheses. Each curve is extended to energy loadings that produce choked flow due to heat additon. For convenience, the con-

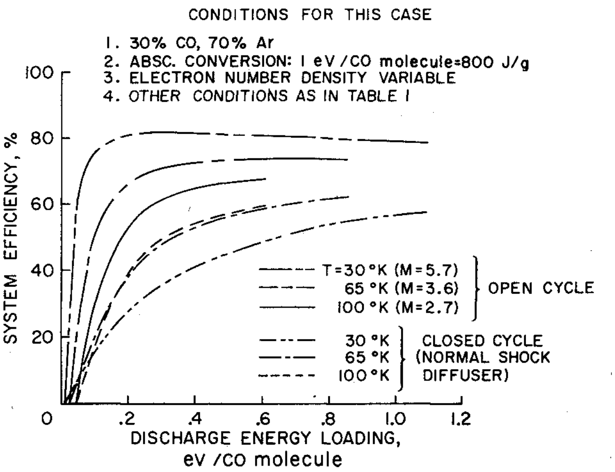

Fig. 6 Open- and closed-cycle system efficiency for CO SEDL with 30% CO, 70% Ar.

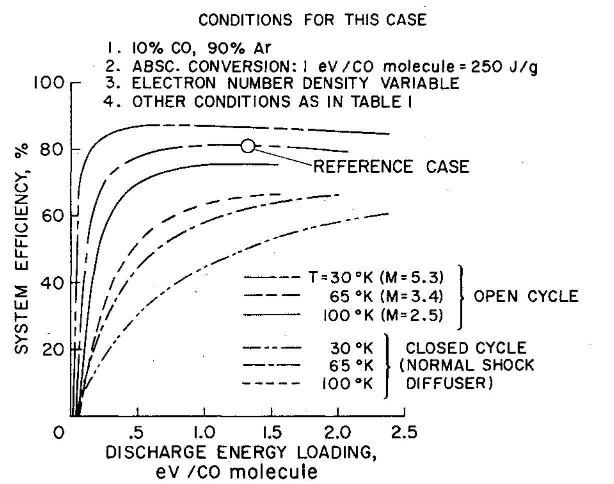

Fig. 7 Open- and closed-cycle system efficiency for CO SEDL with 10% CO, 90% Ar.

version of discharge energy loading in eV/CO molecule into joules/gram is listed for each mixture. Conditions not listed on the figures are given in Table 1.

The results for 100% CO are shown in Fig. 3. Consider the open-cycle results. For each temperature, there is a threshold discharge energy above which the laser turns on. This energy decreases with lower temperature. Above threshold, the efficiency increases rapidly with increased energy loading. Eventually, the efficiency levels off and may actually decrease with increased energy loading due to higher gas temperatures. The best efficiency (72%) is for the lowest gas temperature, 30 K. Other potential advantages of lower temperatures are that they produce high efficiencies at lower energy loadings, and they also allow higher energy loadings before choking occurs.

Consider the closed-cycle results in Fig. 3. Efficiencies are lower than for the open cycle because compressor powers are now included. A peak efficiency of 51% occurs for a gas temperature of 65 K. Lower temperatures (and higher Mach numbers), which produce higher open-cycle efficiencies, now produce increased total pressure losses, which result in worse system performance. Also notice that, for a given temperature, the maximum closed-cycle efficiency always occurs at the maximum energy loading (i.e., at choked flow) because the required mass flow (and compressor power) is at a minimum for a given laser output power.

In Fig. 4, results are shown for a mixture of 30% CO and 70% He. The maximum open-cycle efficiency increases to 81% for a gas temperature of 30 K; the best closed-cycle efficiency increases to 60% at 65 K. Also, compared to pure CO, higher discharge energy loadings are achieved here before choking occurs. The improved results are due to the He acting as a heat sink, which reduces the temperature rise in the gas for a given energy loading. (This benefit, however, is obtained at the expense of greatly increased flow speeds with He, which, in turn requires increased electron number densities to reach a given energy loading.)

The effect of a further reduction in CO content is shown in Fig. 5 for 10% CO and 90% He. The maximum open-cycle efficiency increases to 86% at a temperature of 30 K; closed-cycle efficiency increases slightly to 61% at either 65 or 100 K. Also, compared to the previous case, higher energy loadings are reached before choking. Leaner mixtures of CO and He may give further slight increases in efficiency, but they were not calculated. Eventually, however, one would expect the decreased gain associated with lower CO fractions to result in lower efficiencies.

Rather than using He as a diluent in a CO SEDL, one may use Ar. Results for a mixture of 30% CO and 70% Ar are shown in Fig. 6. A peak open-cycle efficiency of 82% is achieved at a gas temperature of 30 K; the best closed-cycle result is 62% at 65 K. These results are slightly better than for the equivalent mixture with He (see Fig. 4) because of the slower gas speeds (and longer residence times) when using Ar in the laser. A longer residence time (for given length mirrors) allows more of the stored vibrational energy to be lased before it is dumped downstream. Another advantage of the slower speeds with Ar compared to He is that a given energy loading (in eV/CO molecule) may be reached with a lower electron density. A potential disadvantage of Ar compared to He, however, may be the higher mass flow rates required with Ar to reach a given output power (i.e., compare energy loadings in joules/gram for the two mixtures), which could be important for some weight-limited, open-cycle applications.

The effect of a lower fraction of CO in CO-Ar mixtures is shown in Fig. 7 for 10% CO and 90% Ar. A peak open-cycle efficiency of 88% is reached at a temperature of 30 K; the peak closed-cycle result is 67% at either 65 or 100 K. This mixture provided the best results obtained in this study. Also indicated on the figure is the result for the reference case conditions in Table 1.

The discussion thus far has concerned the effects of gas mixture and temperature on open- and closed-cycle system efficiencies for CO SEDL's. The remaining discussion (Figs. 8-13) considers the effect on efficiency of varying the other parameters listed in Table 1 for 10% CO and 90% Ar. (Exceptions to the conditions in Table 1 are noted in the figures.) In some figures, only open-cycle results are shown. However, closed-cycle results will scale up or down proportionately. Although the results are for the reference case conditions, other mixtures and/or temperatures should exhibit qualitatively similar behavior.

The effect of increasing the gas stagnation temperature T_t to 650 K from 300 K is shown in Fig. 8. (High stagnation tem-

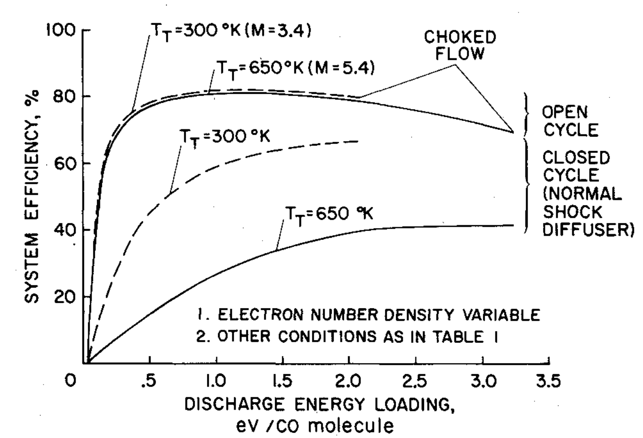

Fig. 8 Total temperature effect on open- and closed-cycle system efficiency for reference case CO SEDL with 10% CO, 90% Ar.

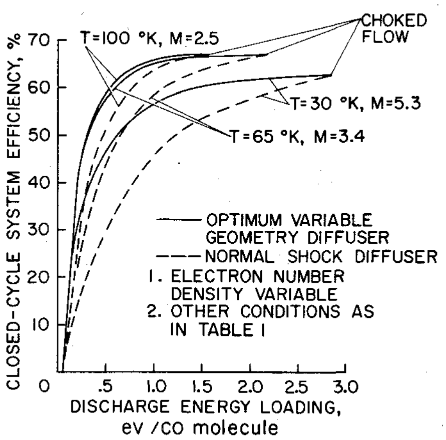

Fig. 9 Supersonic diffuser effect on closed-cycle system efficiency for reference case CO SEDL with 10% CO, 90% Ar.

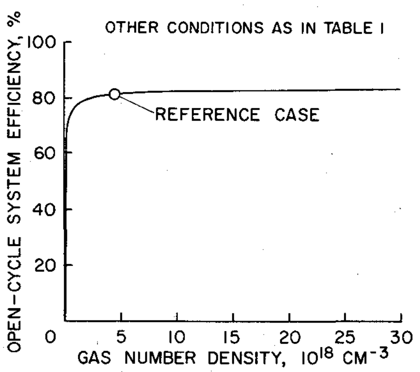

Fig. 10 Gas density effect on open-cycle system efficiency for reference case CO SEDL with 10% CO, 90% Ar.

peratures are advantageous in closed systems for efficiently rejecting waste heat, particularly in space, where radiators must be used.[3]) The open-cycle results are about the same for either total temperature. (The slight decrease observed for 650 K arises from the higher flow speeds for that case – an effect previously observed when comparing He mixtures against Ar.) The higher total temperature does allow a larger energy loading before choking occurs. In contrast to open-cycle results, the closed-cycle results show a large decrease in efficiency for the higher stagnation temperature because of the much larger compressor powers required. Two things cause this: first, the higher Mach number causes greater total pressure losses in the supersonic diffuser and in the discharge where heat is being added; second, for a given pressure ratio across the compressor, a larger enthalpy change in the gas occurs at higher temperature.

The effect of replacing the normal-shock diffuser in a closed-cycle system with an efficient, variable-geometry diffuser is shown in Fig. 9. The results show that the variable-geometry diffuser improves the efficiency over most of the energy loading range, but not at choking, where the peak efficiencies still occur (at choking the Mach number is already unity). For energy loadings less than the value at choking, the best efficiencies are at a gas temperature of 100 K. At that temperature, the variable-geometry diffuser gives only slightly better performance than a normal-shock diffuser.

The effect of varying the gas number density is shown in Fig. 10. Above a density of $3\text{-}5 \times 10^{18}$ cm^{-3}, the efficiency is independent of density. Below that range, efficiency falls off because the lower collision frequency in the gas reduces the rate at which the stored vibrational energy can feed into the lasing lines, and also because the small-signal gain of the inverted lines decreases as Doppler broadening becomes dominant.

In Fig. 11, the result of changing the discharge efficiency from 96% is shown. (The energy loading is reduced from the value in Table 1 to allow a greater range of discharge efficiency to be examined without having choked flow.) The dashed line represents the efficiency that could be obtained if all the energy that goes into vibration could be obtained as laser energy. The solid curve for the actual laser shows a large falloff in system efficiency for decreasing discharge efficiency primarily because of the increasing gas temperature rise through the discharge. The results show the importance of operating a CO SEDL at the highest discharge efficiency possible. For example, the discharge efficiency range for a self-sustaining glow discharge has been estimated from CO ionization and dissociative attachment rate calculations,[15] and the range is shown on the figure. The results indicate that this CO SEDL, operating with a self-sustaining discharge, will only achieve efficiencies between 20 and 42%. The results also show that failure to achieve the maximum discharge efficiency of 96% predicted here will considerably decrease the CO SEDL system efficiencies. The experimental evidence on the validity of this discharge model is mixed at present. Jones et al.[6] measured gas heating in agreement with theory, whereas Lordi et al.,[10] as well as Plummer et al.,[20] measured significantly greater discharge heating than expected. Clearly, accurately predicting discharge efficiency and heating remains an important question to resolve in the future.

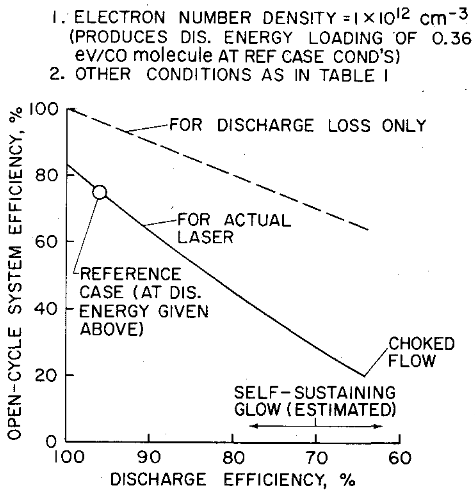

Fig. 11 Discharge efficiency effect on open-cycle system efficiency for reference case CO SEDL with 10% CO, 90% Ar.

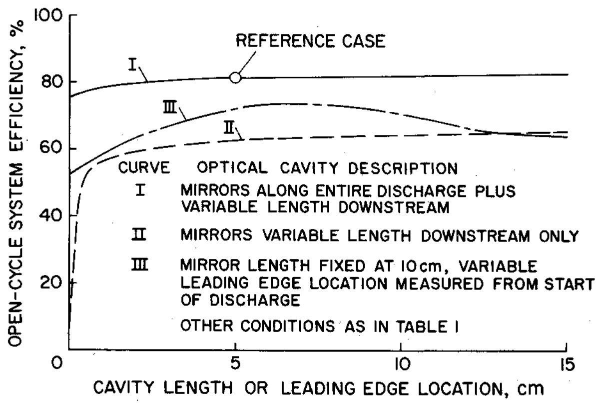

Fig. 12 Optical cavity length and position effect on open-cycle system efficiency for reference case CO SEDL with 10% CO, 90% Ar.

Thus far, all results have been for an optical cavity of fixed length and position. Figure 12 shows the result of changing the cavity length and position. Curve I shows the effect of changing the downstream length of the reference cavity. Lengthening the mirrors fails to increase the efficiency very much. Shortening the mirrors to the length of the discharge causes some efficiency falloff since, in that case, more stored vibrational energy escapes downstream before it can be lased. Curve II shows the effect of varying the length of a down-

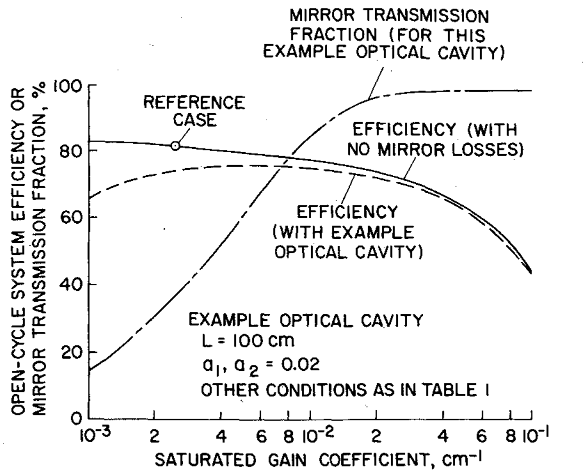

Fig. 13 Saturated gain effect on open-cycle system efficiency for reference case CO SEDL with 10% CO, 90% Ar.

stream cavity that starts at the end of the discharge. The efficiency does not increase for mirrors much longer than 2-4 cm. The achievable efficiencies are quite a bit lower than for curve I, however. With downstream mirrors, too much vibrational energy gets fed into noninverted, high-vibrational levels where it is unavailable for lasing once the cavity is reached. A similar problem would exist for a discharge in the plenum.[10] Finally, curve III is for mirrors with a fixed length of 10 cm. The curve shows the effect of changing the placement of the mirrors with respect to the discharge. (The results are of practical interest if one has mirrors of fixed length and wants to know where they should be placed for best efficiency.) The results show that the cavity leading edge should be 5-9 cm downstream from the start of the discharge for best performance. The efficiencies are still lower than for curve I, however.

A final question that will be discussed is the effect on efficiency of varying the saturated gain coefficient. Before considering this, the saturated gain coefficient α will be related to the optical cavity parameters usually dealt with. Consider a cavity with mirror spacing L, one mirror with transmission fraction t_l and loss coefficient a_l, and a second mirror with loss coefficient a_2 (losses can include absorption, scattering, edge diffraction, etc.). The Fabry-Perot cavity (flat mirrors) model considered here has its optical axis perpendicular to the flow direction. This approximate model neglects the radiative coupling between different points in the flow direction which occurs in a curved mirror system (or when diffraction is considered). Furthermore, the approximate model assumes that the saturated gain on lasing transitions is independent of distance in the direction of the optical axis. Within the limits of this approximate model, the cavity parameters are related to the saturated gain coefficient by[10]

$$2\alpha L = -\ln[(1-a_l-t_l)(1-a_2)] \quad (1)$$

Also, the only useful output from the laser is the radiation transmitted out, not that going into mirror losses. This useful fraction can be defined as a cavity efficiency ϵ_c and written as

$$\epsilon_c = t_l/[t_l + a_l + (a_2 - t_l a_2 - a_l a_2)\exp(\alpha L)] \quad (2)$$

In Fig. 13, the results are presented for a variation in the saturated gain coefficient. The solid curve gives the open-cycle system efficiency with no mirror losses. The efficiency continually increases with decreasing saturated gain because, with a decreased threshold, more lines can lase and more energy can be extracted from each line downstream of the discharge.

With a real optical cavity, however, a smaller saturated gain will not necessarily provide more useful output. To illustrate this, consider the example optical cavity in Fig. 13. The mirror transmission fraction is solved from Eq. (1) and is shown as the dashed-dotted curve in the figure. Knowing the transmission fraction, a cavity efficiency is obtained for each value of saturated gain coefficient using Eq. (2). The cavity efficiency is multiplied by the efficiency with no mirror losses (solid curve) to obtain the dashed curve shown in the figure. This curve is then the system efficiency for a CO SEDL with the example optical cavity. In this example, the best efficiency is obtained for a saturated gain coefficient 0.004-0.01 cm^{-1} (with a corresponding transmission fraction of 52-84%). Below this range, too much radiation goes into mirror losses; above this range, fewer inverted lines exceed the threshold gain. The results illustrate the importance of large size and/or low mirror losses, together with the correct choice of mirror transmission fraction for obtaining efficient operation of CO SEDL's.

Although the present results suggest that high efficiencies may be possible for CO SEDL's, recall that the physical model included a number of assumptions and approximations. Improvement of these in the future could change the efficiencies from those given here. It has already been shown how sensitive the system efficiencies are to discharge efficiency. Fortunately, the system efficiencies are probably much less sensitive to many of the other rates, cross sections, and modeling assumptions in the program (the same can not be said for detailed spectral output or small signal gain). As has been pointed out by Lacina et al.,[4] and others, the total output power or efficiency of a CO laser depends more on the input power loading than it does on the detailed plasma properties or various kinetic rates or cross sections. This effect was observed in a limited way in the present study by recomputing several cases with considerably different V-V rates or electron excitation rates. Very little change in efficiency occurred as long as results were compared at the same energy loading and discharge efficiency. (This also implies that any combination of electron density and discharge length that produces the same energy loading should give about the same output power in a CO SEDL.) Also, the reference case given in Table 1 was recomputed using the recent low-temperature line width measurements of Varanasi.[23] Although changing the line widths reduced the small-signal gains for that case (without mirrors) by 32%, the system efficiency (with mirrors) decreased by less than 0.4%. These same line width computations were also used to estimate the possible effect of resonance self-absorption in the reference case CO SEDL. The present line widths are about an order of magnitude narrower than for an example given by Mann,[4] which showed less than a 10% reduction in laser efficiency due to self-absorption. Thus, resonance self-absorption is probably not important at the low pressures usually considered for CO SEDL's. The present study would, thus, appear to give a reasonable first approximation to expected system efficiencies of open- and closed-cycle CO SEDL's.

Before efficient high-power CO SEDL's become a reality, many tough experimental problems must first be overcome. Probably the most difficult of these is the production of large-volume, uniform glow discharges of the required energy loading and electron energy in the low-temperature supersonic gas within the laser. Recent experimental work of Jones et al.[6] gives hope that this can be done, however, as they have already achieved in a pilot facility CO SEDL an energy loading of 0.6 eV/CO molecule and an electron density of 2×10^{12} cm^{-3} with a mixture of 10% CO and 90% Ar. Other possible discharge-related problems include how to prevent arc breakdown through low-density boundary layers,[6] how to prevent the creation of undesirable discharge-generated minority species that cause arcing,[22] and how to shape electrodes for a uniform discharge while at the same time keeping them flush to the supersonic-flow channel so that the gas is not disturbed.

Problems in other areas include: possible condensing of CO at very low temperatures; developing mirrors and windows that withstand a high cw radiation flux; cooling of electrodes, mirrors, and windows; producing a uniform density field in the presence of boundary layers, discharge heating, and protuberances such as electrodes and mirrors; and designing optical cavities that produce diffraction-limited output beams that fill the required volume within the laser for high efficiency. (With regard to the possible condensing out of the gases at very low temperatures, Lordi et al.[10] have successfully operated a CO SEDL at 40 K with no evidence of saturation. In any case, one could avoid the problem completely by starting the discharge at a lower Mach number and continuing to expand the flow through the heated discharge region. The resulting nearly linear downstream density variation could be compensated for in the optical cavity by simple mirror tilting.) Finally, required supersonic diffusers, compressors, and heat exchangers must be developed for closed-cycle systems.

IV. Conclusions

This investigation shows that a CO SEDL may achieve an open-cycle system efficiency of 80-90%. Mixtures with a low fraction of CO (i.e., about 10%) in a diluent of He or Ar work best. For a given length laser, Ar gives slightly better efficiency and requires lower electron density, whereas He provides superior mass utilization. Efficiency improves with decreased gas temperature (at least to the lowest temperature of 30 K computed here). For any given temperature, peak efficiency is flat over a wide range of discharge energy loading (as long as the turn on threshold value is exceeded by a moderate amount). Stagnation temperature and gas density have little effect on efficiency. High system efficiency depends critically upon operating at as high a discharge efficiency as possible (i.e., at a correct voltage). Achieving a high discharge efficiency requires discharge techniques that separately control electron density and average electron energy (i.e., non-self-sustaining methods). A given result for system efficiency is shown to depend only weakly on the detailed excitation rates and various kinetic rates and cross sections in the theoretical model as long as the discharge energy loading and discharge efficiency are kept the same. Therefore, any combination of electron (or current) density and discharge length in a CO SEDL that produces the same energy loading should give the same result.

The design of the optical cavity in a CO SEDL is shown to be important for achieving maximum system efficiency. The best optical cavity has mirrors that "cover" the discharge and also extend further downstream a short distance. With downstream mirrors only, (i.e., a split configuration) the efficiency is reduced considerably. For fixed-length mirrors shorter than the discharge, the best efficiency is obtained when the trailing edge of the mirrors extends slightly downstream from the end of the discharge. For best efficiency, the optical cavity should also have the proper value of saturated gain (or mirror transmission fraction). This value depends on the spacing and losses of the mirrors. Knowing these parameters, criteria are given in the paper for choosing the correct mirror transmission fraction.

Closed-cycle system efficiencies of 60-70% are predicted. Maximum efficiency here occurs at the maximum discharge energy loading possible (i.e., at choked flow) and at gas temperatures of 65-100 K. Unlike open-cycle systems, efficiency here critically depends on operating at as low a stagnation temperature as possible. Supersonic diffuser design has no effect on the maximum efficiencies achievable (because that always occurs when the flow is choked). Efficiency at lower energy loadings can be improved only slightly by going from a normal-shock diffuser to an efficient variable-geometry diffuser. The rest of the conclusions given for open-cycle systems also apply to closed-cycle systems.

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