Photon Generators and Engines for Laser Power Transmission

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The basic thermodynamics of thermal gas dynamic lasers are reviewed, and it is shown that an efficient coherent photon generator can be developed on a closed cycle principle. The efficiency limits of such a device are explored, and the results of the analysis indicate that the production efficiency of coherent radiation from heat can, in the limit of high-component efficiency, be equal to that of the production of work from heat. An indispensable element of any power transmission system also involves an engine capable of converting transmitted laser energy into useful work. It is shown that a closed cycle system may also be developed in principle which can convert transmitted laser radiation into work with an efficiency approaching one.

Introduction

ONE of the dreams of engineering is the wireless transmission of power. The concept has been a constantly reoccurring theme since the original contribution of Hertz. The development of efficient, high-frequency oscillators has created techniques of beaming energy so that, in a limited sense, wireless power transmission has already been achieved. However, with the development of the laser, much higher frequencies can be generated, and with relatively small optical systems energy may be beamed with little loss for many thousands of kilometers. It thus becomes an engineering possibility to consider the remote operation of machinery by radiant energy power transmission. A host of applications immediately suggest themselves. These range from supplying power to satellites from power plants on Earth, or the reverse, to the remote operation of vehicles of various types such as aircraft supplied by a power plant at a distant point or even in space with possible ecological advantages. The authors are fully aware of the apparent radical nature of these statements and of the many attendant problems of costs, atmospheric transmission, limitations on pointing, and beam divergence. Nonetheless, it would have been facetious prior to the existence of the laser to even reach this level of discussion.

To explore the possibility of power transmission using lasers, this paper will examine the theoretical efficiency limits by which coherent radiation can be generated, and reused as available work. Specifically, thermal lasers of the gasdynamic type using N_2 and CO_2 gas mixtures will be examined using a conceptual coherent photon generator involving rapid expansion processes leading to laser action. It will be shown that the efficiency of such a photon generator can be, in principle, very high; and in the limiting case, the entire amount of work provided to the generator can be converted to laser radiation. Although practical restraints will limit efficiencies, the photon generator does allow us to examine the factors that limit efficiency and to set the goals that we should try to achieve.

An indispensible part of any power transmission system involves not only a generator, but also an engine or device which can receive the light energy and transform it to a usable form. One of the principal barriers to radiant power transmission is the limited thermal efficiency that results if the radiant energy is only used as thermal energy. Here the normal limitations of materials will limit the efficiency of reconversion to between 30% and 40%. What is needed, therefore, is an engine which can be operated directly by radiation at reasonable energy densities and with the possibility of high efficiency. In order to achieve this capability, a device called the photon engine will be described. It can provide a useful function in controlling and transforming coherent radiation. As stated previously, these devices are developed around the operating principle of fluid mechanical thermal lasers, often called gasdynamic lasers, utilizing N_2 and CO_2 gas mixtures as the working fluid.

In the following sections thermal lasers of the N_2–CO_2 type will be described in sufficient detail to develop the concept of a generator which can, in the most efficient manner possible, convert heat to coherent radiation. Utilizing this as a basis, a description will be given of the photon engine which can reconvert laser radiation back to useful work with an efficiency approaching one.

Thermal Lasers

The suggestion that an electronic population inversion could be obtained in a gas was first put forward by Javan[1] in 1959 following the historic paper of Schawlow and Townes.[2] This work led to the development of the first successful gas laser in which electrically excited helium metastables were used to preferentially pump a specific level in neon so that a population inversion was achieved.[3]

In 1962, while examining the processes leading to nonequilibrium in expanding flows, Hurle, Hertzberg, and Buckmaster[4] pointed out that it should be possible to create a population inversion in electronic states by the rapid adiabatic expansion of a gas. If a sufficient equilibrium population of the necessary excited states exists, the rapid expansion could create conditions whereby the population of an upper state would remain essentially frozen, provided that the rate of de-excitation of the upper state was slow compared to the cooling rate. If, at the same time, the lower state could be depopulated either by collisions or by radiative transfer as a result of the rapid cooling, a population inversion could be achieved. The upper and lower levels would of

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necessity have to have different relaxation rates. This work was later expanded and submitted for publication in 1965 (Ref. 5). In that paper, the basic geometry of such fluid mechanical lasers was described and has proved consistent with present developments. At about the same time, Basov et al.[6] independently proposed the use of rapid heating or cooling to produce a population inversion. As gas lasers were still in their infancy many of the systems which have proved so valuable had not yet been created. However, with the development of the N_2–CO_2 laser by Patel[7] in 1964, a new generation of very high power gas lasers became possible. This laser system, which emits in the infrared, typically attains a population inversion in a glow discharge with a gas mixture of N_2 and CO_2 and a suitable catalyst to help depopulate the lower lasing level.

This particular lasing system has proved to be most suitable for application of the rapid expansion scheme suggested by Hurle and Hertzberg since the lasing levels exhibit different relaxation rates, as required for thermal pumping. The identification and experimental verification of this important possibility was carried out at the AVCO Everett Research Lab. and has recently been reported by Gerry.[8] The AVCO group was the first to identify the possibility of a high-energy density system, and to then develop the basic technology whereby large amounts of radiation could be extracted from a flowing gasdynamic system. Independently, Konyukhov and Prokhorov,[9] as well as Basov et al.,[10] identified the possibility of obtaining a population inversion utilizing thermal pumping of an N_2–CO_2 mixture.

An inversion is achieved in the gasdynamic system by the following process. A mixture of N_2–CO_2 containing a small amount of water vapor or helium is heated in the plenum of a conventional convergent-divergent nozzle to a temperature of approximately 2000°K. The heating can conveniently be accomplished in a number of ways, such as with a shock tube, or in an arc jet, or in a rocket motor where the products of combustion include appropriate amounts of N_2 and CO_2. When the N_2–CO_2 gas mixture is so heated, an equilibrium distribution of excited states is produced in both the N_2 and the CO_2. The first vibrational level of N_2 is thermally pumped; and in the case of pure N_2, the vibrational energy in that state represents about 9% of the internal energy (at 2000°K) or about 7% of the flow energy (see Fig. 1). If the gas is expanded rapidly enough through the convergent-divergent nozzle, the cooling rate in the nozzle can be very fast compared to the relaxation rate of the N_2–CO_2 mixture. Hence, it is possible to freeze the populations of the excited vibrational levels of the N_2 in the supersonic expansion part of the nozzle and to maintain a vibrational temperature which is closer to the plenum temperature than to the translational temperature of the expanding gas. Thus, in the supersonic flow region of the nozzle, the fundamental condition necessary to produce a population inversion exists; that is, there exist two very dissimilar temperatures in the gas. Figure 2 shows the main energy levels of the CO_2–N_2 system as well as important collisional and radiative processes. The lower laser level (100) is thermally associated with the very low translational temperature (~300°K) which results from the expansion. All of the lower energy levels of CO_2 would also normally have a population distribution corresponding to this low translational temperature. However, the mechanism that produces an inversion is the near resonant energy transfer which occurs from the vibrationally excited N_2 to the asymmetric vibrational stretch mode of CO_2 (001). A population inversion is then achieved since the upper lasing level of the CO_2 tries to achieve a number density associated with a much higher temperature than the lower laser level, as can be seen in Fig. 3.

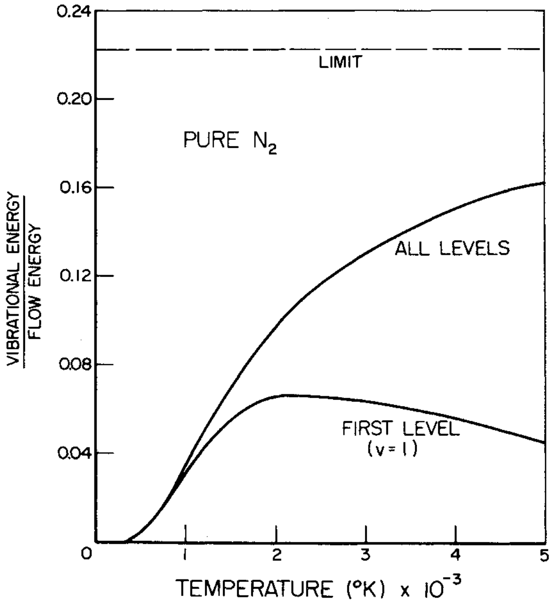

Fig. 1 Temperature dependence of N_2 vibrational energy divided by flow energy.

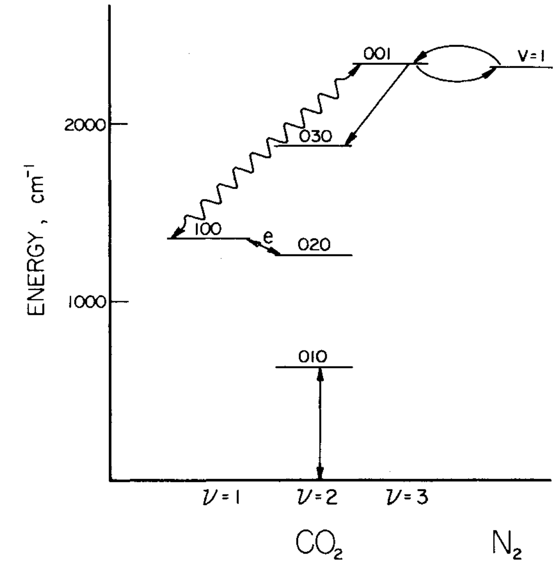

Fig. 2 Simplified N_2 and CO_2 energy level diagram. Important collisional and radiative processes shown by the arrows.

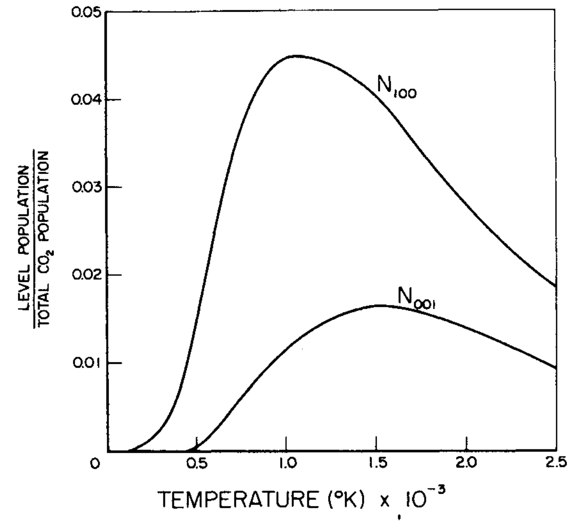

Fig. 3 Temperature dependence of CO_2 level population.

It should be pointed out that very short nozzles are required to rapidly cool the gas in a time that is short compared to the upper level relaxation time. Hurle and Hertzberg[5] pointed out that one of the most rapid possible expansions which could be attained in a practical sense would be via a Prandtl-Meyer expansion fan obtained by a freejet expansion. In a system capable of higher mass handling capacity, they also pointed out that approximately the same results can be achieved by utilizing a grid nozzle of the type first suggested by Ludwieg and described by Royle et al.[11]

The gas kinetic processes involved in this system have been described in detail by Gerry.[8] In addition, detailed studies of the kinetic processes in these machines have been carried out and verified experimentally by Christiansen and Tsongas,[12] and Konyukhov et al.[13] Basov et al.[14] and Anderson[15] have also numerically solved the coupled flow-kinetics problem. In fact, our knowledge of these types of machines has grown quite rapidly, and it is possible to predict with surprising accuracy the amount of energy available for lasing in a machine of any given geometry or size. This fact is of the utmost importance since it provides the basis for calculating the limiting thermodynamic performance of these machines.

Unfortunately, the efficiency of the thermally excited laser described by Gerry is relatively low in that only about 1–2% of the enthalpy of the gas can be extracted as laser radiation. Therefore, these efficiencies do not compare well with the conversion efficiency of conventional electrically excited N_2–CO_2 lasers where efficiencies approaching 30% have been reported.[16] However, it should be pointed out that electrical energy, like work, must be purchased from heat with an efficiency of approximately 30–40%, and hence the over all thermal efficiency of an electrical system operating at its maximum potential is at most about 12%. These efficiencies are not particularly encouraging if one wishes to consider the electrically excited lasing systems as a proper tool for the development of power transmission systems.

It was realized that the amount of energy extracted by the laser barely affects the stagnation temperature of the gas; therefore, an energy recovery system based on a diffuser would be able to repump the gas thermally so that any following expansion could re-excite the system. The system described by Gerry utilized a diffuser for recovering a sufficient amount of the total pressure of the cavity to make it convenient to discharge the laser to the surrounding atmosphere. In 1967 the group at the University of Washington suggested that a logical extension of this laser system would be to close the cycle.

Closed Cycle Photon Generator

In a photon generator (closed cycle gasdynamic laser), the gas would be expanded via a supersonic grid nozzle into the lasing cavity, lasing energy would be extracted, the gas returned to near stagnation temperature with an efficient diffuser, and then recirculated through a heat exchanger and adiabatic compressor to its original lasing configuration. The basic closed cycle system would look very similar to a conventional supersonic closed cycle wind tunnel and is shown in Fig. 4.

One of the chief drawbacks to the practical system is that the temperature of the gas has to exceed the normally available limitation imposed by materials for high-temperature compressors to secure effective lasing action. For example, approximately 1000°K is the limit for an uncooled turbine operating continuously for long periods of time. As seen from Fig. 1, below 1200°K very little energy is available in the N_2 vibrational system and hence a high-temperature compressor must be inserted into this laser system. However, high-temperature compressors of the comprex type have been developed to supply hypersonic wind tunnels for materials testing purposes.[17]

For calculations on the closed cycle gasdynamic laser system, certain assumptions can be made about the nature of the components and the gasdynamic processes which facilitate the analysis. In the plenum, where all the gases involved are in thermodynamic equilibrium, the number distribution in the various energy states is characterized by a single temperature. As the gas flows through the nozzle, full thermal equilibrium is initially maintained; however, as the flow velocity increases, the vibrational temperature tends to remain high as the translational temperature drops. The vibrational temperature of the N_2 will assume some characteristic value appropriate to the dimensions of the nozzle and the gas mixtures employed. For ease of calculation the sudden freezing approximation can be used. In this approximation thermal contact between the vibrational system and the translational system is instantaneously decoupled at some point in the expansion nozzle. In an actual case there is always some energy transfer between the two systems and hence some entropy production, but this loss can be small compared to other losses in the cycle. With the sudden freezing approximation the total entropy of the system remains constant.

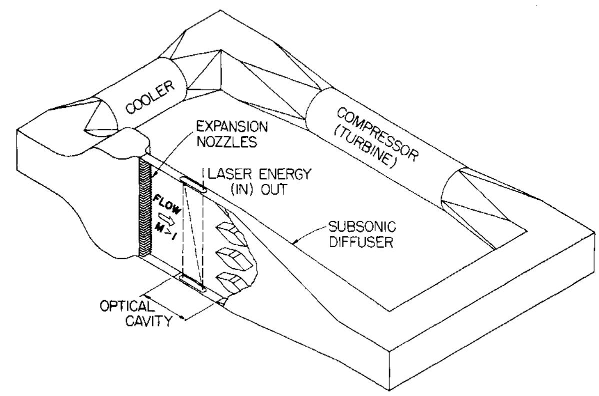

Fig. 4 Schematic diagram of photon generator (photon engine).

The heat transfer to and from the walls, with the exception of the heat exchanger, can be neglected. This assumption is quite reasonable for a relatively large machine in which the walls are modestly insulated and at equilibrium with the gas temperature. The flow losses in the system (e.g. turning vane losses and viscous effects in the nozzle and the duct) can be combined together into an over all pressure drop associated with the diffuser. This assumption is quite conventional in calculating a closed cycle wind tunnel since this loss far outweighs all the others. The compressor is assumed to be adiabatic and the heat exchanger isobaric.

In addition to the diffuser loss, another loss is present in the system which is not normally present in a supersonic wind tunnel. As was pointed out previously, the N_2 vibrational temperature can be maintained at a significantly higher level than the translational temperature in the test section. In the process of lasing, only part of the N_2 vibrational energy can be extracted as radiation; and, because of the processes maintaining the lower laser level at the translational temperature, a significant amount of this energy (approximately 60% of the energy frozen in the N_2) is given up as heat added to the supersonic stream. Assuming that the laser is coupled to an efficient cavity so that most of the radiation energy is removed from the cavity and not absorbed by the mirrors, a very straightforward calculation can be made of the total pressure loss associated with the lasing action. This loss may be large in view of the fact that heat is being added to a relatively high Mach number stream. The remaining processes in the cycle are assumed to be in thermodynamic equilibrium. Figure 5 shows a cycle temperature distribution for a perfect diffuser, an isentropic compressor, an isobaric cooler, and a constant area lasing cavity.

Numerical calculations were made for a closed cycle operating with a lasing medium composed essentially of N_2 in a constant area laser cavity. The cycle was assumed to be efficient enough to extract all the available laser energy from the flowing gas. The calculations for Fig. 6 were based on a plenum temperature of 1700°K, a vibrational freezing temperature of 1417°K, and a Mach number of 4 at the entrance of the laser cavity. Figure 6 shows the efficiency for converting thermal energy to laser energy as a function of the over-all pressure drop associated with the diffuser. It has been assumed that thermal energy can be converted to work with an efficiency of 40%. This is the efficiency with which the heat removed by the cooler can be converted into work going into the compressor, thereby providing regeneration.

From Fig. 6 it is seen that even with a perfect diffuser the con-

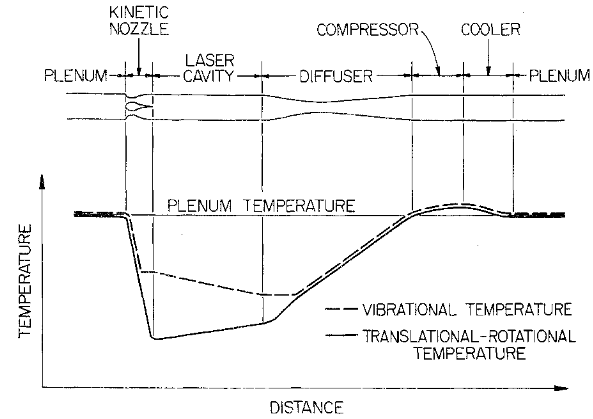

Fig. 5 Temperature distribution for a closed cycle laser with a constant area lasing cavity, a perfect diffuser, an isentropic compressor, and an isobaric cooler.

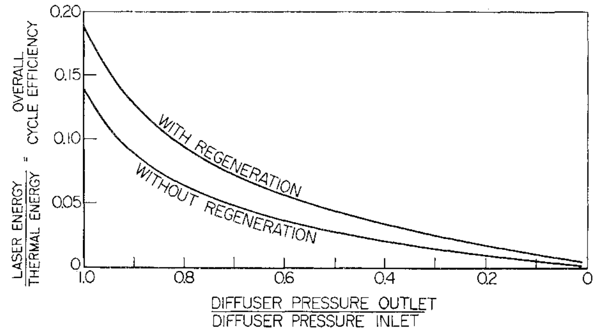

Fig. 6 The effect of diffuser recovery on the over-all cycle efficiency of the photon generator.

version efficiency is around 19 %. The reason for this low efficiency is the large loss in total pressure during lasing (about 25 %). Efforts to increase the output of laser energy by varying the operating temperatures in a constant area lasing cavity resulted in a lower production efficiency. The results shown in Fig. 6 are typical of the performance of closed cycle gasdynamic lasers using N_2–CO_2 mixtures. These results are consistent with independent calculations by Tulip and Sequin.[18] While small variations are possible by adjusting the parameters of the system (such as varying the mixture ratio or the Mach number of the flow) the results may be regarded as typical. They reveal that our chief concern must lie in reducing the total pressure loss due to lasing and developing high-efficiency diffusers to work in laser configurations. Indeed, these results are typical of any closed system in which the energy extracted is only a small percentage of the circulating energy. As can be demonstrated by elementary calculations, such systems are particularly sensitive to component efficiency. Therefore, as pointed out earlier, the diffuser loss tends to dominate in such flow systems. The inclusion of the other minor component losses with the diffuser loss yields approximately the same result. For example, with a pressure recovery of one-half in the diffuser, the compressor pressure ratio required to make up this loss is only two. Compressor efficiencies in this region can be high (>90 %). However, unless the total pressure drop due to lasing can be significantly reduced, a high-efficiency system is not obtainable. These results therefore motivated a deeper study of the thermodynamics of closed cycle lasers in the hope of improving their efficiency.

Many practical difficulties will have to be overcome in building a machine of this type, but it is felt that the problems are within the limits of technical feasibility. In addition, the potential for very high efficiency makes devices of this type worth serious further consideration.

The Photon Engine

As stated previously, an effective power transmission system must consist of both a generator and an engine. The actual transmission will be accomplished by a suitable system of optics to collimate the radiation and a corresponding system of optics at the point of application to direct the energy flux into the engine. The photon generator and the photon engine are similar to the electric generator and the electric motor in that in both cases the motor and the generator can interchange roles. It will be shown that coherent radiation will be absorbed and shaft work efficiently produced.

The modification is explained as follows. With reference to Fig. 4, flow is expanded from a plenum through a supersonic nozzle. However, a more conventional supersonic nozzle rather than a grid nozzle is used since a condition close to thermal equilibrium is required in the absorbing section which replaces the laser cavity. The stagnation temperature of the flow is selected so that at the supersonic Mach number in the absorbing section the static temperature of the mixture is about 600°K. The laser radiation is coupled to this section and if the intensity is sufficiently high the following processes will take place. For example, as the mixture of N_2–CO_2–He enters the absorption region, the lower level is thermally populated to the degree shown in Fig. 7,

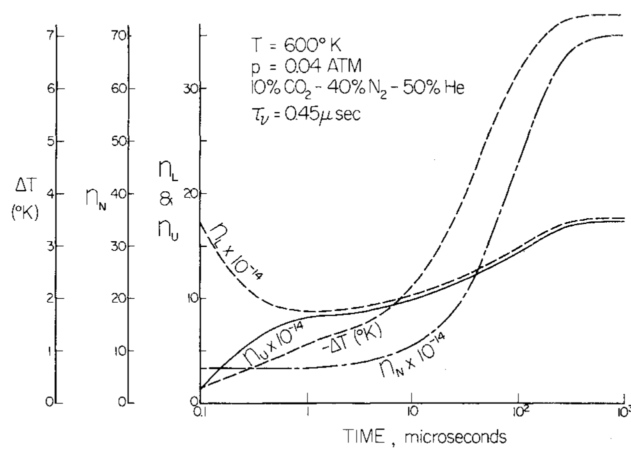

Fig. 7 Temperature and population variations of the important levels in a N_2–CO_2–He mixture during bleaching.

while the upper laser level has a much smaller population density. In this figure the energy states of a volume moving with the fluid velocity in the absorbing section are followed at constant input intensity for a specific case. Therefore, the variations of energy states are shown as a function of time rather than distance. This distribution of states is the reverse of population inversion and the laser radiation is absorbed. Both the lower laser level and the upper laser level now attempt to find a new equilibrium in the presence of the radiation field. For a sufficiently high radiation intensity the population of the lower laser level n_L will decrease and the population of the upper laser level n_U will increase until the two are equal. The gas is said to be bleached when $n_U = n_L$. However, since the gas contains N_2 there is an efficient transfer of the energy of the upper laser level to the first vibrational level of N_2. Since this is a resonant $V - V$ transition it is quite rapid and the final bleaching condition occurs when the populations of the two laser levels are equal and the vibrational temperature of N_2 is equal to the temperature of the upper laser level of CO_2. Now, since the energy is stored in the $N_2(v = 1)$ state, translational-rotational energy is removed from the gas producing a cooling of the supersonic flow. For each N_2 molecule excited to the $v = 1$ state only 40 % of the energy came from the laser. The remainder came from $T - V$ transitions populating the lower laser level and reducing the translational temperature. Depending on the mixture ratio and temperature of these gases, the cooling can be significant (varying between 1 % and 5 % of the translational temperature).

In reverse of the case of heating of a supersonic gas, the cooling of a supersonic gas will result in a total pressure increase. After the bleaching process, the gas is coupled to a grid diffuser and the gas is returned to a new equilibrium by the process of sudden unfreezing. After the diffuser the gas mixture would be at a final stagnation pressure somewhat higher than the corresponding pressure upstream. As the gas returns around the cycle, heat is again extracted from the cooler; but since the total pressure is now increased, the compressor now becomes a turbine and shaft work can be extracted from the system. This device is therefore called a photon engine.

In carrying out calculations, it was determined that a specific balance between the translational-rotational temperature and the vibrational temperature is required in order to achieve a net work output. As can be seen in the section on thermodynamic limits the correct temperature balance leads to the possibility of a highly efficient photon engine in which the entire amount of radiation absorbed can be transformed into shaft energy. In an actual photon engine the efficiencies of its components would not allow the realization of the indicated potential efficiency of 100%.

It should also be pointed out that the idea of supersonic cooling to obtain a closed cycle system in which a gas is pumped around a loop is not new. However, A. H. Shapiro has remarked that the heat-transfer mechanism of a conventional heat exchanger placed in a supersonic flow involved frictional losses which in general would exceed any increase in total head due to cooling. In the case of the photon engine, the cooling takes place in the volume without friction and this limitation does not necessarily apply.

Thermodynamic Limits of Photon Generators and Engines

In this section the thermodynamics of the photon generator and the photon engine are examined to determine the fundamental limits on their operation. Now the closed cycle gasdynamic laser is very similar to a closed circuit supersonic wind tunnel as stated previously. The dissipative processes in flow machinery are understood in relation to photon generation (see section titled A Closed Cycle Photon Generator), but in this section these dissipative processes are ideally reduced to zero. The purpose of this section is to examine those factors affecting the efficiency that are intrinsic to the lasing process itself.

In view of the significant developments in the N_2–CO_2 laser, the analysis will be further restricted to an N_2–CO_2 system. The analysis can be extended to include other lasers such as the N_2–CO_2 system, but in this development it will be clearer to retain one model. The gas mixture is assumed to be predominantly N_2 with just enough CO_2 and catalyst to provide the laser action, but not so much as to contribute appreciably to the total enthalpy of the gas. A one-dimensional flow process is considered and the thermodynamic state of the gas is assumed to be characterized by the pressure and two temperatures, T_V and T. The temperature T_V characterizes the population distribution of all vibrational states of N_2 as well as the upper laser level of CO_2. The temperature, T, describes the distribution of the translational and rotational states and the lower laser level. The temperature T and T_V are defined by a Boltzmann population of the upper level at T_V, $n_U = A\ \exp(-\varepsilon_U/\kappa T_V)$, and a lower level at T, $n_L = A\exp(-\varepsilon_L/\kappa T_L)$ where ε_L and ε_U are the energy levels of the lower and the upper laser levels, respectively. The nonequilibrium represented by the difference of the two temperatures is produced by a supersonic expansion. It is also assumed that the freezing process is perfect so that once T_V is greater than T, T_V is changed only by the removal of laser radiation. Indeed, the losses associated with collisions and florescence in CO_2 rich mixtures can be neglected because the percentage of CO_2 is assumed to be small. Reducing the CO_2 concentration has been shown by Christiansen and Tsongas[12] to be realizable in practice and supports the utilization of this simplification to study the ideal thermodynamic limits. As the flow is recompressed, equilibrium is re-established when $T = T_V$.

The efficiency of the closed cycle laser will be calculated by following a unit mass of gas through the cycle. The analysis starts at the lasing stage where a small amount of laser energy per unit mass, δq_L, is radiated by the system in a constant area duct. Conservation of energy requires that

$$-\delta q_L = \delta\varepsilon_V + \delta h_{T,R} + \delta(U^2/2) \tag{1}$$

where $\delta\varepsilon_V$ is the change in the vibrational energy per unit mass flow, $\delta h_{T,R}$ is the change in the translational-rotational enthalpy per unit mass flow characterized by the translational temperature T and the gas constant R, and U is the directed velocity. From the thermodynamic relation

$$T\delta s_{T,R} = \delta h_{T,R} - \rho^{-1}\delta p \tag{2}$$

where ρ, p, and $s_{T,R}$ are the mass density, static pressure, and the change in the entropy of the translational-rotational system, respectively. Solving for $\delta h_{T,R}$ and substituting into Eq. (2)

$$-\delta q_L = \delta\varepsilon_V + T\delta s_{T,R} + \rho^{-1}\delta p + \delta(U^2/2) \tag{3}$$

Conservation of mass and momentum in one-dimensional motion gives

$$\rho^{-1}\delta p + \delta(U^2/2) = 0 \tag{4}$$

Equation (3) then reduces to

$$-\delta q_L = \delta\varepsilon_V + T\delta s_{T,R} \tag{5a}$$

or

$$-\delta q_L = T_V\delta s_V + T\delta s_{T,R} \tag{5b}$$

where δs_V is equal to the change in the entropy of the vibrational system.

It is assumed that the collisions with N_2 molecules which excite the CO_2 molecules to the upper laser level from the ground state are exactly resonant to a good approximation. As a result of lasing, an energy $\delta\varepsilon_V$ is taken out of the vibrational subsystem at temperature T_V, a part of it, $\varepsilon_L\varepsilon_U^{-1}\delta\varepsilon_V$, goes to the translational-rotational subsystem at temperature T, and $(\varepsilon_U - \varepsilon_L)\varepsilon_U^{-1}\delta\varepsilon_V$ becomes laser radiation $-\delta q_L$.

From the preceding it is seen that

$$-\delta q_L = (\varepsilon_U - \varepsilon_L)\varepsilon_U^{-1}\delta\varepsilon_V$$

or

$$\delta s_V = -(\alpha T_V)^{-1}\delta q_L \tag{6}$$

where $\alpha = (\varepsilon_U - \varepsilon_L)\varepsilon_U^{-1}$, the quantum efficiency of the laser transition. For CO_2, $\varepsilon_L = 1388\ \text{cm}^{-1}$ and $\varepsilon_U = 2349\ \text{cm}^{-1}$ so that $\alpha = 0.40$. The assumptions made in this development are appropriate to the N_2–CO_2 laser. At present there are no other *GDL*'s to which these values are appropriate, but α is left as a parameter. (Actually, even in the CO_2 *GDL*, one could lase at 9.6μ where the lower laser level is the 02°0 state with $\varepsilon_L = 1286$ cm^{-1} and $\alpha = 0.44$.) Substituting Eq. (6) into Eq. (5) and solving for $\delta s_{T,R}$

$$\delta s_{T,R} = -(T_V/T)(1-\alpha)\delta s_V \tag{7}$$

The total entropy change $(\delta s_V + \delta s_{T,R})$ for the flowing gas due to lasing is therefore,

$$\delta s_{LG} = \delta s_V - (T_V/T)(1-\alpha)\delta s_V$$

or

$$\delta s_{LG} = [(1-\alpha)(T_V/T) - 1](\alpha T_V)^{-1}\delta q_L \tag{8}$$

The requirement that the gas lase is guaranteed by the existence of a population inversion, i.e., $n_U/n_L > 1$ which for the definitions of T and T_V reduces to $T_V/T > \varepsilon_U/\varepsilon_L$ or $T_V/T > (1-\alpha)^{-1}$. Thus Eq. (8) shows that a change in energy of δq_L due to lasing is accompanied by an increase in entropy proportional to δq_L.

The other operations of the cycle restore the energy and entropy to their prelasing values and must be calculated to complete the analysis. After lasing, the flow is assumed isentropic to stagnation conditions at the exit of the diffuser where it enters the isentropic compressor whose function is to return the stagnation pressure to its original value. The amount of work the compressor has to do to bring about this recovery is now calculated.

Suppose that the stagnation temperature and pressure are T_o and p_o before entering the expansion nozzle and the latter is changed by δp_o as a result of lasing. Since the change in energy is $-\delta q_L$ the change in entropy δs_{LG} can be expressed in terms of stagnation conditions as

$$\delta s_{LG} = -T_o^{-1}\delta q_L - Rp_o^{-1}\delta p_o \tag{9}$$

where R is the gas constant per unit mass. Combining Eqs. (8) and (9) gives

$$Rp_o^{-1}\delta p_o = -\{[(1-\alpha)(T_V/T) - 1](\alpha T_V)^{-1} + T_o^{-1}\}\delta q_L \tag{10}$$

from which the change in stagnation pressure δp_o due to the removal of laser radiation δq_L can be determined. With δh_w equal to the change in enthalpy and $-\delta p_o$ the change in pressure in the isentropic compressor, the following thermodynamic relation must be satisfied,

$$T_o^{-1}\delta h_w + Rp_o^{-1}\delta p_o = 0 \tag{11}$$

From Eq. (10), δh_w, the work done by the compressor to restore the total pressure to p_o, is found to be

$$\delta h_w = \{(T_o/\alpha T_V)[(1-\alpha)(T_V/T) - 1] + 1\}\delta q_L \tag{12}$$

With the stagnation pressure back to its pre-expansion value, the final step in the cycle is to return the stagnation temperature to T_o and thereby return the unit mass of gas to the reservoir ahead of the expansion nozzle. This final processing is accomplished by an isobaric cooler. The amount of heat δh_Q given to the cooler can be easily determined from the relation

$$-\delta s_{LG} = \delta h_Q/T_o \tag{13}$$

with Eq. (8) it becomes

$$\delta h_Q = -(T_o/\alpha T_V)[(1-\alpha)(T_V/T) - 1]\delta q_L \tag{14}$$

The thermodynamic consequences of taking a unit mass around this very idealized closed cycle gasdynamic laser are: a) laser energy δq_L is radiated; b) work δh_w is done on the gas by the compressor; and c) heat is rejected by the cooler. For a fixed value of δq_L the value of δh_w and δh_Q depend on α, T, T_V, and T_o. The quotient T_V/T is not arbitrary however, but must be large enough to achieve a population inversion if the gas is to lase. The necessary condition for a population inversion in Eq. (13) shows that $\delta h_Q < 0$, which means that the designation of the heat exchanger as a cooler is correct.

Define the efficiency of the conversion of work δh_w into laser radiation δq_L as η_{GDL}, then

$$\begin{aligned} \eta_{GDL} &\equiv \delta q_L/\delta h_w \\ \eta_{GDL} &= \{(T_o/\alpha T_V)[(1-\alpha)(T_V/T) - 1] + 1\}^{-1} \end{aligned} \tag{15}$$

Note that this efficiency is different from the over-all cycle efficiency reported in Fig. 6 where the efficiency of converting heat into work was also included. Because $\eta_U > \eta_L$, not only is $0 < \eta_{GDL} < 1$, but η_{GDL} can be made arbitrarily close to one by appropriate choice of conditions, giving virtually complete conversion of work into laser radiation. Thermodynamically speaking, this near complete conversion is possible because the change in the entropy of the gas during lasing can be made arbitrarily small, thereby requiring only an arbitrarily small transference of heat to the cooler.

The earlier analysis prior to the introduction of the lasing condition also applies to the photon engine. Now, however, δq_L is negative and there is an absorption condition defined by $\eta_U < \eta_L$. The efficiency of the photon engine is defined as

$$\begin{aligned} \eta_{PE} &\equiv \delta h_w/\delta q_L \\ \eta_{PE} &= 1 + (T_o/\alpha T_V)[(1-\alpha)(T_V/T) - 1] \end{aligned} \tag{16}$$

In contrast to the laser, η_{PE} can be negative. For example, if $T_o > T_V = T$, then $\eta_{PE} = 1 - T_o/T < 0$. A negative value for the efficiency of the photon engine means that the entropy of the gas is increased so much during the laser radiation absorption process that additional energy in the form of work done on the gas (making $\delta h_w < 0$) must be supplied to help transfer entropy to the cooler.

Now consider the case when the laser energy per unit mass flow either given off by the laser or absorbed by the flow is not infinitesimal but is a finite quantity. Laser radiation can be removed in the laser cavity as long as the lasing condition, $T_V/T > (1-\alpha)^{-1}$ is satisfied. As laser energy is removed from the flowing gas in a constant area duct, however, the quotient T_V/T is reduced until it reaches $(1-\alpha)^{-1}$ at which point lasing ceases. Figure 5 shows a cycle temperature distribution for this case. Similarly for the photon engine, absorption in a constant area duct continues until T_V/T increases to $(1-\alpha)^{-1}$ and absorption stops. For a constant area duct, the amount of laser energy obtainable per cycle depends on the value of T_V/T at the entrance to the lasing duct, this energy being greater for larger values of T_V/T. Similarly for the photon engine, the laser energy absorbed per cycle depends on the value of T_V/T at the entrance to the constant area absorption duct. However, for this case the capacity increases with decreasing T_V/T. From Eqs. (15) and (16), it is seen that efficiencies decrease for values of T_V/T significantly different from $(1-\alpha)^{-1}$. For a constant area lasing and absorption duct, greater energy transference results in lower average conversion efficiencies.

This situation is altered if a variable area duct is used in place of the constant area duct. Suppose that the area in the radiation extraction section of the laser increases in the flow direction such that T_V/T is maintained constant over its entire length. Then T_V/T can be maintained at a value slightly greater than $(1-\alpha)^{-1}$, resulting in a high efficiency. At the same time a finite amount of laser energy per cycle can be extracted. A finite amount of work can also be obtained at a high efficiency from the photon engine by using an absorption duct whose area decreases in the flow direction.

This development has shown that the thermodynamic limit for the efficiency of producing finite amounts of laser radiation from work or for generating work from laser radiation is one. This limit is achieved only if the machine is properly loaded and certain idealized assumptions of component efficiencies can be realized.

Conclusions

In the preceding section, the thermodynamics of thermal lasers of the gasdynamic type have been examined. These studies have led to a conceptual device in which the limitation of transforming heat into coherent radiation can be examined. By exploring the basic thermodynamic relationships controlling the operation of this device, it is concluded that a closed cycle gasdynamic laser is possible in which all of the work supplied can be turned into laser radiation. Hence, it is possible in principle to convert heat into coherent radiation with approximately the same efficiency with which heat may be converted into work.

By modifying the closed cycle gasdynamic laser system, it is shown that this system can be operated in reverse and the incoming radiation may be used to pump the gas in the loop so that work can be extracted. By carefully controlling the temperature distribution in this machine, laser energy can be converted into work with an efficiency approaching one.

The authors are aware that these machines are conceptual in nature and that practical and useful devices would require component efficiencies pushing the state-of-the-art. However, these machines have demonstrated that the limits of the efficiency are high and, therefore, it is hoped that they will stimulate thinking leading to the development of practical devices which will make the concept of radiant energy power transmission a reality.

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Nuclear Pumped Gas Lasers

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New areas in plasma physics and plasma dynamics are entered by research on gas lasers directly excited by nuclear reactions. Recent development of high-power, high-pressure gas lasers results in improved aspects of laser pumping by nuclear energy. Population inversion in gaseous laser media can occur as a result of interactions with fission fragment, α-particles, fast protons or γ-rays. Such interactions may be the sole cause of population inversion or they may augment other means of laser pumping. The possibilities of achieving population inversion by nuclear reactions are discussed. Work in this field is reviewed and suggestions for further research are made.

Introduction

THE interest in using nuclear energy for laser power is almost as old as the gas laser itself. Papers dealing with this subject began to appear around 1961. The potential of high-power density inherent to nuclear reactions has appeared attractive in regard to high laser power output.

Various authors have also speculated on higher efficiencies, as compared to electrically excited lasers on the basis of an all-component system analysis which includes the various phases of energy conversion from an original heat source to laser light. In addition, more compact systems were expected with obvious tradeoffs, for example, in space applications.

As power sources, nuclear reactors or radioisotopes have been suggested to pump a laser either indirectly by means of thermal conversion, such as in a thermionic diode arrangement, in which the discharge plasma can exhibit population inversion,[1–3] or directly. In this case, the energetic reaction products, such as fission fragments, recoil particles, and γ-rays, interact with the laser material to produce population inversion.

Methods have been suggested for γ-ray lasers[4–8] by which stimulated emission is obtained from metastable excited nuclei.[9] Isomeres suited for such γ-ray amplification would have an extremely high-energy content in the order of several tens of kev per atom or 10^{12} joules/kg.

Stimulated emission from outer shell transitions of lattice atoms excited by fast particles and gammas have been investigated.[10–24] Much of this research is based on previous investigations of luminescence of solids and liquids induced by nuclear radiation. In several cases γ-irradiation has reduced threshold power for optical pumping. In other experiments such irradiation had adverse effects as to cut off lasing action. The reason is believed to be radiation damages which degrade the optical properties of the lasing material. This paper deals with nuclear pumped gas lasers only.

Earlier reports reflect the limitation of low pressure for gas lasers in the order of 1–10 torr. At this pressure the stopping distance of high-energy particles is much larger than laser tube dimensions and energy deposition in the lasing gas appears to be

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Index categories: Plasma Dynamics and MHD; Atomic, Molecular, and Plasma Properties; Radiation and Radiative Heat Transfer.

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