INITIAL EXPERIMENTS WITH A LASER DRIVEN STIRLING ENGINE

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ABSTRACT

During the Spring and Summer of 1974 three students* taking my Quantum Electronics Laboratory Course and I set out to build a laser driven engine. To our delight we succeeded for a brief time in driving a Beale free piston Stirling engine with a 40 W CO_2 laser. I have no doubt that our initial experimental success is but a first step in efficient energy conversion of laser radiation by engines.

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I. INTRODUCTION

The ability to transform energy from one form to another has fascinated engineers for over a century. Although our preliminary experiments were motivated by the thought of transmitting energy over great distances by a beam of light and then efficiently converting the received energy to electricity, we are not the first with such a dream. Figure 1 shows an early solar driven steam engine exhibited at the Paris World's Fair by Mouchot, nearly one hundred years ago.[1]

We became interested in the possibility of demonstrating a laser driven engine following the pioneering work of A. Herzberg et al.[2] Unfortunately, the photon engine in the form described by Herzberg proved to be unrealizable in practice.[3] Thus the problem of actually constructing a laser driven engine remained unresolved. As sometimes happens, a chance remark by Max Garbuny of his work on the problem[4] renewed our interest and led to new ideas in ways to overcome the experimental difficulties. Our experimental constraints of low available CO_2 power and a requirement for closed cycle operation led to consideration of a Stirling engine. Fortunately, Stirling engines have been extensively reviewed recently[5] and a number of design alternatives are possible. The elegantly simple free piston Stirling engine invented by Professor W.T. Beale of the University of Ohio seemed to meet our needs. A call to Professor Beale led to the purchase of a single piston, closed volume demonstration engine with drive power requirements between 30 and 50 watts. After modifying the engine by adding a window to transmit CO_2 laser radiation we arranged to borrow a 40 W CO_2 laser and begin our "research" investigation.

II. BEALE FREE PISTON STIRLING ENGINE

Figure 2 shows a schematic of a small free piston Stirling engine designed to produce useful work by pumping water through a simple check valve arrangement. The engine consists of a displacer piston and an engine piston which is coupled to an inertia mass load which drives the pump ram. The expansion space at the end of the displacer piston is heated and the compression space between the displacer and engine piston is cooled for operation. The engine is filled with air or helium to between 2 and 4 atm. For the laser experiments, a transmitting window was added at the end of the displacer cylinder to allow direct heating of the gas in the expansion space volume by the laser radiation.

The operating cycle of the Beale free piston Stirling engine is shown in Fig. 4. The illustrated cycle is representative of the engine's performance as determined in detailed studies by Agbi.[8] Figure 5 shows the oscillating frequency, power output and operating efficiency (percent) of our particular engine operating under the conditions indicated with air as the working gas. The 2.5% thermal efficiency is quite good for such a small engine with relatively large losses due to mechanical resistance and thermal conduction. However, it is by no means a limit as Agbi has obtained efficiencies of up to 8% with air and 13% with helium as working gases in a similar engine.

The oscillating frequency of the engine is given by[6]

$$f = 0.7 \left(\frac{A^2/V \; P_o \; \gamma}{M} \right)^{\frac{1}{2}} \tag{1}$$

where A and V are the piston area and working space volume, M is the oscillating mass P_o the charge pressure and $\gamma = C_p/C_v$. Our engine operated at near 11 Hz but higher frequency operation is possible. Higher frequency oscillation would allow the use of a linear alternator in place of the water pump to efficiently couple power from the engine as direct electrical output.

The Beale engine operates with a sealed closed volume of gas. Furthermore, it is a simple mechanical device without gears, valves or bearings and thus offers the possibility of lubrication free long operating life. Finally, direct mechanical to electrical generation is possible with a simple linear alternator arrangement. These advantages make the Beale type engine ideal for conversion of small powers such as in solar power conversion or artificial heart pumps.[5]

III. LASER EXPERIMENTS

Prior to operating the engine with a CO_2 laser source, we performed linear absorption measurements on helium - SF_6 gas mixtures. Our preliminary measurements showed that 100 torr of SF_6 in 1 atm of helium was adequate to absorb the CO_2 incident beam in less than a 1 cm path length. We arranged a gas manifold system that allowed introduction of SF_6, He and CO_2 to the engine at a total pressure up to four atmospheres.

Our initial irradiation of the engine with a 40 W cw CO_2 beam immediately broke the salt input window. After replacing the window we began more cautiously by first electrically heating the engine to near its operating temperature and then applying the CO_2 laser beam. Under these conditions the engine operated for a few minutes before the salt window again cracked. However, inspection of the window showed that the inner surface next to the engine's heated gas had melted and then cracked from thermal stress. Unfortunately, the very short availability time of the CO_2 laser did not give any alternative but to continue with the experiments using salt windows.

These early results raised some questions about the engine's operation that prompted further study. The questions included whether the cylinder walls had to be hot for engine operation or whether a hot gas was sufficient. Also, was the SF_6 - He gas mixture being directly heated by the CO_2 laser radiation or being heated indirectly from a hot window or displacer piston? Finally, was the gas mixture optimum?

Further testing and then a call to Professor Beale verified our suspicion that the cylinder wall did have to be heated near 200°C for engine operation. A cold wall leads to gas quenching and non-ideal circulation by the displacer piston. We therefore arranged to heat the cylinder wall.

To check whether the gas was being heated directly by absorption, we attempted to operate the engine without the SF_6 dopant in the helium. The engine did not run and furthermore, the displacer piston did not even respond to a sudden turn on of the CO_2 laser beam. These results indicate that gas absorption was responsible for the engine's operation.

The ideal gas mixture was more difficult to determine given the short operating times between window failure and a lack of a quantitative engine performance measurement. However, the engine did seem to perform better with SF_6 dopant, 1 atm of CO_2 and the balance of helium up to a total pressure of four atmospheres. The engine would also run without SF_6 at 1 atm of CO_2 plus three atmospheres of helium. However, the engine would not run on CO_2 alone presumably due to the incorrect visiosity for the 0.010" displacer piston to cylinder clearance.

As a final experiment, we operated the engine with a chopped CO_2 laser beam. A variable speed chopper allowed operation at a 50% duty cycle at chopping frequencies from above to below the engine's resonant frequency near 11 Hz. The engine showed a definite resonance when pumped by radiation chopped near its resonance frequency and operated poorly when pumped only slightly off resonance. It ceased to run when pumped at a very high chopping frequency or at a very low chopping low frequency. These observations indicate that higher efficiency operation may be possible by driving the engine with pulsed laser radiation at a pulse rate nearer the engine resonant frequency.

The lack of time and also of salt windows prevented further, more quantitative work with the laser driven engine. However, for demonstration purposes the engine will operate with a 35 W average power alcohol lamp which heats a brass plate in place of the salt window.

IV. CONCLUSION

It is interesting to speculate about the future of laser energy conversion by engines. If the initial negative reaction to energy conversion using such a mundane device as an eighteenth century engine is overcome, then the approach is seen to offer a number of advantages. First, a laser driven engine should operate at greater than the 40% conversion efficiency which is now obtainable from 160 hp (0.122 MW) conventional Stirling engines.[5] Secondly, closed cycle operation allows optimization of the gas mixture for both absorption of the laser radiation and engine operation. Thirdly, the engines can be very simple in construction, small in volume and light weight per unit of output energy.

However, there are limitations that arise due to the use of the laser as the energy source. These include window damage problems, gas absorption, saturation and dissociation, and mechanical vibration due to engine operation.

High power infrared window materials have been extensively investigated and their power and energy density limits are now known. With the exception of diamond and sapphire, infrared windows of salt or semiconductor materials withstand up to 1 - 10 kW/cm^2 of continuous power density. The small size of available diamond windows may limit their use, but diamond can withstand over 2 MW/cm^2 of continuous intensity at 10.6 μm.[10] Sapphire is nearly an ideal window material for wavelengths less than 5.5 μm, because of its mechanical strength as well as optical quality.

If higher intensities could be handled by the window materials, they would probably not be useful since saturation and dissociation become important at intensities less than 10 kW/cm^2. For example, Karlov et al.,[11] have shown that $BC\ell_3$ and SF_6 are more than 97% dissociated at an incident CO_2 laser intensity of 10 kW/cm^2. In this regard CO may prove to be an optimum engine fluid due to its high dissociation energy. Finally, at high gas temperatures absorption bands begin to become transparent due to the reduced population. For example, CO_2 absorption coefficients for the 9.6 μm and 10.6 μm bands peak at 0.04 cm^{-1} at 900°K and fall to approximately 0.01 cm^{-1} by 1500°K.[12]

In spite of these limitations the laser driven engine does offer the possibility of efficiently converting absorbed laser energy to either mechanical or electrical energy. The efficient operation of a heat engine through laser heated gas is not accidental. Under most circumstances of interest, the heat engine cycle times are long enough to allow vibrational to translational energy conversion but short enough to prevent excessive heat losses due to thermal conduction to the walls.

With very high average power lasers now available, remote power transmission and conversion is indeed possible. Stirling or perhaps Brayton cycle engines offer a very viable alternative to efficient remote energy conversion. Closed cycle operation, long life inexpensive construction and size scalability to 100 MW are significant potential advantages. Our preliminary experimental results show that nineteenth century heat engines may fulfill a twentieth century energy conversion need.

ACKNOWLEDGEMENT

We wish to acknowledge Coherent Radiation Laboratory of Palo Alto, California, for the use of a CO_2 laser.

FIGURE CAPTIONS

1. A Solar driven steam engine exhibited at the 1878 Paris World's Fair by Mouchot.

2. A schematic of the Beale free piston Stirling engine.

3. Operating cycle, displacement of pistons and pressure vs time for the Beale engine.

4. Oscillating frequency, power output and operating efficiency (percent) of our engine.

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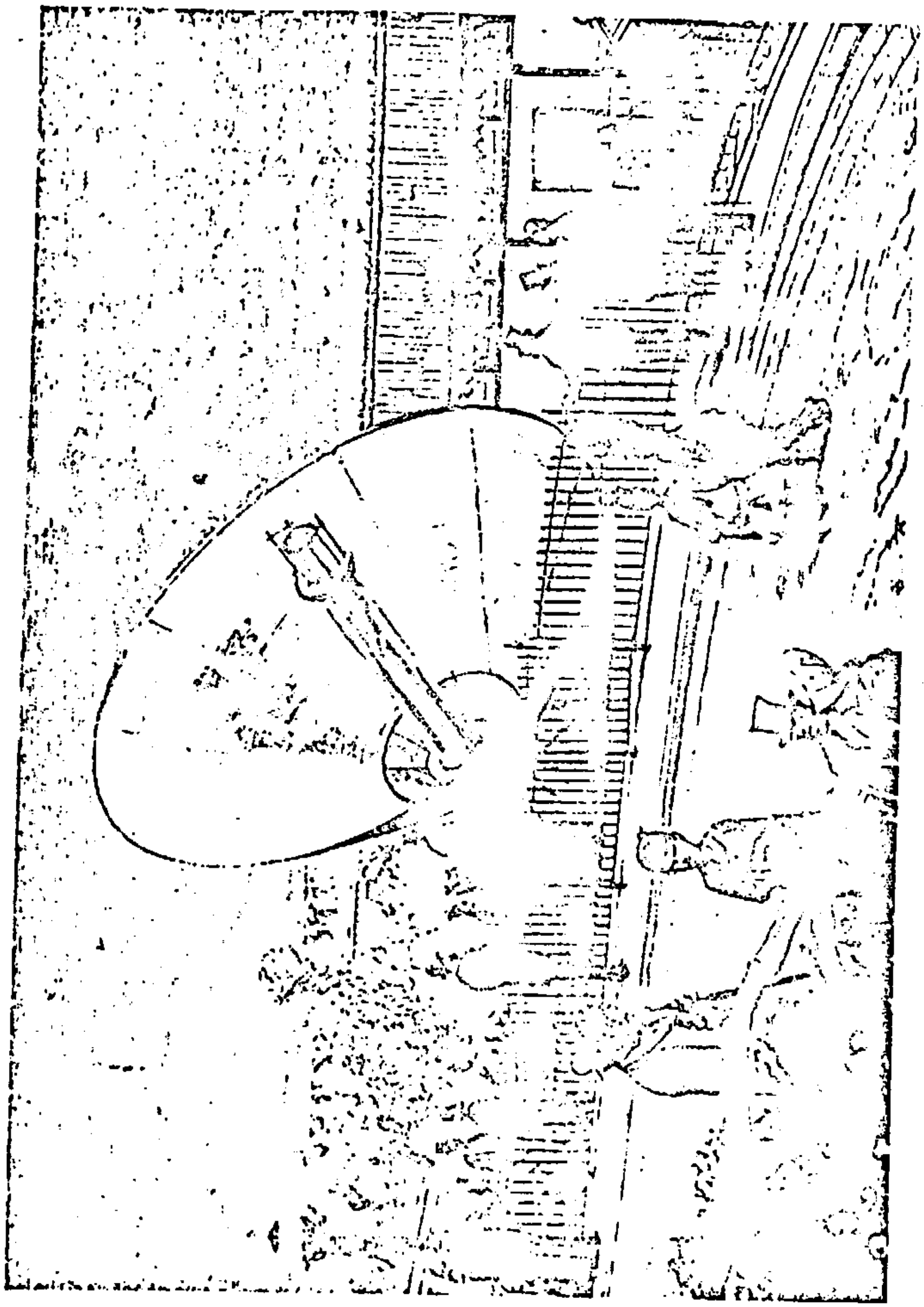

FIGURE 1

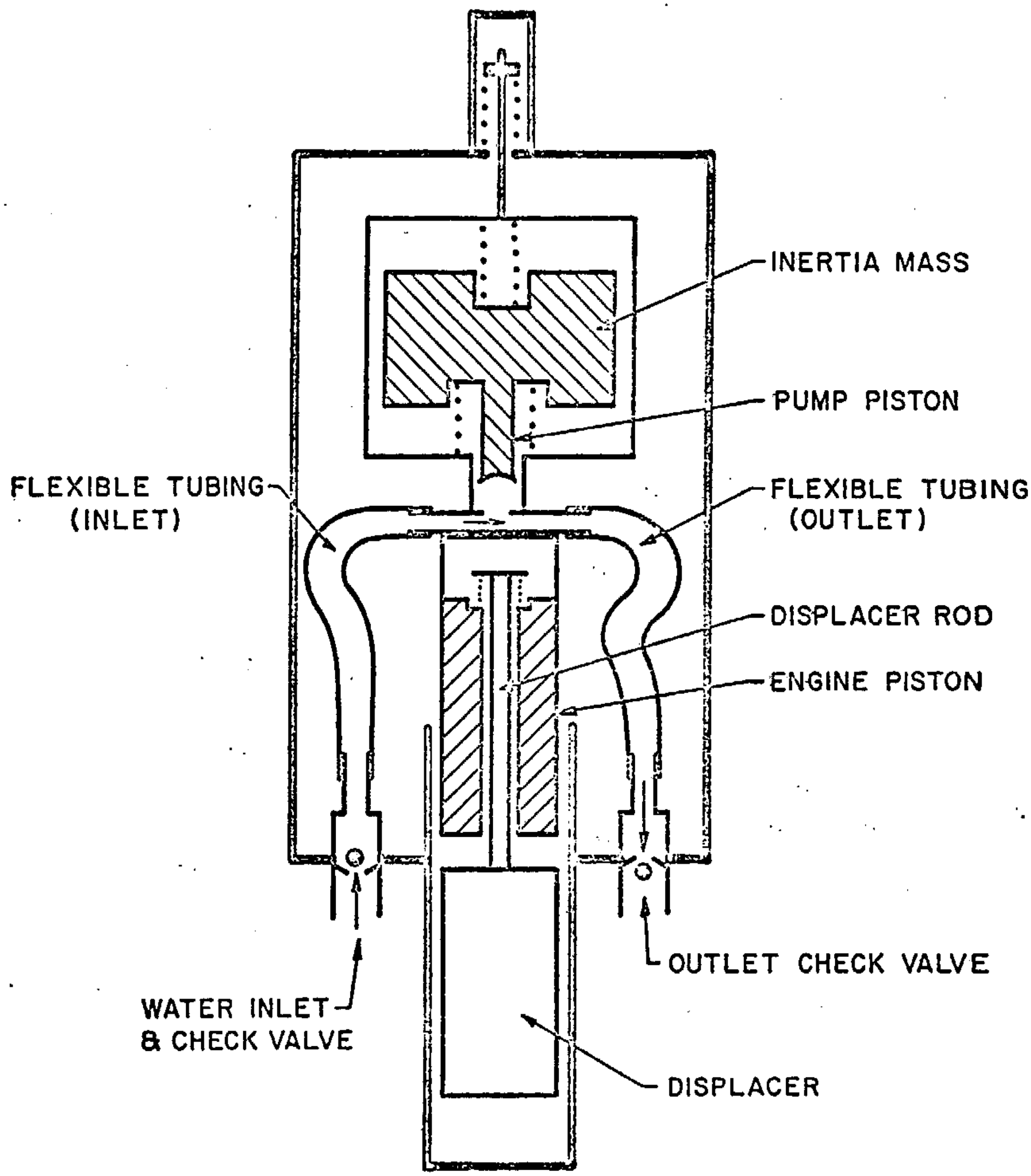
INERTIA MASS
PUMP PISTON
FLEXIBLE TUBING
(INLET)
FLEXIBLE TUBING
(OUTLET)
DISPLACER ROD
ENGINE PISTON
OUTLET CHECK VALVE
WATER INLET
& CHECK VALVE
DISPLACER

FIGURE 2

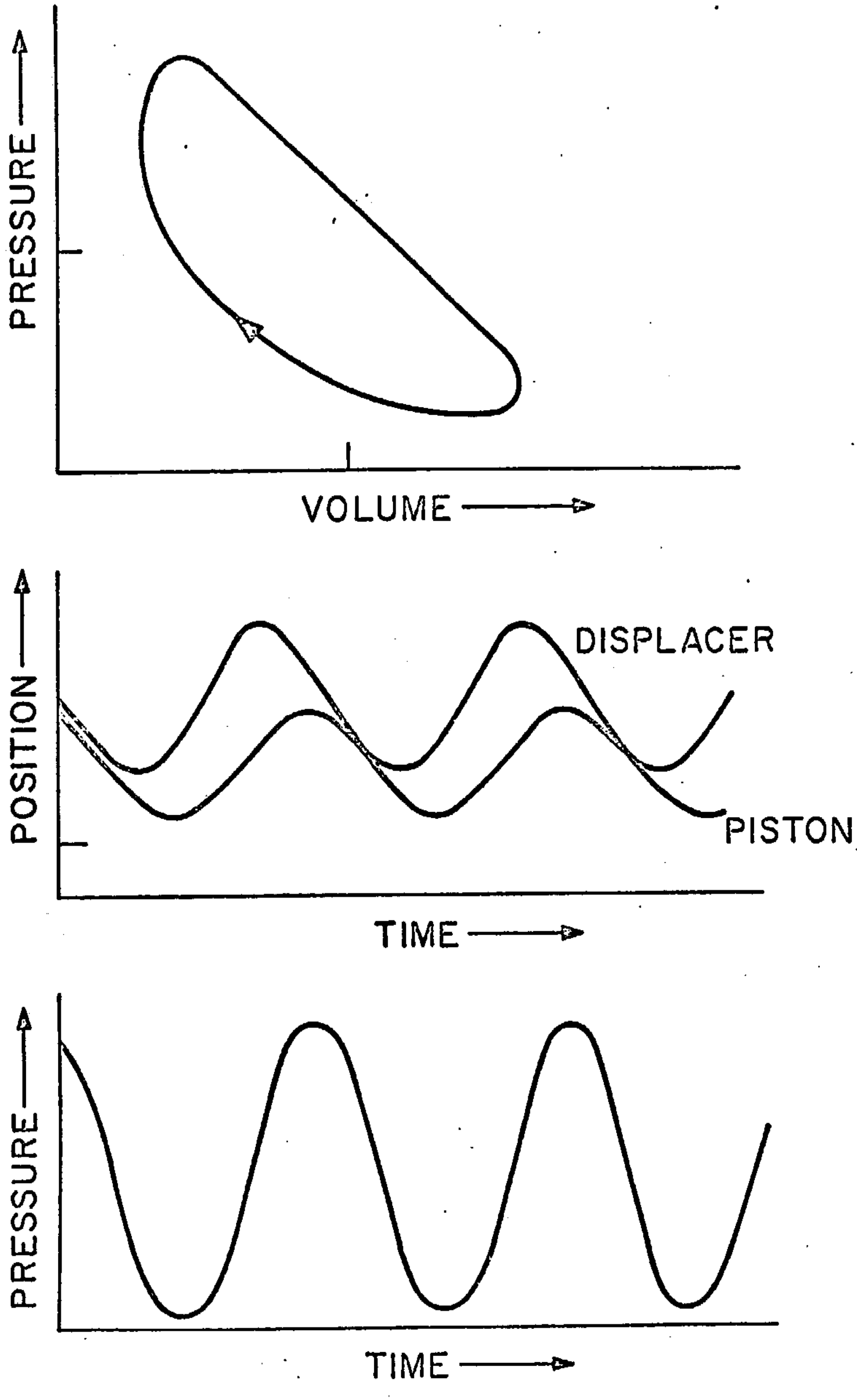
PRESSURE
VOLUME
POSITION
DISPLACER
PISTON
TIME
PRESSURE
TIME

FIGURE 3

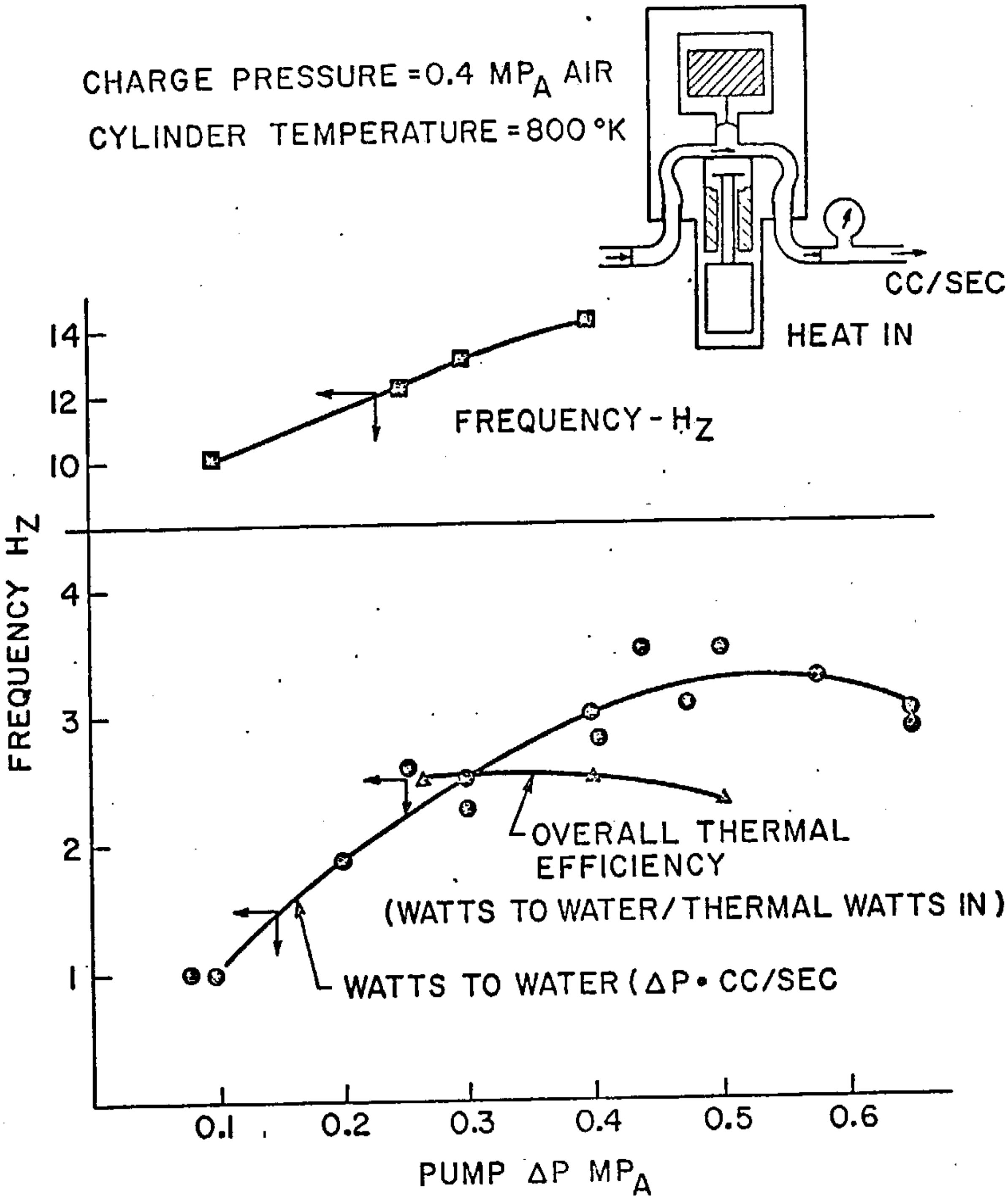
CHARGE PRESSURE = 0.4 MPA AIR
CYLINDER TEMPERATURE = 800 °K
CC/SEC
HEAT IN
14
12
10
FREQUENCY - HZ
FREQUENCY HZ
4
3
2
1
OVERALL THERMAL EFFICIENCY
(WATTS TO WATER/THERMAL WATTS IN)
WATTS TO WATER (ΔP • CC/SEC
0.1
0.2
0.3
0.4
0.5
0.6
PUMP ΔP MPA

FIGURE 4