‘VETT’ – A New Approach to Very Low Head Tidal Power Generation

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***Abstract*—The Venturi-Enhanced Turbine Technology (‘VETT’) energy converter is a new device that improves the cost-effectiveness of conventional hydro turbines in producing electrical power from very low head sources (circa 2m) such as tides and rivers. A number of large models in the laboratory and the field, backed up by CFD studies, have demonstrated its performance. It is expected to show a uniquely benign impact on the environment. A live-fish testing programme is planned to demonstrate those characteristics with a view to operating without power wasting and expensive fine-mesh screens. VerdErg Renewable Energy Ltd, VETT’s developer, participated in the UK Government’s Severn Estuary Technology Scheme, and has made contributions to a later Government review of the Severn proposal. There are many thousands of river sites and very large number of tidal situations in which VET Technology could find an application.**

***Keywords*— VETT, tidal energy, marine renewable energy, hydropower, venturi, VerdErg.**

I. Introduction

Generating electricity from water sources with turbines at medium and high heads is now mature technology, having been developed over the last 150 years or so. Many of the best available resources of this type world-wide have now been exploited. In contrast, technology for generating power from tidal streams and rivers (sometimes referred to as ‘zero-head’, though in general some head drop is needed even if it is imperceptible), has only received significant attention in the last 15 years. Those machines do not resemble conventional hydro turbines; many examples are more similar to wind turbines.

Between those two extremes there is a very considerable resource available worldwide at head drops in the range between, say, 1 m to 3 m, both in tidal estuaries and rivers. Although the oldest water power machines operate in that range (waterwheels; tide mills etc) the resource is at present largely unused. This range may be called ‘very low head hydro’, or VLHH.

The reason for this lack of exploitation stems from the fundamental relationship between the power lost by a flow rate of water Q experiencing a pressure drop Δp:

$$P = Q \times \Delta p$$

This is true to first order for tidal stream, ‘zero-head’ devices in an open channel as well as for conventional turbines [1]. If Δp is small then Q must be large for a given power. A conventional turbine handling a large flow rate will be bigger and much more expensive than one handling a small flow rate, and is likely to be uneconomic.

Venturi-Enhanced Turbine Technology (‘VETT’) improves the cost-effectiveness of conventional hydropower turbines in producing electrical power from very low head sources such as waves, tides and rivers. VETT technology (previously under the project name SMEC, for Spectral Marine Energy Converter) has been under development since 2006 by VerdErg Renewable Energy Ltd, based in Woking, England.

The new VETT technology concept is a way of efficiently matching low-head hydropower sources to conventional turbines. It takes a large, useless, low pressure flow as input and usefully outputs a fifth of the flow at four to five times higher pressure.

VETT’s unique feature is that the head drop across its turbine is amplified (on the suction side) by a venturi. It engages 100% of the tidal flow, with the majority of the stream (approx. 80%) passing through a primary path which is entirely passive – there are no moving parts. The remainder passes through a secondary path that contains the turbine. The primary path contains a venturi, creating a low-pressure zone which draws the secondary flow through the turbine at significantly amplified head. Typically a 2m head across the VETT creates an 8m head drop across its turbine in the 20% of the total flow forming the secondary flow, at which head drop the turbine works at high efficiency and cost effectiveness.

VETT can therefore be seen as a kind of ‘pressure amplifier’, the fluid analogue of an electrical transformer stepping up voltage, or a gearbox multiplying torque. A turbine operating with a relatively low flow rate at high pressure is much smaller than one of the same power throughput at a high flow rate at low pressure. It also spins much faster, so that the alternator is smaller. It can be direct-coupled to the turbine with no need for a gearbox. A theoretical study [2] has shown that conventional turbines and generators designed for elevated head and a corresponding fraction of the flow (that is with the same hydrodynamic power) can be an order of magnitude less expensive than they would be at the original head.

This paper describes the operating principles, development to date, and the environmental benefits of the VETT.

II. Operating Principles

A. Description

VETT is a passive device consisting of a series of carefully profiled channels that induce low pressure in a venturi. This low pressure region is connected to the discharge side of a conventional Kaplan or bulb turbine, while the intake side is connected in the normal way to the high level water source.

In Figure 1 flow is from left to right driven by a low head of pressure, typically 2 m. The main part of the flow is accelerated in a contracting region. At the venturi its pressure is very much lower, according to Bernouilli's equation. A small proportion, typically one-fifth, of the total flow is led through a turbine whose discharge port is connected to the venturi. This so-called 'secondary' flow emerges into the main flow and mixes with it. By the end of the venturi section mixing is complete and the combined flow is decelerated in an expanding section in which the kinetic energy of the fast stream is recovered in increased static pressure. Exit pressure is, as mentioned, typically 20 kPa lower than intake, a head of 2 mWG.

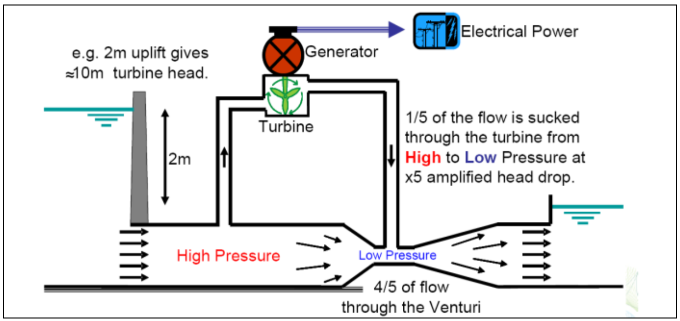

Figure 1 Operating principle of the VETT

The turbine is of conventional, well understood design. However, it is much smaller than would be required without VETT due to the head applied being up to four times greater than that available across the whole machine.

The VETT's performance is characterised by three parameters:

Pressure ratio

The enhancement of pressure across the turbine in a VETT, compared to what it would have been if it had been installed into the site directly, is termed the pressure ratio:

$$PR = \frac{p_{upstream} - p_{venturi}}{p_{upstream} - p_{downstream}}$$

To account for any level changes and velocity changes total pressures should be used.

A typical value of pressure ratio might be 4.

Flow rate fraction

This is the fraction of total flow that is taken by the turbine:

$$FRF = \frac{Q_{turbine}}{Q_{total}}$$

A typical value of flow rate fraction might be 0.2 .

Hydrodynamic efficiency

The total flow of water loses energy as it travels from up to downstream. Ideally all of that energy would be lost in the turbine, that is to say, available for use by the turbine. That implies here that all of the energy in the main flow would be transferred to the secondary flow.

To characterise the extent to which a real VETT approaches this ideal a hydrodynamic efficiency for the can be defined:

$$\eta_H = \frac{hydrodynamic\ power\ lost\ by\ flow\ in\ the\ turbine}{hydrodynamic\ power\ lost\ by\ total\ flow}$$

And since hydrodynamic power is equal to the product of flow rate and pressure change

$$\eta_H = \frac{Q_{turbine} \times (p_{upstream} - p_{venturi})}{Q_{total} \times (p_{upstream} - p_{downstream})}$$

It is clear by inspection that

$$\eta_H = PR \times FRF$$

For example, if the flow rate fraction is set by the design to one-fifth, and the turbine experiences a pressure drop of four times that corresponding to the available head, then the hydrodynamic efficiency is 80%:

$$\eta_H = PR \times FRF = 0.2 \times 4 = 0.8$$

B. Energy losses

For good efficiency the main flow must transfer as much as possible of its energy to the secondary flow in the mixing region. It is also necessary that losses due to wall friction throughout and breakaway in the diverging section be minimised. The latter losses can be minimised by good design. A portion of the overall energy loss, however, is due to the basic mechanism of energy exchange between two flows possessing different kinetic energies. That loss is a function of the relative speeds of the two flows before mixing, and of the cross sectional areas of the flows at the entry to the mixing region. It cannot be avoided completely.

The hydrodynamic efficiency that would result if that fundamental loss were the only loss is analogous to the Carnot efficiency of a heat engine, whose efficiency has a top limit defined by the temperatures at which heat is added and removed from the working fluid. In the same way, in a VETT this limiting efficiency is defined by the differences in speeds of the two flows before mixing. If they are very different it is inevitable that considerable energy is lost in mixing. If they are similar then this fundamental loss is very small. The problem about making the two speeds similar is that not much power is extracted by the turbine per unit total mass flow rate. Any extra, non-mixing losses (such as wall friction, diffuser breakaway) would be large in comparison, and overall hydrodynamic efficiency would suffer.

A balance therefore has to be struck between an acceptable fundamental mixing loss and the acceptable effect of wall friction and similar losses, so that the overall efficiency is maximised. We have developed design tools to help achieve an optimum compromise.

We are currently working on designs in which the fundamental mixing losses correspond to a hydrodynamic efficiency of over 80%. Further information may be found on VerdErg Renewable Energy's website [3].

III. Development

Venturi-Enhanced Turbine Technology (actually in the SMEC version) was patented by VerdErg Renewable Energy Ltd in 2006 and has since been subject to an intensive development programme, starting with experiments to prove the principle and continuing with trials to further improve performance.

A. Physical model testing

Experiments to prove the principle started with two programmes at IFREMER in Boulogne, France [4]; and continued with three separate programmes at BHRGroup, Cranfield in the UK. In all those tests the model was quite large, and for many applications would represent one module of a real VETT at full scale. The working section in the BHR tests is 500 x 300 mm, and takes flows of up to 500 litres per second (Figure 2). At each stage our knowledge of the main loss mechanisms has improved leading to modifications in the geometry. Performance of the device has improved correspondingly while retaining the fish-friendly characteristics and the essential simplicity of the concept.

Figure 2: The VETT model at BHRGroup, showing a 3m header tank in the background; sink tank in the foreground and in between the acrylic model with steel bracing.

A video that includes work at BHRGroup was made in 2010 with the assistance of a Rushlight Award [5].

After the Summer 2012 test programme a major modification to the geometry was proposed to address losses in the expanding section. A new model is under construction at the time of writing (March 2013), and arrangements for a further test programme at BHRGroup are being finalised.

B. Computational fluid dynamics (CFD) studies

Several CFD studies have been conducted and more are ongoing to run alongside the physical model testing.

The first runs were commissioned in 2006 to investigate how water might flow through and around a fence constructed of VETTs. Also a study was done to simulate water emerging from a grid of orifices and mixing with the main flow. The complexity of those processes was too great for the CFD to produce realistic answers.

In 2011 a simulation was run of the contracting and mixing sections of the VETT under test at BHRGroup. Useful insights were obtained although some inconsistencies were observed (Figure 3).

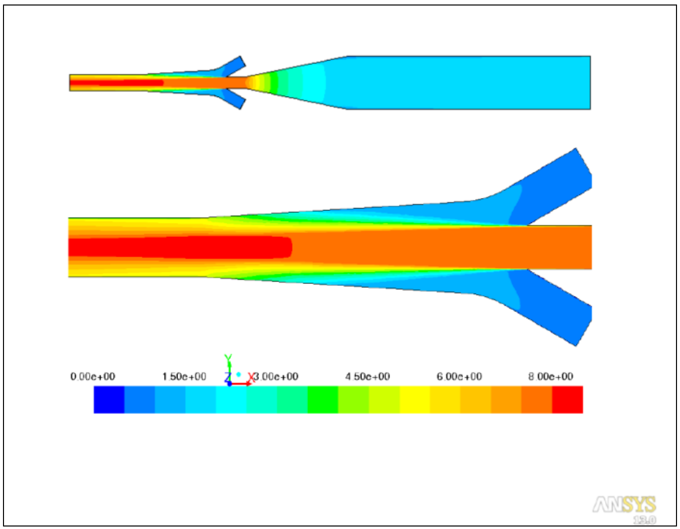

Figure 3: CFD simulation of velocities in the VETT's mixing region. Faster main flow approaches down the centre from the right and mixes with the slower (blue) secondary flow.

A further study was commissioned in 2012 of the diverging section alone, and was followed by several other simulations of that section with different geometry.

So far these studies have produced good agreement with measured pressures from the laboratory in most parts of the device, and the extra detail that CFD provides over a set of discrete measurements has been very useful. However, in the more complex flow areas predicted and measured pressures are not always in good agreement. It has been necessary to use the physical model results to validate CFD results for certain areas of the device, and at this stage we would not be able to rely with confidence on the evaluation of new designs by CFD alone. That situation may change as CFD capabilities continue to develop.

A simulation of the entire process (converging, mixing and diverging sections) is planned for 2013.

C. *Field trials*

In November 2012 one of the models from BHR was removed and installed into the River Caldew at Dalston, near Carlisle, UK. Pressure measurements were made for comparison with those made in the lab. They covered all the overall performance parameters of the VETT, but detailed performance data for individual components was not required from this exercise.

The measurements demonstrated near identical performance to the laboratory, as was of course expected. The main benefit of the exercise was to learn about the practicalities of deploying the device rather than about the hydrodynamics, and in that it was successful. Permissions and approvals, in particular, take considerable effort to obtain.

D. *External validation*

Funded by The Carbon Trust, the consultants Atkins independently analysed VETT's operation in 2009 and confirmed VerdErg's own analysis. Other leading consultants have also reviewed and confirmed our proposals for schemes on the Rivers Mersey and Derwent, and the Mersey Estuary at Liverpool.

Results from the laboratory and from the field installation at Dalston have been validated by Lloyds Register [6].

IV. Environmental Impacts

VETT was conceived from the outset to offer minimal environmental impact as a performance parameter of equal significance with cost and power output.

A. *Fish*

The effect of hydro machines on fish is recognised to be of crucial importance, both in rivers and tidal estuaries. For example, in a conventional barrage/turbine installation sea water flows freely into the estuary through open sluice gates. Twice a day a large proportion of the water in the estuary will flow out on the ebb. Clearly it is important that no more than a very small proportion of marine life in the water should be lost in each journey through the turbines. VETT is inherently 'fish-friendly'. Work is ongoing to demonstrate that.

With only 20% of tidal flow passing though the turbine screening of the turbine inlet is relatively simple and fish strike is thereby eliminated. Turbine design can be optimised for efficiency without compromise. It is not necessary to reduce rotational speeds, modify blade profiles or limit pressure magnitudes or pressure gradients.

80% of the water (and marine life) passes straight through the passive sections in which there are no moving parts or edges presented to the flow. The main residual issue is the tolerance of fish to the low pressure transient as they pass through the venturi. This varies from species to species and with age, and also to pressure assimilation of the fish in the water column immediately before transit. Fish with swim bladders react differently to fish without swim bladders.

Measured water pressures are available from laboratory tests at a dense coverage of points in the VETT. Those measurements, fixed in space, have been transformed numerically into pressure-time histories of the water as it flows through. That information is available to specialists to predict effects on fish. A test installation dedicated to proving VETT's mild effect on a wide range of species and age of fish has been established in Holland. Results from the first observed and validated live fish tests are expected in June this year.

B. Birds

Considerable concern has been expressed by powerful lobby groups in the UK over the possible effect of tidal barrages on the intertidal habitat for wading birds. The most-studied case is that of the Severn Estuary scheme. The conventional barrage/turbine solution was predicted to reduce the present high water level in the estuary a little (less than a metre) and set a new low water level at around the present mid-tide level. That would cause a significant loss to the intertidal area.

When incorporated into a tidal barrage, VETT's ability to generate at low head shows a significantly lower inundation of upstream wetlands thereby minimising the loss of intertidal habitat. A study for the UK Government on the operation of VETT in a barrage across the Severn Estuary ('SETS') [7] showed that a VETT installation would generate 70 to 80% of the power of a scheme with conventional turbines at about one-third the cost, while causing much reduced loss of the intertidal birdlife habitat.

This result is a consequence of VETT's effective porosity. VETT does not impound water or significantly distort the tidal signal since it is a much lower head device than a conventional turbine Ebb-Flow barrage. Figure 4 shows the results of a simulation for a Severn Barrage fitted with Venturi-Enhanced Turbines on an alignment from Cardiff to Weston. The landward curve is significantly phase shifted from the seaward curve, but only slightly attenuated. The phase shifting is presumed to have no environmental impact *per se*.

However, it does result in considerable level differences at given instants in time, Figure 5, which is available for conversion into electrical power.

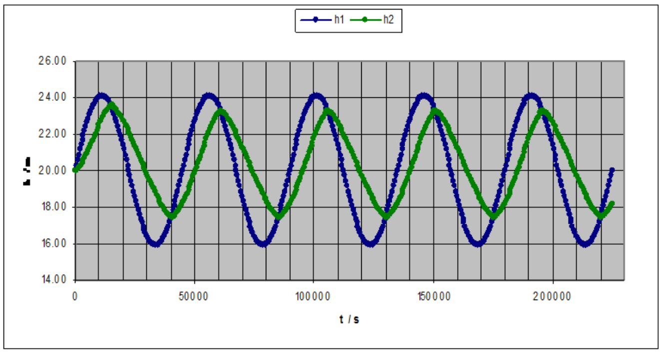

Figure 4: Effect on Basin Levels from a VETT installation in the Severn Blue (h1) is the seaward level, and green (h2) is the water level inside the barrage, over time. Tidal range to seaward is 8 m; range upstream is 6 m.

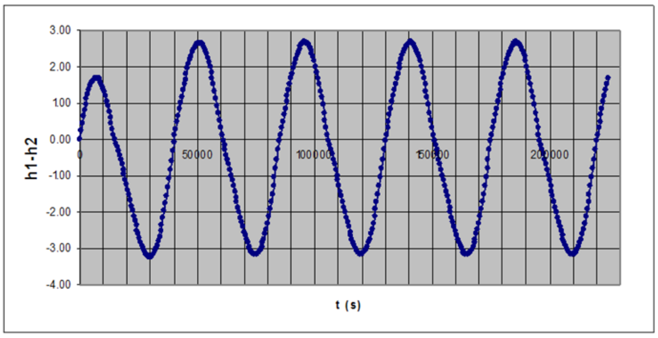

Figure 5: Head developed across the VETTs taken from Figure 4.

This argument applies to any estuary or tidal lagoon. VETT should allow a real life tidal lagoon to continue to experience most of the natural tidal range as well as the periodic exposure of estuarine mud flats that are essential feeding grounds for migratory birds.

The porosity of the device should also inhibit any build up of sediment in and around the lagoon. It allows plenty of water in and out the coastal zone keeping the near-shore region well replenished with sea water, so preventing contaminated fresh water runoff building up to form stagnant areas.

C. Visual intrusion

In common with many tidal energy converters all VETT's working parts are under water. That is not, however, the case for many hydropower machines designed for rivers. A scheme with VETTs can therefore be planned that makes very little impact on the natural beauty of sites in which that is important.

A typical layout is shown in Figure 6. The Planning Authority for this sensitive area was prepared to grant permission provided the installation was effectively invisible.

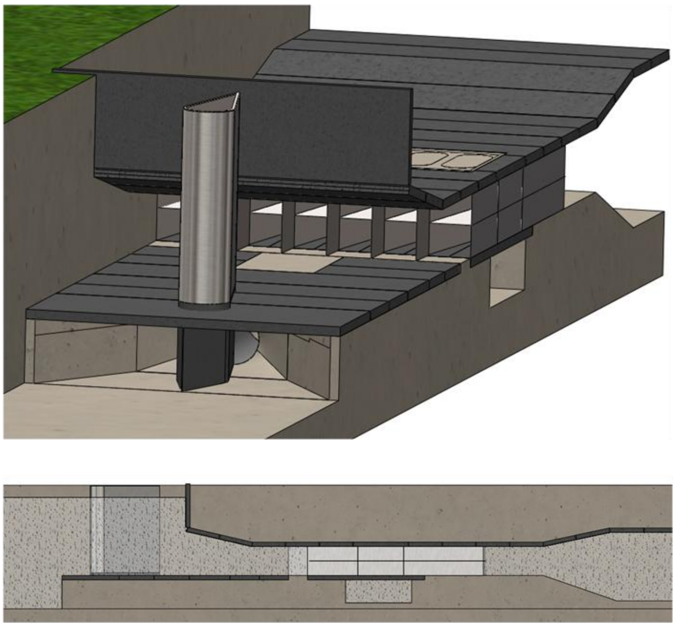

Figure 6: A VETT layout for a river installation. Flow is from left to right. A number of venturi channels acting in parallel de-pressurise the manifold below. A single turbine discharges into the manifold, and the generator is mounted in a faired housing on the intake side.

In a tidal estuary part of the barrage or wall is of course above water level. Overall, however, a scheme can bring about considerable improvement. The much-studied crossing of the Severn provides an example. At present the Cardiff – Western area of the Bristol Channel presents a very bleak and muddy prospect at low water. The scheme could result in a more pleasant environment, as the adjacent Cardiff Bay barrage has done. Before construction of the new barrage the Cardiff Dock area was unattractive with large areas of mud exposed at low tide. That part of Cardiff was in previous years noted for social problems. The new Cardiff Bay is attractive, home of the Welsh Assembly and includes high quality housing, shops and restaurants. The water is clear and of improving quality permitting water sports such as boating and angling.

V. Sites for Installation

A. Rivers

The first sites for installing VETT energy converters will be on rivers where existing weirs maintain a head of approximately 2 m. The advantage of selecting those first is that access is easier than for most tidal settings, grid connection is easier, and the flow is uni-directional and of more constant head. Although VETTs are in principle suitable for bi-directional flows it is prudent to acquire operational experience in the least demanding situations first. Environment Agency data reveals some 26,000 suitable sites of this type in the UK, with a total potential of 1.5 GW capacity.

Likely locations for early commercial installations are on the River Mersey at Warrington, some 17 miles upstream of Liverpool, and on the River Caldew at Dalston, four miles south of Carlisle. Studies have been carried out on many other sites. Around 30 communities, large landowners and companies have approached VerdErg for river installations.

B. Tidal estuaries

The flow – head characteristic of the VETT is particularly well suited to tidal estuaries. Wherever a tidal estuary can permit the construction of a bar or low barrage into which VETTs are installed then far more power can be extracted than with 'zero head' free stream generators [1], yet without the high cost and possibility of environmental damage associated with the full size conventional barrage solution. An example is provided by the results of work done on proposals for the Severn Estuary.

The Government's Severn Embryonic Technologies Scheme (SETS) [7] provided funds for developers of novel devices to make proposals for the Severn Barrage. Those were then expertly evaluated in order to advise ministers whether any new technologies should be considered alongside the conventional for that scheme. Seventeen groups bid for the funds; three were successful of which one was VerdErg.

Each group used the same tidal and site data and costs for construction so that a fair comparison could be made. The SETS panel reported in 2010. It concluded that VerdErg's VETT (the SMEC acronym was still being used for VerdErg's VET technology devices at that time) would reduce the capital cost of the scheme to approximately £9.85 billion using the metrics laid down for all participants in the study. This saving of two-thirds of the published capital cost estimated for a conventional barrage was mainly due to the much smaller barrage which would need to withstand only one-quarter of the load due to the smaller head difference. Further cost savings are due to the inherent cost effectiveness of VETT itself in permitting much smaller and higher speed turbines and generators. The very substantially lower cost would be achieved at the comparatively minor expense of producing around 20% less power (11.74 TWh per year).

Further, VETT technology would bring important environmental benefits as described above, and grid compatibility benefits due to the less peaky power curve. A barrage with Venturi-Enhanced Turbines generates power on all four quarter-cycles of the tide (flood, MSL to HW; ebb HW to MSL; ebb MSL to LW, and flood LW to MSL). A barrage with conventional turbines only generates for closer to one quarter-cycle (water is allowed to flow into the estuary through open sluice gates, and then out through the turbines only when there is sufficient head to permit efficient working).

At the time of writing the UK Government has decided not to commit public money to constructing a Severn Barrage, but has not ruled out privately funded proposals.

In the North West of England, Solway Energy Gateway Ltd is proposing a barrage at an old railway crossing of the estuary from Annan to Bowness that was removed in the 1920s.

VETT has been selected for this – the ‘Solway Energy Gateway Project’ (Figure 7).

Also in the North West VerdErg’s VETT was one of the technologies (with its old name ‘SMEC’) under consideration in the Mersey Tidal Power Feasibility Study, carried out for Peel Energy by the consultants Scott Wilson and EDF, with contributions from APEM, HR Wallingford, Proudman Oceanographic Laboratory and others. All criteria were assessed as ‘passed’ by VETT though it was correctly noted that the technology was at too early a stage in development for selection for a scheme commencing in 2011.

The potential for capacity from tidal installations such as these around the UK is thought to be in the region of 3.5 GW.

Figure 7: Impression of a new crossing of the Solway Firth incorporating VETT units and a roadway. (Produced for Solway Energy Gateway Ltd.)

VI. Structural Design and Construction

From the point of view of construction materials and techniques VETT has two distinct sections. Firstly the turbine and electrical generator, which are conventional units. These are likely to be selected from a range of existing products, possibly with some fine tuning to the design to ensure optimum performance in any particular installation. The precise type of turbine (radial, axial etc) are not fixed by the VETT itself; the designer has a free hand to select the best technology for cost effectiveness. In practice, with an amplified head in the region of 8 m an axial device with Kaplan style impeller is a likely choice. Since screening the relatively small flow of water entering the turbine is a practical possibility the turbine design need not be compromised by any requirement to protect fish. That is likely to result in better performance.

The same flexibility applies to the layout: housing the generator in a sealed bulb, or taking the drive shaft out through the secondary path wall, are both options that may be selected to suit the particular installation.

The other distinct section is the passive, patented part of the VETT. Here again, the designer has a relatively free hand in selecting materials and construction techniques. The hydrodynamics requires only a certain geometry - not held to any particularly fine tolerances - and reasonably smooth wetted surfaces in regions of faster flow. Options include stainless steel, composites such as GRP, wood and concrete; alone or in combination. Clearly the selection depends on unit size: a small 10 kW unit is likely to be made in a workshop from steel sheet, or even plywood, while units for an estuary crossing are likely to involve reinforced concrete, and might be integrated into the barrage structure (Figure 7).

The VETT units proposed for various tidal estuaries on the UK West Coast are gravity-base reinforced concrete structures designed with suitable safety factors against overturning and sliding under extreme environmental conditions. The units could be towed to site from nearby fabrication facilities and would be designed to be buoyant in the transit condition.

As indicated above, the overturning moment on a barrage structure equipped with VETT units rather than conventional turbines and sluice gates is much smaller – for the Severn, the overturning moment head from VETT is approximately 2.5m compared to 11m across an Ebb-Flow Barrage – so the VETT structure will be very much lighter and cheaper.

VII. Conclusions

The Venturi-Enhanced Turbine Technology (‘VETT’) energy converter is a new device that improves the cost-effectiveness of conventional hydro turbines in producing electrical power from very low head sources such as tides and rivers.

It has been shown through a thorough programme of physical model testing and CFD to be a cost effective way of utilising hydropower resources in the very low head (circa 2m) range. Development continues to improve efficiency further. It is expected to show a uniquely benign impact on the environment. A live-fish testing programme is planned to demonstrate those characteristics with a view to operating without power wasting and expensive fine-mesh screens.

There are many thousands of river sites and very large number of tidal situations in which VET Technology could find an application.

VerdErg has entered into a number of commercial arrangements and understandings with a number of site owners and partners. Keen interest has been shown by other potential operators, at sites such as the Camel Estuary in Cornwall.

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