OPTIMIZATION OF ENGINES OPERATED REMOTELY BY LASER POWER*

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INTRODUCTION

The concept of converting electromagnetic energy, such as from solar or microwave power, remotely into work has been considered for several decades. Only recently, however, have such conjectures approached feasibility due to the availability of laser beams with aperture – limited directivity and enormous power flux densities. There exist three basic alternatives for the conversion of laser energy into mechanical work by an engine. These are, in ascending order of intricacy, as well in degree of utilization of the coherence properties of the laser, the following: (1) the boiler approach in which laser power is applied externally to a heat reservoir just as fossil fuel to a steam engine; (2) internal heating of a working fluid by resonance absorption of laser radiation admitted through a suitable window; and (3) selective resonance excitation of a single degree of freedom without increase of the translational temperature.

Clearly, aside from the optical beam tracking problem, the first approach reverts to the case of conventional engines. It should be noted that because thermal materials limitations and reradiation limit the temperature of the heat reservoir, an important advantage of laser radiation is forfeited. As will be shown, this disadvantage is, at least in principle, avoided in the second method (ref. 1). Furthermore, although this approach amounts to a mere modification of conventional engines, it lends itself to types of operation not achievable in ordinary heat-to-work converters. This leads to new considerations of engineering thermodynamics, and the scope of this paper is in the main limited to them. The third approach, first suggested in the concept of the *photon engine* (refs. 2 and 3) is conceptually more profound. However, it is a field by itself. Moreover, the practical realization of its various alternatives encounters obstacles which may prove insurmountable.

GENERAL FEATURES OF LASER ENGINES

Engines of the second type, that is, those in which laser radiation is absorbed by the molecular resonances of a gas, converted into translational heat, and thus used to perform mechanical work, are in the following referred to as laser engines. In principle, any conventional engine which can admit radiation through a window to a working fluid, can be modified for this purpose. There exist now several types of lasers that can deliver, or promise to deliver, high powers in pulsed, continuous, or shaped-pulse operation. Examples are the gas lasers based on CO_2 near 10 μ, CO near 5 μ, HCl near 3.5 μ, and HF near 2.8 μ. The wavelengths of these lasers can be matched with the resonances of many gases, cross sections of absorption varying from 10^{-19} to $10^{-17} cm^2$ or more. Thus absorption is nearly complete at 1 atm over path lengths that may be as short as 0.1 mm or less or, admixed at 1 volume percent to a nonabsorbing gas, over 1 cm or less. The working fluid

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may therefore be a monoatomic gas with its $K = c_p/c_v = 1.666$. In addition, such gases as helium were found to have a fast quenching effect so that the time in which the vibrational excitation is dissipated into a thermal equilibrium is negligible compared with that of the pertinent engine cycle.

The maximum achievable temperature in such an engine deserves some discussion. The laser, in principle, is a source of infinite black body temperature. An absorbing gas, again in principle, could also reach an infinite temperature. There are, of course, material restraints, but these will be considerably less than in the boiler appraoch. A gas mixture, as described in the previous paragraph, has a negligible coefficient of thermal emission throughout the spectral range of interest, including the resonance line. Thus the temperature the gas can reach, or is allowed to reach, is determined by other factors. These are considered in the following:

1. Engine walls will not tolerate temperatures much in excess of about 2,000°K. However, in certain configurations, such as that of a piston cylinder, the laser radiation may be focused into a smaller space well shielded by the surrounding gas from the walls. Thus an effective temperature may be reached which is much higher than that which the walls can tolerate.

2. Bleaching, that is, the production of equal populations in the upper and lower levels of the absorbing transition occurs at sufficiently high radiant flux densities so that radiation is no longer absorbed. These power levels, however, increase with the rate of quenching and lead to a temperature limit much higher than that determined by the other factors.

3. Thermal saturation of the upper level leads to an effect similar to bleaching. Specifically, in thermal equilibrium, the ratio of upper level populations n_2 and lower level populations n_1 is given by $n_2/n_1 = (g_2/g_1) \exp(-h\nu/kT)$. One can thus define a limiting temperature T_s at which $h\nu = kT_s$ so that appreciable reduction of absorption occurs; (that is, neglecting the ratio of the statistical weights g. Except for the effect of the statistical weights, T_s is characteristic to some extent of the laser wavelength rather than of the absorbing molecule. Values of T_s for the lasers mentioned before and their wavelengths are listed in table I. As defined, the values of T_s provide only an approximate value for the temperatures at which absorption is significantly reduced. For example, for $g_1=g_2$, the absorption cross section of an ideal two-level system decreases to 0.46 of its value at low temperatures, but will be lower for a multi-level molecule.

4. Dissociation is a third cause for the reduction of absorption at elevated temperatures. The last column of table I shows the dissociation energies (ref. 4) of some gases resonant with the wavelengths of the four lasers cited. These values provide only a guide for the comparison of various gases. The rate, as well as the equilibrium value, of dissociation as a function of temperature still depend on other parameters, notably the collision rate and cross section.

Nevertheless, one can conclude on the basis of these considerations that laser engines can operate with effective temperatures between 2,000° and 3,000°K, if lasers with wavelengths shorter than about 5 μ are used as radiation sources. There are two additional features that set laser engines apart from ordinary heat-to-work converters, at least when applied in combination. The first is the application of an essentially monoatomic gas as working fluid. The second feature is the option of the pulse shape. In the internal combustion engine, for example, power is applied in pulses; but the working fluid is, of necessity, a polyatomic gas mixture.

Schematic diagrams of laser piston engines, including one for experimental use in a simplified version, are shown in figure 1. In addition, figure 2 shows certain optional features such as a change of absorption cross section, hence of depletion depth, by frequency shift as the laser pulse develops and also the method of focusing the laser radiation into a smaller space within the cylinder volume. The P–V diagram of the engine in figure 3 shows four steps of the simplified cycle: (1) isochoric pressure increase as the laser pulse arrives; (2) adiabatic expansion (2 – 3) performing external work; (3) isobaric compression which restores the initial temperature T_1; and (4) isothermal compression (4 – 1) which restores the initial volume V_1 at the starting point 1.

The performance of the engine depends, first of all, on its (theoretical) thermal efficiency η, defined by

$$\eta = 1 - \frac{\Sigma Q_{out}}{Q_{in}} \tag{1}$$

or, alternatively, by

$$\eta = \frac{\phi\delta W}{Q_{in}} = \frac{W_{out} - \Sigma W_{in}}{Q_{in}} \tag{2}$$

where Q_{in} represents the heat provided by the laser, ΣQ_{out} the heat rejected by the engine, and $\phi\delta W$ represents the sum of the positive and negative work terms.

The actual efficiency depends also on the efficiency of the work terms, that is, the losses encountered in isobaric and isothermal compression, as well as in the expansion step. A practical merit factor is given by the work ratio r_w, defined as

$$r_w = \frac{W_{out}}{\Sigma W_{in}} \tag{3}$$

Thermal efficiency and work ratio are best expressed in terms of the ratios $A = V_3/V_1$ (that is, the ratio of the volumes after, and before, the expansion step 2 – 3) and $B = T_2/T_1$ (that is, the ratio of the temperatures after, and before, the heating step 1 – 2). One has then

$$\eta = 1 - \frac{Q_{3-4} + Q_{4-1}}{Q_{in}} = \frac{C_p (A^{1-K} - B^{-1}) + RB^{-1} \ln (A^K/B)}{C_v (1 - B^{-1})} \tag{4}$$

and

$$r_w = \frac{(C_v/R)(1 - A^{1-K})}{A^{1-K} - B^{-1} + B^{-1} \ln (A^K/B)} \tag{5}$$

Once the maximum permissible temperature ratio B and a monoatomic gas are chosen, the only adjustable parameter is the compression ratio A. From equation (4) the maximum thermal efficiency is derived for the condition

$$A^{K-1} = B \tag{6}$$

It is easy to show that this amounts to the condition that $T_3 = T_1$, (that is, that the heat received by the engine in step 1 – 2 is equal to the work of expansion 2 – 3. By introducing equation (6) into equation (4), one obtains the maximum thermal efficiency

$$\eta_{max} = 1 - \frac{\ln B}{B-1} \tag{7}$$

Conservative choices of T_1 and T_2 are, respectively, 300° and 2,000°K so that B = 6.67. We obtain then from equation (7), η_{max} = 67 percent.

Note that the maximum efficiency depends only on B and not even on the ratio K of specific heats. Thus this efficiency should be obtainable also for polyatomic gases. However, this can not be achieved for them because of equation (6). Since $A = B^{1/(K-1)}$, they require at least a compression ratio of 246, whereas monoatomic gases require only that A = 17.2.

The work ratio at maximum thermal efficiency follows from substitution of equation (6) in equation (5). In combination with equation (7), one obtains then the relationship between work ratio and maximum thermal efficiency

$$r_w = \frac{1}{1-\eta_{max}} \tag{8}$$

One can quite generally show that equation (8) is equivalent to the condition $Q_{in} = W_{out}$. Since

$$W_{out} - \Sigma W_{in} = Q_{in} - \Sigma Q_{out} \tag{8}$$

one obtains then from equation (1):

$$\eta = 1 - \frac{\Sigma W_{in}}{W_{out}} = 1 - \frac{1}{r_w} \tag{9}$$

which is the statement of equation (8).

If we ask, independent of the thermal efficiency, for maximum work ratio r_w, one obtains a different value for A. Figure 4 shows a graph of r_w vs. A obtained with equation (5) for B = 6.666. One obtains a shallow maximum at A = 7 that is only about 10 percent larger than the value r_w = 3 at maximum thermal efficiency. Because r_w is nearly constant around that point, the optimized laser energy operates under the condition given by equation (6). The P–V and T–S diagram show then a particularly simple form, since the isobaric compression step has vanished (see figs. 5 and 6).

C-3

BRAYTON AND STIRLING CYCLES

We have performed a similar analysis for the laser powered turbine and Stirling engine. The conditions of the Brayton cycle are summarized in Figure 7. While the efficiency η is fixed for a given temperature ratio T_2/T_1, a maximum work ratio is obtained when

$$r_w = \frac{1}{1 - \eta} \tag{10}$$

as before.

The laser powered turbine operates with continuous wave (cw) radiation. The turbine, however, requires *a priori* larger powers than the piston engine.

The Stirling engine can be embodied in a variety of designs. One that appears particularly suitable for modification to laser power is shown in figure 8 and 9 (originally a Phillips, Eindhoven design). The theoretical thermal efficiency is that of the Carnot engine, and the work ratio is related to it by equation (10) see (fig. 10).

REFERENCES

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TABLE 1. – VALUES OF T_s

Laser	Wavelength, μ	$h\nu$, eV	$T_s = h\nu/k$, °K	Absorbing gas	E_{diss}, eV
CO_2	10.6	0.11	1,300	SF_6	3.13
CO	4.7	0.26	3,000	CO	11.1
HCl	3.5	0.35	4,100	HCl	4.4
HF	2.8	0.44	5,100	HF	5.9

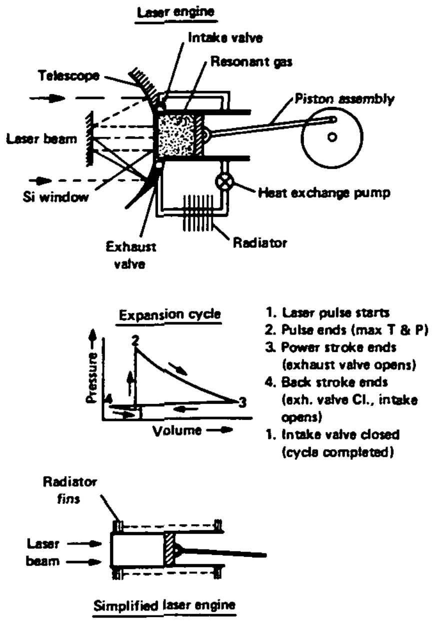


Figure 1.– The laser engine and PV diagram.

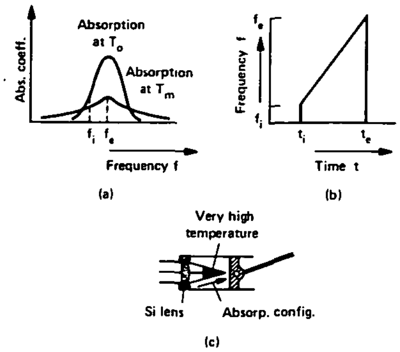


Figure 2.– Alternative details of operation.

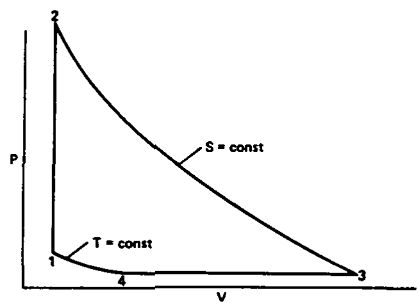


Figure 3.– Laser piston engine (not optimized).

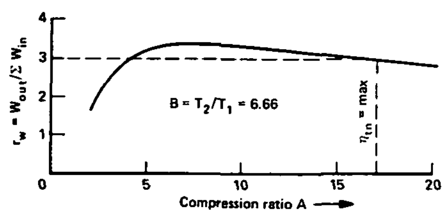


Figure 4.– Work ratio vs compression ratio in laser piston engine.

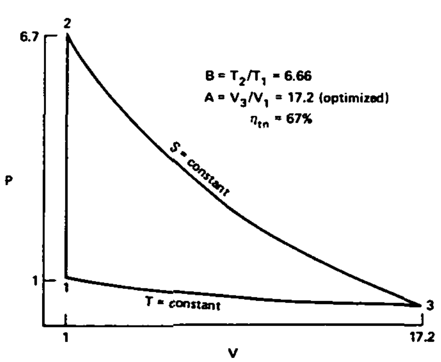


Figure 5.– PV diagram for the pulsed piston laser engine.

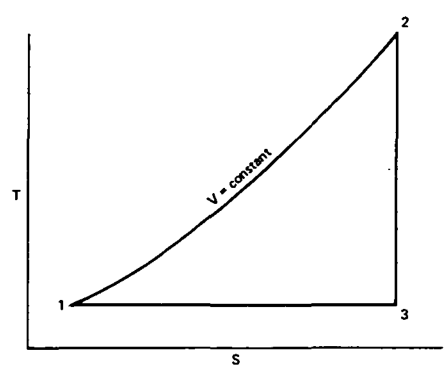
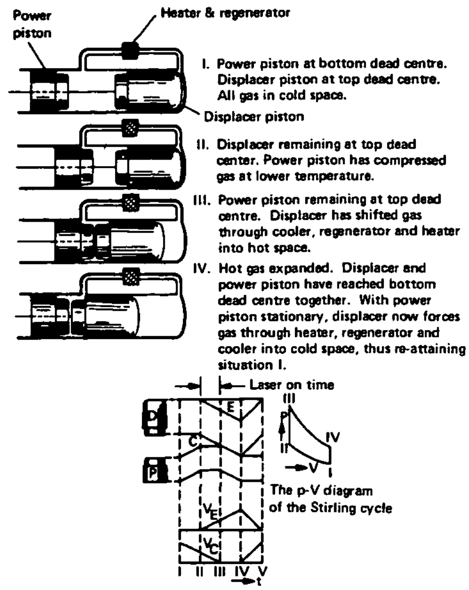


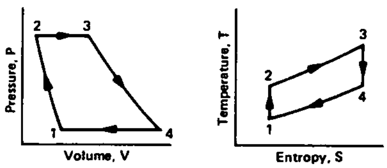
Figure 6.– Temperature-entropy diagram for the pulsed piston laser engine.

Diagram of the Stirling cycle. For clarity, the piston and displacer are assumed to move discontinuously.



The discontinuous movement of piston and displacer as a function of time. B and E indicates the changes in volume of the hot space (V_E), band C those of the cold space (V_C). The changes in volume are plotted separately below.

Figure 8.– The Stirling engine.



1 → 2 Isentropic compression
2 → 3 Isobaric heat addition
3 → 4 Isentropic expansion
4 → 1 Isobaric heat rejection

Efficiency; $\eta = 1 - \frac{T_1}{T_2} = 1 - \frac{1}{\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}}$

Work ratio; $r_w = \frac{T_3}{T_2}\left\{\frac{\frac{h}{k-1} + \left(1 - \frac{T_2}{T_3}\right)}{\frac{\eta}{k-1} + \eta - \left(1 - \frac{T_4}{T_2}\right)}\right\}$

r_w maximum when $T_2 = T_4$

$(r_w)_{max} = \frac{1}{1-\eta}$

Figure 7.– The Brayton Cycle.

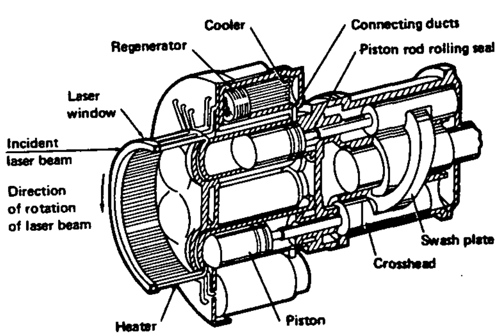
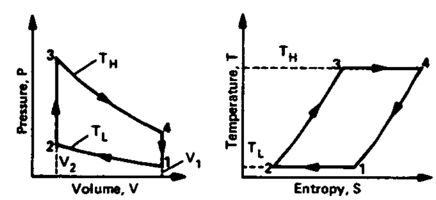


Figure 9.– Laser-driven Stirling engine.



Efficiency; $\eta = 1 - \frac{T_L}{T_H}$

Work ratio; $r_w = \frac{T_H}{T_L} = \frac{1}{1-\eta}$

1 → 2 Isothermal heat rejection
2 → 3 Regeneration process
3 → 4 Isothermal expansion
4 → 1 Storage process

Figure 10.– Thermodynamic cycles for the Stirling engine.

DISCUSSION

Ken Billman, NASA Ames Research Center – Max, it was not apparent to me why you have concentrated on the piston engine. In other words, why is the turbine not a viable alternative?

Answer: Well, actually it is. In a long term approach, however, we are restricted with maximum turbine blade temperatures of 2000°K. In the near term approach, we looked into various turbines and found that they require much higher power than those around the laboratory, that is, 20 to 30 kW. But the real reason is, of course, that although they run CW, we will have to get around the turbine blade problem.

Ned Rasor, Rasor Associates – I think you showed a 67 percent thermodynamic efficiency. How does that translate into overall efficiency, or is that the overall efficiency?

Answer: No, we don't claim that we have achieved it – it will be the case when it is built. This is our hope and aim, if we can work at this temperature.

Dick Pantell, Stanford University – You described that the third approach, direct use of vibrational energy, suffered from the engineering problem of separating the upper and lower energy states?

Answer: Well, actually I must confess that I haven't considered using inhomogeneous fields for separation.

Dick Pantell, Stanford University – Yes, that is what I was going to suggest – to use inhomogeneous electrostatic fields.

Answer: Yes, it may work, but it seems to be beset with great complexity. I believe a wise man would not undertake such a scheme easily.

Abe Hertzberg, University of Washington – Let me comment! Piston engines actually scale down better than gas turbines. There are good large piston engines, however, such as a good diesel engine which could have a thermal efficiency of 60 percent and maybe you have been working on something closer to the Sargent cycle which will be a little higher. But the real efficiencies tend to be closer to 37 percent. This is due to the pumping work, friction, and so on.

Answer: Yes, but it's a "bird in the hand".

Abe Hertzberg, University of Washington – Oh yes, I agree.

Max Garbuny: Incidently, I might mention here something that I glossed over – the window problem. As was mentioned at the last meeting, it must handle these temperatures with good transmission and strength. Well if we go to CO wavelengths, we can solve this with the marvelous material: sapphire which can handle something like 170,000 lbs/in^2 pressure. So this problem can be solved.