ADVANCED PHOTON ENGINES

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At the University of Washington as part of studies relating to the conversion of laser energy into useful forms of work, it has been established that coherent radiation is a form of work. This study led to the design of concepts (ref. 1) which could convert coherent laser radiation into flow energy with a theoretical efficiency of unity. However, in examining the practical efficiencies that could be achieved, it was also found that the fraction of energy that was converted on each pass of the fluid was very small compared to the flow energy. Hence, only by extremely efficient design could successful photon engines of this class be created.

However, the coherent energy field of a laser can be concentrated into a small volume so that high energy densities and high gas temperatures are easily achieved. A normal thermodynamic engine working over this temperature range also produced efficiencies close to one. Nonetheless, this heat energy cannot be converted into work with a very high efficiency due to the well known limitations of high temperature materials.

A class of heat engines developed some years ago has proved capable of operation above normal material temperatures. Essentially, these heat engines use a device called the Energy Exchanger (ref. 2) which is related to principles developed by Claude Seippel of Brown Bovari (ref. 3). This principle has shown that energy can be directly exchanged between high temperature and low temperature gases so that the wall temperature of the machine sees only an average. An extension of this principle has shown that this energy exchange can in principle be also made highly efficient if an acoustic velocity match between the hot and cold gas is maintained. This ratio is easily maintained in working machinery by use of high molecular weight gases in contact with low molecular weight gases. Indeed, temperature ratios as high as 10 can be achieved. With these high temperatures the circulating power fraction becomes very small since the work available per unit of mass flow is correspondingly large. Indeed, in the limit of very high temperatures, it can be shown that for a simple cycle such as the Brayton cycle, the component inefficiency can be tolerated as shown in figure 1. When combined with recent studies showing that lasers can be used to heat gases to extremely high temperatures, such as has been proposed at this meeting for jet propulsion and as proposed for wind tunnel research (ref. 4), it is evident that very high thermal efficiencies are achievable. A reasonable extrapolation of this technology suggests that it is within engineering capabilities today to produce a practical engine that can convert coherent radiation back to work with efficiencies of approximately 60 percent. It is expected that further studies will show how this efficiency can be increased to 75 percent.

A proposed method of operating such a machine would involve the following operation as a Brayton cycle as shown in figure 2. We will consider here for simplicity only a simple regenerated Brayton cycle with the addition of an energy exchanger device. A compressor will be used, using a suitable intercooler, to bring the gas to a reasonably high compression ratio. The working gas could be in this example argon or water vapor. The working gas would then be passed to the equivalent of the combustion chamber in a normal gas turbine cycle. However, rather than using combustion, heating would take place directly by laser energy addition. The laser heating techniques would closely follow those proposed by NASA in its program for space propulsion.

Roughly speaking the same problems of laser energy coupling and heating will be involved. After heating, however, the temperatures required in such a cycle would not be as high as that necessary for propulsion. The use of argon or water vapor of course would be necessary. After heating, the gas would be expanded into an energy exchanger device (ref. 2) as shown in figure 3 and give up its enthalpy directly to a gas of low molecular weight. For example, steam or hydrogen could prove interesting. The temperature of the driven gas would be limited to 1000°K, the conventional turbine inlet temperature. Since the molecular weight of argon is approximately 40 and that of hydrogen approximately 2, the temperature ratio for perfect acoustic impedance matching, which is required for efficient energy exchanger operation in this case, would allow a theoretical argon temperature of nearly 20,000°K. Hence the hydrogen temperature can either be made correspondingly low or gases of higher molecular weight can be used. This is of course an example of the extremes of operation. Steam might indeed be a very practical driver gas though the temperature ratios achievable for highest efficiency are not near as high.

The hydrogen or steam in the driven gas loop now has nearly the entire enthalpy of the laser heated gas at a much lower temperature. It then enters the turbine, expands through the turbine, and returns through the energy exchanger for recompression. The argon or steam, after it is discharged from the energy exchanger then passes through a conventional heat exchanger and is returned to the cycle. Thus we have the elements of a completely closed cycle as shown in figure 4. While the energy exchanger adds an element of inefficiency, the very high enthalpies involved mean a very small circulating power fraction which tends to reduce the effect of component inefficiencies and make it possible to achieve nearly ideal Brayton cycle efficiency.

We have yet to explore all of the problems involved in the optimal design of such a cycle. For example, the temperature limits on the argon could be such that they would involve a high radiative heat loss thus effectively limiting the advantages of laser heating. In addition there will be mixing of the driver and driven gas and hence some type of separation mechanism may have to be employed. This of course would be simplified by using steam in the driver or driven loop of the cycle since it could easily be condensed out as part of the operation and returned to the cycle. As pointed out previously, even when working with air, thermal efficiencies approaching 50 percent were achieved and certainly in this configuration we could expect to easily exceed this value. As a practical thermal-cycle this appears very appealing at this state, since it is capable not only of high conversion efficiency but involves concepts built around existing thermal machinery and has a capability for handling large amounts of power in principle.

In view of the potential of this approach, work in this area is continuing and studies of cycles of this type will be carried out to examine the limits of operation.

REFERENCES

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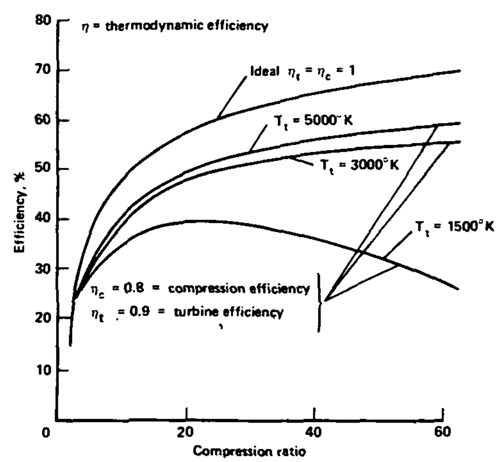

Figure 1.– Brayton cycle efficiency.

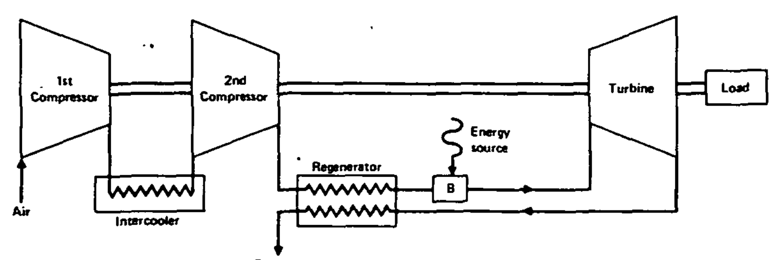

Figure 2.– Basic regeneration type gas turbine cycle.

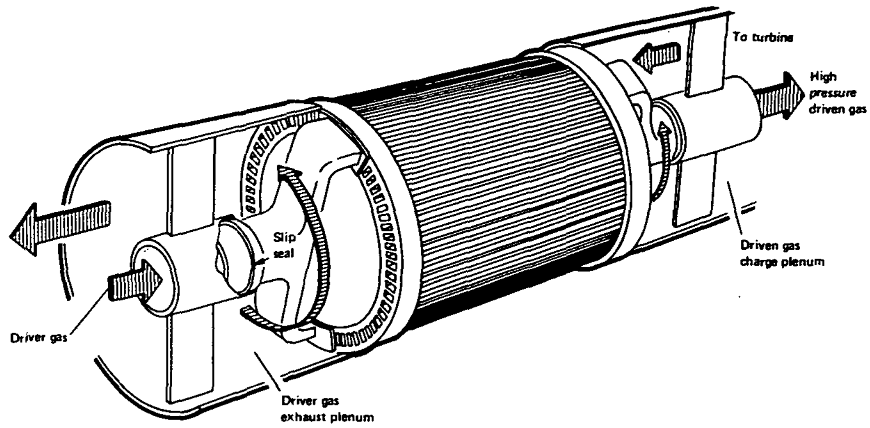

Figure 3.– Illustration of energy exchanger with fixed tubes.

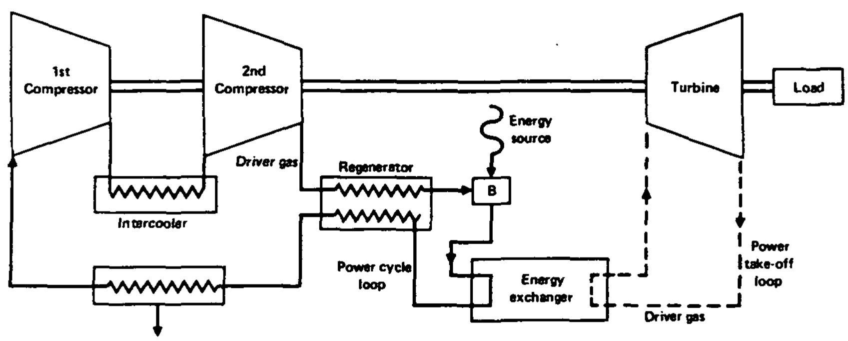

Figure 4.– Closed regeneration cycle with energy exchanger.

DISCUSSION

Ned Rasor, Rasor Associates – At what point do you add the heat from the laser to the cycle? At the high temperature?

Answer: That is where you want to add it to keep the entropy low. But look, between infinite temperature and 5000 degrees, there is enough ΔT to make heat transfer possible. Look, just imagine the rocket nozzle sitting in space and these tubes rotating by it. So we then use this as an energy exchanger, or really an enthalpy exchanger. The trick in getting it to be efficient is, if I can run this in two closed cycles, I can use gases of *vastly* different molecular weight which are commonly available and which are very compatible with real machinery. Argon is inert, helium is inert, the quantities needed are not large, and, finally, they are recyclable.

Arthur Cohn, Electric Power Research Institute – What is the efficiency of the gas-dynamic compressor like?

Answer: Well, in a widely unread paper (good thing you asked that question, sir!) we examined that. The machine is not for "smallies" – leakage and viscous losses will kill you. What we did is optimize it for several different cycles. The paper is "The Energy Exchanger – A New Concept for High Efficiency Gas Turbines" written in about 1966. Incidently, we found you could not sell, in those days, high efficiency gas turbines since people said, look at the cost of fuel compared with the capital cost! So it was unsaleable. But things have changed a little and that is why we are going back to look at it. We assumed just steam and air, not perfectly impedance matched, and found the efficiency of the exchanger to be 15 percent. So you add that loss; you optimize your cycle, adding a little turbine reheat, etc., and you find the cycle efficiency to be over 60 percent. So remember, if I apply it with perfect impedance matching, I would estimate, even at higher temperatures, I could keep the same 15 percent loss. But remember that those losses begin to disappear because the enthalpy per pound of gas going through there is so high that the inefficiencies working on it have less chance of being deadly. High temperatures are the salvation of almost any thermal machine. It even makes something like MHD which has a conversion of approximately 30 percent mechanical to electrical look more attractive (if things don't melt). So we continue to examine this. We wish it would work with coal but it's hard to believe that all that rotating machinery will live in such a dusty environment.

Ken Billman, NASA Ames Research Center – Abe, what was the exact reference of the paper?

Answer: It was presented at the Gas Turbine Conference at Zurich, Switzerland of 1966; American Society of Mechanical Engineers, Paper No. 66-GT-117. It is an archival reference.

Gerald Dzakowic, Lawrence Livermore Laboratory – How high a temperature difference can the Comprex machine tolerate across the unit? Will you eventually become radiation limited?

Answer: Yes, I'll become radiation limited at about 5000°K. Remember, when we expand the gas into the Comprex its ambient temperature, in the Comprex, is quite a bit lower. However, the time that the gas is at stagnation at 5000°K is very small and the radiation transfer will be significant at that temperature. We haven't done all the numbers yet, however. But a good point to mention is that at some temperature we are forbidden to use high molecular weight gases since they are great radiators.

Gary Russell, J. P. L. – Abe, as I remember, you applied that concept at Cornell to heat wind tunnels. Was the motivation the same or was it just an inexpensive approach to that problem?

Answer: Well, there was no other way to get air at 5000°K, 1500 psi total pressure. And, by the way, there still isn't – we've done better in an arc but not at those pressures. Nobody has been able to hit stagnation temperatures like that. In fact, we never found anything that would stand up to that blast coming out. Nothing!