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Energy storage for construction robots

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ABSTRACT

In the construction and nuclear industries the typical robotic tasks, such as tearing, shearing and pushing are repetitive and require intermittently applied high strengths. Control of machine activity is often by machine operator via thin wire umbilical or telemetry link. In these cases, robot autonomy depends on powerful actuators and an independent power source rather than external sensing and 'on-board' intelligence.

Compressed gas has the potential to provide a controllable energy source with a high power to weight ratio. This form of energy storage is therefore well suited to mobile robots having large intermittent load requirements. In certain types of construction equipment it may be useful to have the extra weight due to a massive power plant sized for maximum load. However, for any machine that is required to walk, climb or crawl through tunnels, a high power to weight ratio is essential.

A power source for hydraulic actuators and motivation is presented which incorporates the essential features of low weight, high efficiency and large energy store. A proof-of-principle device has been constructed which is being used as a basis for a more refined design. The prototype will eventually provide power for a small independent construction robot. Test results indicate that a reasonable goal is for 0. 2 m^3 of compressed gas at 200 Bar and 200°K to provide 3 kW power output for hourly intervals between recharging. On-board recharging using a small heat engine should extend this operating time indefinitely.

The prototype design is purposely simple, just elaborate enough to expand the compressed gas efficiently, while providing control of variable intermittent loads. The processes used are not new, but firmly based on classical thermodynamic principles. The practical use of isothermal expansion may appear novel but this is only because high rotational speeds of conventional power plant do not allow sufficient time for isothermal Processes

Preliminary results are provided from tests conducted to determine likely power output and conversion efficiency.

1. INTRODUCTION

This paper describes a method of utilising stored pneumatic energy as a means of powering high pressure hydraulic mechanisms in large robots used in the construction and nuclear power industries. The system is not intended for use in industrial robots which have access to factory power supplies, and often use low pressure pneumatic or hydraulic systems to reduce the weight of components and hence inertia.

Benefits are that pneumatic storage can be integrated directly with hydraulic circuits thus eliminating the need for intermediate power conversion such as combustion engine to hydraulic pump, or batteries to electric motor to pump, which have disadvantaged robot hydraulics in the past [1]. It is also possible to conveniently control a group of actuators (as might be found on a work head) from a block of 1/4" or 1/8" B.S.P. air control valves. Moreover, inert gases can be used to reduce the

risk in dangerous environments. For all these reasons, Carbon Dioxide and compressed Nitrogen have previously been used to motivate robots.

The key to effective use of pneumatic storage is efficient expansion of the gas, and the maximisation of stored energy density . Towards this end, a prototype device has been built with the ultimate intention of providing motive energy for a mobile robot. The design, which attempts to balance maximum energy conversion with the problems of practical implementation, raises interesting engineering questions. A number of configurations were tested, and will be illustrated and discussed as optional models.

In all cases the expanding gas is in direct contact with the hydraulic oil. This removes the need for separate expanders, such as air turbines or air motors, which require gearing as well as many stages to expand the high pressure gas efficiently.

The 'Oil Displacement' method of expansion used in the prototype has a relatively long expansion/exhaust cycle time. However, the low power output compared to conventional gas expanders e.g. air turbines, was considered acceptable when design simplicity and weight savings are taken into account. Also, there are thermodynamic advantages in having direct contact between the oil and expanding gas, as discussed in Section 3

2. BACKGROUND

Underground compressed air storage (CAS) schemes which are designed to produce electricity independent of other energy sources, have been studied by electrical utility companies and found to be viable [2]. The most famous practical implementation is at Huntorf near Bremen, where air is stored in an underground cavern at 37°C and 68 Bar. This is not a truly independent CAS scheme because fuel is burnt in the compressed air flow before it enters a turbine, however it does provide data on overall effectiveness and practicality of the method.

Based on this and other studies, it was recognised that CAS has a high power density(W/Kg) which is capable of competing with most non-chemical storage methods; large amounts of power become available simply by opening a valve to the turbine. Hence, so far, CAS has a primary role in Electrical Power Peaking. However the reason for its non-acceptance in other applications such as transport, is the low energy density(Wh/Kg) hitherto associated with compressed gas [3]. This does not affect the viability of electrical utility schemes, providing there is a convenient underground cavern nearby.

Obviously robots cannot depend on voluminous quantities of compressed air for their motive power. So the remainder of this paper will concentrate on the techniques adopted to improve the energy density of pneumatic storage suitable for construction robots.

3. IMPROVEMENTS TO THE ENERGY DENSITY OF COMPRESSED GAS

A double strategy is proposed to improve energy densities in pneumatic storage systems, as they might be applied to robots. Firstly, the conversion rate of pneumatic to mechanical energy must be increased. This is mainly done by improving the efficiency of gas expansion, using methods that are incorporated in the prototype, and discussed in Section 4.0 Secondly, this section deals with ways of increasing the density(Kg/m^3)of the stored gas itself, and hence its total energy content.

The density of the gas is increased simply by raising the storage pressure and reducing the temperature. An increase in (isothermal) storage pressure from 68 Bar to 200 Bar (320°K) will increase gas density by a factor of 2.8, as shown in figure 1. Reducing the storage temperature from 320°K to 200°K (-73°C) will further increase the gas density by 1.6.

Low storage temperatures do not present an insurmountable problem, since differentials of 100°C are common in engineering situations(e.g. domestic hot water systems). The thermal insulation necessary to maintain a temperature of -73°C would be fairly lightweight and approximately 25mm thick; a fraction of that required for thermal energy storage.

It is not practical to expand gas from an initial temperature -73°C since the hydraulic oil would solidify, so the prototype is fitted with a heat exchanger to raise gas temperature to ambient; prior to expansion. A non-return valve is connected to the inlet of the heat exchanger and there is a control valve at the outlet. Heating effectively takes place at constant volume hence, an increase in temperature is accompanied by an increase in pressure which further raises the overall energy density of the stored gas.

Assuming that the stored gas is expanded isothermally, according to the expression:

$$E = TdS \text{ (Ki /Kq)} \quad \text{[Or equivalently } E=MRT\, Ln(Ve/Ns)\text{]}$$

where E is the Energy Content of 1 kg of gas (Kj)
T is the isothermal temperature (°K)
ds is the change in entropy over the range of expansion pressures (Kj/kg . °K)
M is the mass of gas. 1 kg in this case
R is the Universal Gas Constant
V_e is the expanded volume (m^3)
V_s is the storage (initial) volume (m^3)

where the total energy density of air at 200Bar and -73°C will be approximately 243 Mj/m^3; after constant volume heating to 320°K. The mean* energy density for 1 m^3 of compressed gas will be approximately 163 Mj/m3. This places pneumatic storage within the energy density ranges of most other non-chemical storage media[3], and is higher than gaseous hydrogen (on a volumetric basis) particularly when the camot efficiency of the thermal energy converter is taken into account.

Thus, a cylinder 0.5m dia and 1.0m ht, containing 0.2m3 of compressed air at 200Bar and the hydraulic turbine shown in Figure 4 was tried in place of the hydraulic motor. However, due to parasitic losses in the interconnecting pipe work and blading, the results were disappointing. The hydraulic motor which was eventually used in the prototype is not really intended to operate much lower than 30Bar, nevertheless, its performance down to 7Bar was much better than the hydraulic turbine. The results of experiments and the effects of varying parameters are discussed in Section 5.0.

4.2 Utilisation of the Total Mass of Stored Gas

The effectiveness of pneumatic storage in conventional arrangements is dramatically limited by the fall in reservoir pressure after relatively short periods of use. For example, the requirement for a minimum system pressure of 100Bar means that only half the mass of stored gas can be utilised in a cylinder initially at 200Bar.

Pressure intensifiers might be used to supply high pressure oil from low pressure air remaining in the cylinder, but these add weight to the robot and, in any case, do not expand the gas efficiently.

Obviously, raising initial storage pressure will increase the fraction of usable mass, but 200Bar is the limiting pressure for light commercially available cylinders. Moreover, to supply 200Bar from higher storage pressures would require a pressure reducing valve. These valves are inherently energy inefficient because, unlike expansion through a turbine, the throttling process does not recover any energy.

Liquefied gas has the capability of supplying high (saturated vapour) pressures for long periods of time, but liquid air presents serious operating problems due to low temperatures, as well as sourcing problems and the danger of explosive oxidation with hydraulic oils.

The prototype solution is to transform low pressures in the storage cylinder (below 100Bar) into high oil pressures using the motor/pump arrangement, previously described.

4.3 Recovery of Thermal Energy

A further problem with pneumatic storage is the difficulty in recovering thermal energy absorbed during the compression process:

4.3.1 Compression

Isothermal, rather than adiabatic, compression of gas is used because this requires the least amount of compressor work and the gas can be stored easily at ambient temperatures.

4.3.2 Expansion

Low (cryogenic) temperatures result from the adiabatic expansion of high pressure air at ambient temperature. The isothermal expansion used in the prototype removes this problem, and is easily realisable with direct contact between hydraulic oil and expanding gas. The oil supplies heat to maintain isothermal conditions in the gas.

4.3.3 Recharging

If a heat engine is used to compress the gas, overall thermodynamic efficiency can be improved by transferring heat from the engine exhaust and refrigerator condenser to the isothermally compressed gas; under constant volume conditions. The extra energy can be extracted by expanding the gas and producing useful work.

200°K (-73°C) will theoretically be able to provide sufficient energy for either:
... 534Kw for one minute (with an air turbine expander), 3Kw for three hours, 3Kw/1 Kw cycle lasting 5 seconds at each power level, for 4.5 hours.

4.0 IMPROVEMENTS IN ENERGY CONVERSION EFFICIENCY

There are three essential reasons for the low energy conversion rates in conventional pneumatic energy systems:

i) Inefficient expansion .
ii) Incomplete utilisation of the total mass of compressed gas.
iii) Inability to utilise thermal energy.

.... each of these will now be discussed, together with the proposed prototype solutions.

4.1 Expansion Process

The process of expanding gas at constant pressure (e.g. in pneumatic actuators) is very inefficient. It leaves the gas at the end of the stroke in an unexpanded state. When this gas is exhausted to atmospheric pressure most of the compression energy is lost. Full (reversible) expansion of the gas is necessary to transfer all available compression energy to the piston or hydraulic fluid.

*calculated using a mean pressure of 100Bar; should be integrated over the pressure range 200 to 1 Bar for more accuracy.

In high pressure hydraulic systems (approx 200Bar) full expansion of the gas is not possible because pressures in the final stage of expansion cannot be utilised.

In the prototype device this problem is overcome by allowing the expanding air to force oil through a hydraulic motor . The motor drives a hydraulic pump which maintains a high system operating pressure, regardless of motive air pressure.

Figure 2 shows the 4Kw hydraulic motor/pump combination used in the prototype. Figure 2a shows a 15Kw arrangement where the pump has a separate cog-drive which can be driven by a recharging I.C. engine. During recharging, the hydraulic motor can be disengaged from the gear-tooth coupling.

A diagram of the complete operating system is shown in Figure 3. After expansion of the gas is complete low pressure oil from a reservoir is admitted to the expansion chamber to replace the oil which has passed through the hydraulic motor. This incoming oil pushes expanded gas through a vent valve, until the chamber is full of oil again. The cycle repeats itself when the control valve on the outlet of the heat exchanger opens to the oil filled chamber.

This is a somewhat unusual arrangement which, in order to minimise hydraulic friction losses, must be carefully integrated with the system. A fundamental problem is to find the hydrodynamic or hydraulic machine that is capable of operating efficiently over the range of pressures that exist during the gas expansion process; i.e. from 200 to 7Bar. For this reason

5.0 RESULTS AND DISCUSSION

Separate tests were carried out to determine the effectiveness of the ambient heat exchanger in the low temperature storage system, and the energy conversion efficiency of the motor/pump arrangement. Preliminary results are now discussed.

5.1 Low temperature store heat exchanger

In the initial series of experiments, the gas storage temperature was limited to -40°C rather than -73°C. This was conveniently achieved using CO_2 as the cooling agent.

Even at these higher storage temperatures it was possible to judge the effectiveness of the constant volume heat exchanger used to warm stored air to ambient temperatures (approx. 300°K). It was found that the actual pressures achieved after heating the gas to 300°K, were considerably lower than the theoretical values obtained from charts, shown in Figure 1. This suggested low heat transfer rates and relatively high dead volumes i.e. the gas is not in contact with the heating surface. A new design of heat exchanger is intended to improve this situation.

5.2 Energy conversion efficiency

The overall conversion efficiency of pneumatic energy to hydraulic power was determined by comparing the theoretical energy content of a measured volume (38ml) of high pressure gas with the energy output from the pump .Since gas expansion, hydraulic motor operation and pumping occur simultaneously, the energy conversion efficiency can simply be expressed as:

$$\text{Conversion Efficiency (CE)} = \frac{\text{Work Output from the pump}}{\text{Work done during the reversible isothermal compression from 1 to 200Bar of a measured volume of gas.}}$$

$$\text{Therefore CE} = \frac{Pm.Vo}{T.ds.p.Vm}$$

Where:

Pm is the mean pump output pressure(N/m^3)
Vo is the volume of oil pumped(m^3)
p is the density of gas at initial pressure(Kg/m^3)
Vm is the measured volume of gas i.e. 38ml(m^3)
ds is the entropy change of isothermal expansion(Kj/Kg.°K)

Conversion efficiencies were obtained for various values of mean pump pressure i.e. the average of maximum and minimum output pressure measured during each test.

The mean pump pressure was varied by closing a control valve on the discharge pipe. Gas pressure at the start of each test was 100Bar.

Initial results were encouraging and are presented in Table 1:

Table 1 shows that the conversion efficiency (i.e. expansion work: pump output) of the motor and pump arrangement is high, approximately 70%. Also, the prototype device is capable of converting gas pressures which are less than 100Bar to hydraulic pressures greater than 175Bar; it would therefore appear to perform adequately.

However, stopping gas expansion at 30 Bar drastically reduces the amount of compression energy that can be extracted from the gas; a maximum overall cycle efficiency (i.e. compressor work: pump output) of only 20% is possible because the compressor work done from 1 Bar to 30 Bar is completely lost.

Continuing the expansion to 7Bar would improve the overall cycle efficiency, resulting in a theoretical value of 60%. A lower end-of-expansion pressure can be achieved simply by increasing the diameter of the pipe connection to the hydraulic motor. During these tests, small pipe diameters were purposely used to restrict oil flow and consequently increase the operating time of the motor. This expedient was necessary to allow more time to take pressure measurements, which were read manually. In future, an electronic pressure transducer will be used in conjunction with a data logger.

Efficiency can also be improved by reducing frictional pressure losses in the other pipe work. These losses are mainly due to the experimental nature of the prototype i.e. 90° bends and tee connections.

5.3 Power Output

For a fixed amount of gas energy input (i.e. 38ml of gas at 100Bar), the power output of the device is determined by the time taken to complete expansion and exhaust of the gas. In this particular series of tests, the expansion time was about 3 seconds. This relatively long period is due to deliberate restriction of oil flow to the motor, which is intended to increase operating time and hence reduce pressure measurement error; as previously explained. Future test will concentrate on obtaining maximum power output from the prototype. In order to obtain the 4Kw maximum from the existing motor, the expansion/exhaust cycle time has to be reduced to approximately 0.3 seconds. This time can only be achieved by a combination of methods, which are now discussed in terms of past test results and future work:

5.3.1 End-of-Expansion Pressure

Increasing the end-of-expansion pressure will reduce motor operating time, but also the amount of energy extracted from the gas. In this case, power requirements are opposite to those of efficiency. A complicated relationship exists between motor performance at low pressures, pump characteristics, minimum exhaust pressure and end-of-expansion pressure. However, in the interest of higher overall cycle efficiency, future designs will aim for the lowest possible end-of-expansion pressure. The optimum value can only be determined by experimental means.

Inertia was added to the rotating parts of the motor in order to smooth pump pressure fluctuations and to keep the motor/pump turning at the low pressure end of expansion .

5.3.2 Motor Performance

With the low end-of-expansion pressures necessary to obtain good efficiencies, high power outputs may be possible only with over-sized motors capable of passing high flows at low pressure. Thus a 4Kw output may require a 6Kw motor; the design limit is when the motor ceases to be an inherently efficient hydrostatic device and becomes more like a turbine, with all the friction losses associated with high oil flows. The next series of tests will incorporate the 15Kw Motor/Pump combination shown in figure 2.

5.3.3 Reducing Pipe Friction

Reducing friction in all interconnecting pipe work is important, but it is essential for the piped connection between the oil reservoir and expansion chamber. Because this pipe carries the oil which pushes expanded gas through the vent-valve to atmosphere. A small pipe diameter will restrict flow and increase the exhaust time, as well as raising the necessary reservoir pressure.

5.3.4 Expansion Chamber Design

High power outputs (i.e. above 3Kw) will require multiple expansion chambers. Their operation will need to be sequenced so that while one chamber is in the exhaust phase, the other is in the expansion phase.

CONCLUSIONS

Test results on a prototype device have shown that the principle of pneumatic storage when applied to the production of hydraulic power is feasible. An arrangement of hydraulic motor coupled to a pump was able to convert relatively low gas pressures (i.e. below normal system operating pressure) to hydraulic pressures above 175 Bar. It was able to this at high efficiencies and power to weight ratio higher than the electrical equivalent, which is a tribute to the effectiveness of commercially available hydraulic equipment.

However, the tests also indicate that to avoid low power output and low overall efficiency (i.e. compressor work ~ pump output), system design parameters such as end-of-expansion pressure, hydraulic friction losses and motor selection are critical. Further prototype designs and testing is therefore required.

Ancillary equipment is straightforward, consisting of valves, pipes (or hoses) and a reservoir. Some of the piping would be needed for conventional hydraulic systems in any case. The expansion chamber can become part of this; with thoughtful design. Thus the position of components is flexible, for instance heavier equipment can be sited on the body of the robot while actuators are part of a work head.

Theoretical considerations indicate that pneumatic storage has the potential for very high energy densities in light containers (e.g. insulated aluminium alloy) simply by reducing the storage temperature of the gas. There is an additional heat exchanger required, but it is small and can be connected to the oil circuit on the secondary side. The thermodynamic efficiency of the recharging process can be improved by transferring heat from engine exhaust and refrigeration condenser to (isothermally) compressed gas in the constant volume heat exchanger. The extra energy is recovered by expanding the gas. The next stage of development will be to build a prototype closer to the robot application.

REFERENCES

1 Carrara,G.,De Paulis,A.,Tantussi,G.,1992: 'SSR:a mobile robot on ferromagnetic surfaces' paper in AUTOMATION IN CONSTRUCTION, Vol 1, N° 1., Elsevier, Netherlands., pp 47-53.

2 Glendenning,1.,1979: 'Advanced Mechanical Storage' paper in energy storage and transportation., D.Reidal Co, U.S.A., pp 49-85 3 Jensen. J.. Sorenson. B.. 1984: 'fundamentals of energy storage', John Wiley & Sons, Inc., U.S.A., pp 32-35.

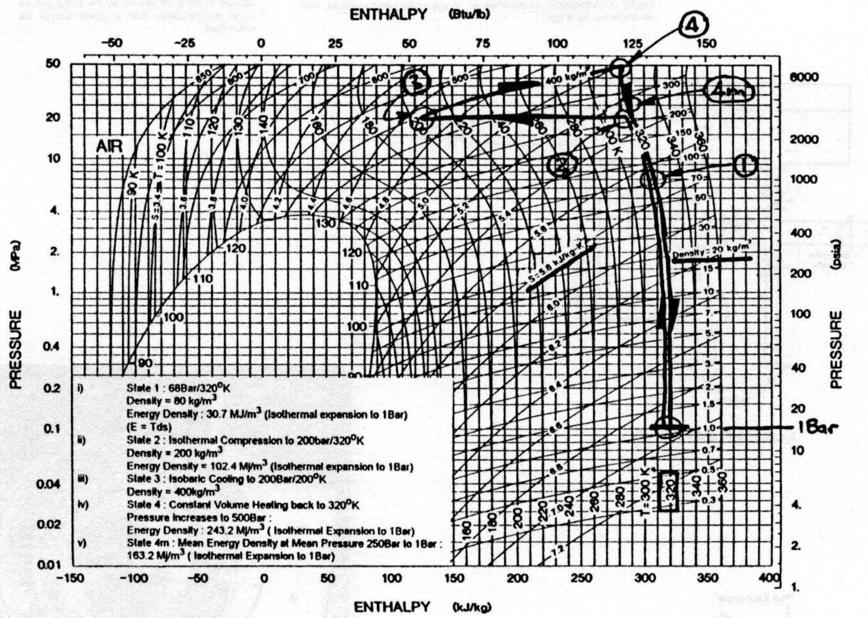

Figure 1 Energy Density of Air at 68Bar/320^{O}K and 200Bar/200^{O}K

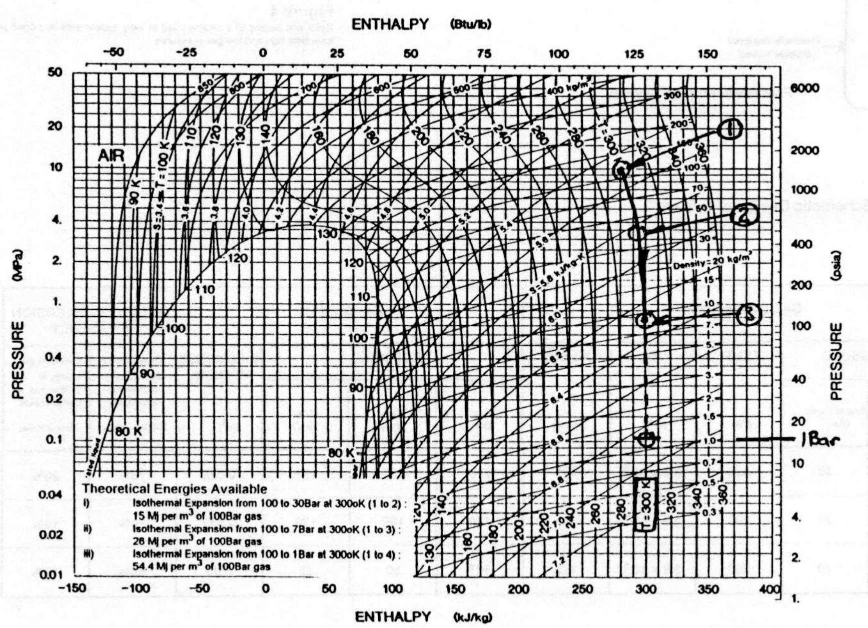

Figure 1a Test Results

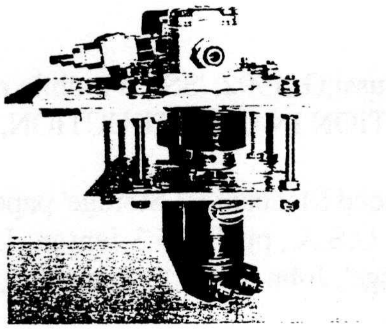

Figure 2
Proto'ype pneumatic/hydraulic energy converter : 4Kw hydraulic motor driving a 4Kw hydraulic pump through a gear coupling. Approximate weight of motor/pump combination is 4 kgs. Approximate weight 4Kw electric motor is 8 kgs.

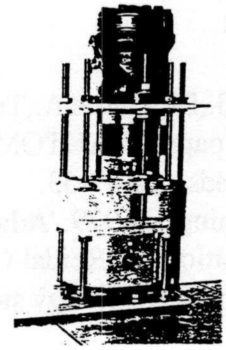

Figure 2a
15 Kw hyydraulic motor driving a 40 Kw hydraulic pump through a gear coupling. The motor drive is capable of being withdrawn, so the pump can be driven independantly from a power source via chain drive.

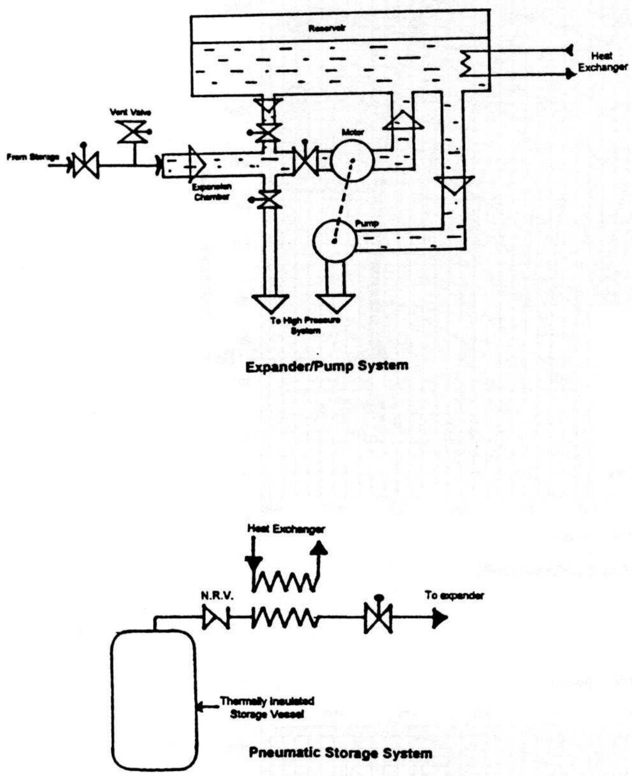

Figure 3 Schematic Design of System

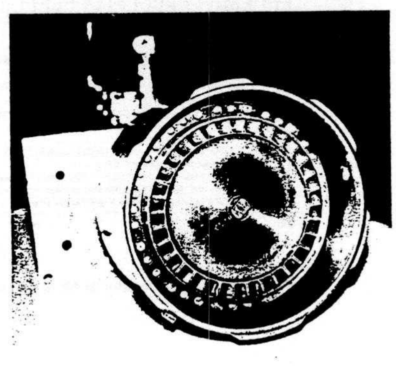

Figure 4
Rotor and blading of a turbine used in early experiments to extract power from both high and low gas pressures.

GAS CONDITIONS					PUMP OUTPUT				ENERGY CONVERSION EFFICIENCY	
PRESSURE		TEMP	VOL	DENSITY	PRESSURE			DISCHARGE VOLUME	Based on the energy from Isothermal Expansion	Based on the energy in Isothermal Compression
Start of Expn. (Bar)	End of Expn. (Bar)	(°K)	(m^3)	(kg/m^3)	Max (Bar)	Min (Bar)	Mean (Bar)	(m^3)	200Bar- 30Bar	1Bar-200Bar
100*	30	300	3.8×10^{-5}	125	200	133	167	0.025	73%	20%
100*	30	300	3.8×10^{-5}	125	140	100	120	0.033	70%	19%
100*	30	300	3.8×10^{-5}	125	107	50	78	0.05	68%	18%

Table 1 : TEST RESULTS OF PROTOTYPE PNEUMATIC / HYDRAULIC ENERGY CONVERTER

* The gas pressure in this series of tests was limited to 100Bar, since it is gas expansion below the normal hydraulic system pressure that is critical to the viability of the proposed system. Pressures 100Bar upwards are transferred directly to the actuator oil as shown in Figure 3, using either isothermal, polytropic or constant pressure expansion.