Low-head hydroelectric power using pneumatic conversion

New hydroelectric power installations at low-head river sites are often an uneconomic proposition using conventional water turbines. This article deals with alternative power-conversion systems based on air as an intermediate fluid which are aimed at achieving a more economic solution to the problem. A novel water-to-air power-conversion system has been built at Borrowash on the River Derwent which utilises a flexible membrane as a self-oscillating interface between water and air to drive an air turbine and generator. Problems of this new technology are discussed and a number of improvements are proposed which should lead to a viable and economic alternative to conventional low-head hydro stations

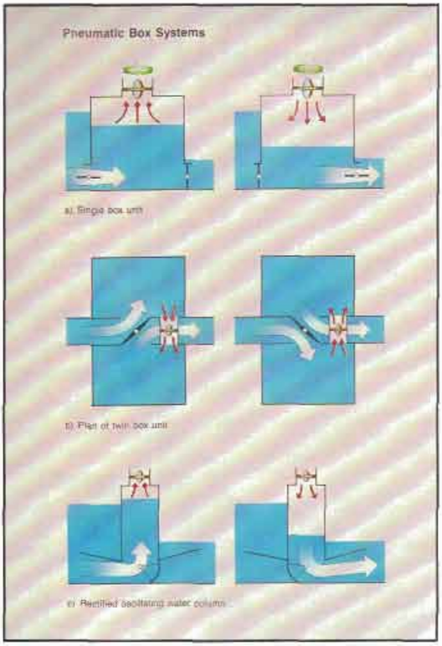
by N. W. Bellamy

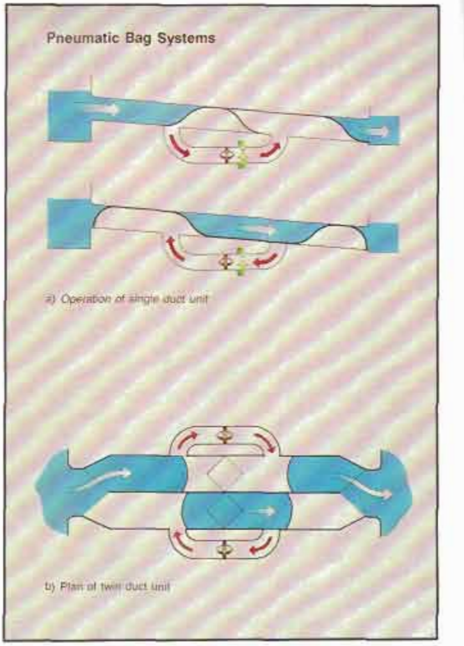
Hydroelectric power has made an important contribution to energy generation since the middle ages. It has had a varied history in economic terms, and developments this century have often been affected by competition from low-cost fossil fuels. Large hydro stations are generally economic in the long term but further developments are limited by site availability and environmental problems. Smaller, micro and mini, hydro stations are again gaining favour throughout the world after interest waned following the cheap fossil-fuel era which started in the 1950s. For instance there are now some 90 000 small hydro sets operated by the Chinese and it is estimated that the total economic exploitable world reserve is 10 000 TWh per year of which 15% is in production at this time.

This article concentrates on micro hydroelectric generation, i.e. power levels in the range 5-5000 kW, at low-head sites with heads from 2 to 5 m. The majority of low-head hydro sites occur at river weirs of former mills, at navigation locks and at irrigation works in certain countries. Normally it is not economic to build weirs for the sole purpose of power generation although it may be opportune to install a hydro station if a head is produced for other reasons. The development of many hydraulically suitable sites is restricted or prevented by other factors such as environmental considerations, existing buildings, leisure pursuits and site ownership. Even if these factors are overcome the economics have to be sufficiently attractive to secure the capital investment and to provide the will to proceed.

The idea of transforming the potential and kinetic energy of water in a river into usable mechanical energy is very old; and the first machines for this transformation were waterwheels which could be used on small heads. The first waterwheels were slow and very inefficient and significant power generation had to wait until the development of modern water turbines of high performance. Even so, low-head turbines are still expensive due to their large diameters and the need for speed increasing gearboxes to drive electrical generators at sensible speeds. Today it appears that conventional low-head hydroelectric stations at sites with heads of less than 4 m and with powers of less than 500 kW are

1 The SEA Clam wave-energy convertor—model under test on Loch Ness





2 Pneumatic-box systems: ***(a)* Single-box unit;** ***(b)* Twin-box unit;** ***(c)* Rectified oscillating water column**

3 Pneumatic-bag systems: ***(a)* Operation of single duct unit;** ***(b)* Plan of twin duct unit**

unlikely to be economic except where do-it-yourself costing applies. Hence a new approach is required to harness low-head hydropower which avoids the current expensive water turbine technology.

During the UK wave-energy programme, 1976-1982, a research team at Coventry Polytechnic developed a wave-energy device called the SEA Clam[1] which was deemed to be the leading device arising out of the national wave-energy programme. The key features contributing to the success of the SEA Clam, and its successor the Circular SEA Clam[2] shown in Fig. 1, were the air-power conversion system utilising flexible membranes and the self-rectifying Wells air turbine.[3] Wave-energy convertors essentially harness a low-head water resource, albeit oscillating, and hence one would expect solutions to both wave and low-head hydro technologies to involve similar power-conversion systems. With the demise of wave-energy research in the UK, the Energy Systems Group at Coventry Polytechnic applied its wave-energy technology to hydroelectric power and developed a range of novel pneumatic power-conversion systems aimed at harnessing low-head hydropower.

Water-to-air power transformers

To produce respectable power outputs from low-head sources the energy contained in large flows of low-pressure water has to be extracted. If this low-grade water power was converted into air power then high-speed turbogenerators could produce the electrical power. In effect, a water-to-air power convertor would act as a transformer or gearbox and large expensive water turbines replaced by much smaller and cheaper air turbines.

The displacement of air by water within a closed structure is the most promising approach to efficient water-to-air power conversion. It follows that displaced air has to be replaced and hence power-conversion systems tend to utilise reversing air flow and require special self-rectifying turbines. Other methods can produce continuous air flow such as air injection into venturies or vortices, but none has led to economic energy-conversion systems.

Pneumatic box systems

One simple but effective pneumatic conversion method aimed at small-scale low-head hydroelectric applications is known generically as the box system and is shown in its various configurations in Fig. 2. In the basic single-box arrangement[4] air is driven in and out of a closed chamber through a self-rectifying Wells turbine by water filling and emptying the chamber through controlled intake and outlet valves. The electrical power output of this system with carefully designed valves is about 4 kWe per metre of water head for each cubic metre of water flow, giving a water to air efficiency of approximately 55% and an air to electrical efficiency of approximately 75%. This box device is suited to modular units of less than 100 kW in order to ease the problems associated with large mechanical water valves.

Output power varies significantly over the 10-20 s switching cycle of the valve operation and is only suitable for feeding into a firm electrical grid. Box systems are generally very flexible in that they can be used as sluice gates or operated in reverse, features useful in tidal-power applications in shallow coastal inlets.

More recently a twin-box design has been developed which is much more efficient and cost effective than the single box and is to be proved as an EEC Energy Demonstration Project at a site in Derbyshire. This twin-box system enables water to flow continuously through the unit via a single valve unit and hence attain water-to-air efficiencies of up to 80%. The economics of the design make it an attractive proposition at many low-head sites, particularly if the power output is smoothed by flywheel storage and sold at a higher price direct to the customer.

Smooth electrical power controlled to match the customer's demand is a necessary design objective for any stand-alone generating system. One method under development to achieve this objective is based on the well known three-phase power concept where three sinusoidal phases spaced 120° apart can be summed to give a constant-amplitude waveform. Sinusoidal air power can be generated by a resonant water column system which is energised by applying the upstream and downstream water heads at the appropriate cycle times. This rectified oscillating water column resonates at a frequency dictated by the enclosed mass of water in the system and the spring rate of the column. The peak-to-peak amplitude of the oscillation is controlled by the damping exerted by the air turbine and normally exceeds the water head for higher power outputs. With sufficient water mass in the system the oscillation is near sinusoidal despite the non-linear forcing function applied by the hydraulic head. Three units with air-turbine-generator systems connected in star or delta should be capable of producing a constant electrical output with voltage variations within a few percent. The system is structurally efficient by virtue of its fast cycle time of 5-10 s and appears to be the most promising way forward to develop box systems with mechanical valves.

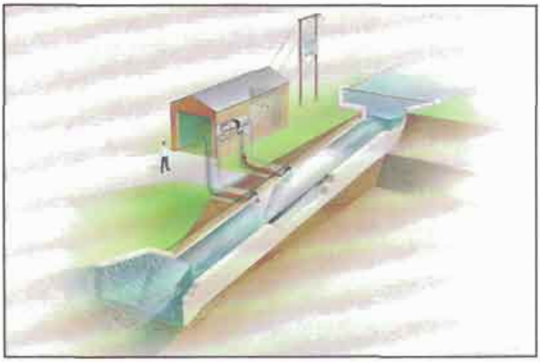
Pneumatic-bag systems

An alternative approach to pneumatic conversion which avoids the use of mechanical valves can be achieved by means of a flexible membrane separating water from air in an unstable orientation defined by a support structure[5] The schematic diagrams shown in Fig. 3 explain the mechanism by which closed-circuit air in two air bags is pumped backwards and forwards through a self-rectifying air turbine by the action of slugs of water passing through an inclined duct. The basic action appears simple but the underlying mechanism is rather complex and needs explanation.

In a single-duct unit water flows over two air bags defined by a flexible membrane with a dividing septum. In normal operation the system contains one bag full of air which allows water to enter the duct and displace the air from the top bag to the bottom bag. The slug of water then passes down the duct displacing air from the bottom bag back into the top bag thereby sealing the entrance to the duct. The sequence then repeats itself when the slug of water leaves the duct and water is allowed to enter the duct again.

The formation of water slugs inside the duct is due to the negative spring characteristic of the water-membrane-air interface which causes the interface to exhibit a bistable action. This bistable action ensures that the membrane is only stable in either the lower profile position allowing water flow or in the upper profile position thereby sealing the duct. During the passage of a slug of water the bistable switching action propagates along the duct in the direction of water flow to give a travelling-wave motion. The air pressure across the

4 Borrowash hydro site on the River Derwent



5 Cutaway view showing operation of Borrowash scheme

turbine is the difference between the individual bag pressures and ideally should approximate to a square wave with an amplitude of half the pressure due to the available water head.

A single-duct system gives intermittent water flow over the normal 10-20 s cycle time of operation. A more efficient and cost-effective arrangement which gives constant water flow can be implemented by using twin ducts working in antiphase and built to operate in the syphon mode to aid maintenance and avoid intake and outlet gates. Output power varies over a cycle and with present designs is only suitable for supply to the grid. Further development of the air-bag concept is aimed at three-phase operation in circular structures to produce smooth controllable power at reduced unit costs.

Borrowash hydroelectric scheme

A pneumatic hydroelectric bag system is at present being tested by Hydro Energy Associates Ltd. on the River Derwent at Borrowash in Derbyshire with the help of a 1985 EEC Energy Demonstration Project grant. The site with a 2·8 m head at an existing weir, shown in Fig. 4, is typical in the UK and the water flow is sufficient to support a single-duct unit rated at 150 kW electrical output. The artist's impression (Fig. 5) shows the hidden workings of the unit and the arrangement of the principal components, concrete duct, reinforced rubber membrane and Wells turbine. Each of these components represents significant steps forward in technology and has incurred challenging development problems. Nevertheless the station has demonstrated that the system operates as predicted although it will be some time before full system efficiency and output power are achieved.

It was predicted at the outset of the project that the membrane and its edge attachment would present major problems in design, manufacture and material development. The membrane shown installed in Fig. 6 is some 30 m long by 5 m wide and prototype manufacturing problems decreed that it should be made from individual panels jointed together. The material chosen for the membrane was two-ply Kevlar-reinforced rubber because of its high strength and dimensional stability. Each ply has unidirectional cords which are aligned at a narrow angle to the other ply cords to give a material with transverse strength and longitudinal elasticity. This property allows the flat material to profile in three dimensions without creasing. In operation the material met the basic requirements but incurred some failures due to discontinuities in load sharing at the joints and complications arising from using high-modulus cord fibres like polyamides. These material development problems are being overcome and there appears to be no fundamental reason why this key component cannot be developed to give an adequate operating life.

The self-rectifying air turbine is a Wells type approximately 1 m in diameter. The single rotor shown in Fig. 7 has six symmetrical aerofoil blades and is coupled direct to a 3000 rev/min induction generator synchronously connected to the grid. Two disc brakes are fitted to prevent overspeed if the electrical load is lost.

6 Membrane installed in hydro duct

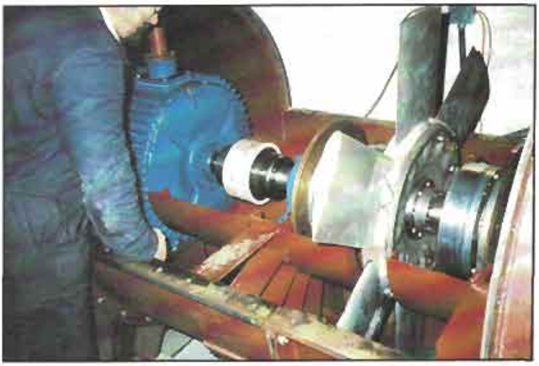
The unit is simple, reliable and very much cheaper to manufacture than an equivalent-rated low-head water turbine. To achieve maximum efficiency and power rating careful attention has had to be given to aerodynamic profiles of the rotor and internal air-duct fittings. Early worries concerning possible noise problems have proved to be unfounded and confirm one of the benefits of the closed-air-system design.

Construction of the civil works and installation of equipment was carried out without undue delay. Early problems associated with membrane edge connection and water hammer were resolved quickly, and subsequent testing of the unit, as shown in Fig. 8, has concentrated on the failure mechanisms in the membrane itself. The unit is well instrumented and the predictable duty cycle enables accurate data collection to be made of air flow, water and air pressures, and efficiencies of each stage of power conversion. Output power is controlled by the amount of air in the system, although an instability problem associated with the membrane interface needs to be overcome before full output power can be achieved. The water intake to the unit is supplied unscreened through syphons and the whole unit appears to pass debris of all kinds without difficulty or harm. The downstream race needs flushing out by continuous use in order to realise the full available site head. Electrical connection to the grid is straightforward with a minimum of switchgear and via a 440 V/3·3 kV pole-mounted transformer. Metering records exported kW and imported kW and kVAR, with the appropriately applied tariff. Income is expected to average about 2·7 pence per exported unit over an operational year.

A number of factors have emerged during the design, construction and commissioning phases which will have a bearing on future designs and give rise to major improvements. First, the economics of construction and maintenance would be improved if the unit was raised by designing it to operate in the syphon mode. This would reduce the civil excavation required below water levels and allow easy access for the maintenance of key components. Secondly, twin or multiple units at larger-capacity sites would improve efficiency by enabling constant water flow at intake and outlet of the ducts, as well as taking advantage of the economies of scale. And thirdly, the ability to produce smooth controllable power at sites of potential customers would nearly double the market value of the electricity produced.

Conclusions

There is a major market for hydroelectric installations capable of exploiting economically the energy available at low-head sites. A novel approach to the problem has been outlined which is based on the pneumatic conversion of water power to electrical power. A number of devices have been defined which will perform this function and details given of their performance characteristics. Finally, a 150 kWe demonstration scheme at Borrowash on the River Derwent is described and the experiences and lessons gained during operation are discussed.



7 Wells air turbine and generator

8 Downstream view of the Borrowash scheme in operation

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