‘VETT’– Reducing the Cost of Tidal Power Generation

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***Abstract*—The Venturi-Enhanced Turbine Technology (‘VETT’) energy converter improves the cost-effectiveness of conventional hydro turbines in producing electrical power from very low head sources such as tides and rivers. A number of large models in the laboratory and a prototype in the field have demonstrated its performance. Physical model testing has been complemented by computational fluid dynamics studies, theoretical analysis, automated optimisation and particle image velocimetry. VETT has a uniquely benign impact on the environment. Two major live-fish testing programmes have demonstrated those characteristics with a view to operating without power-wasting and expensive fine-mesh screens. VETT is expected to have an important role in harnessing tidal power. VerdErg Renewable Energy Ltd, VETT’s developer, participated in the UK Government’s Severn Embryonic Technology Scheme, and made contributions to a later Government review of the Severn proposal. Proposals have been put forward to install a VETT scheme in the Solway Firth and on the Wyre.**

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

I. INTRODUCTION

Venturi-Enhanced Turbine Technology (‘VETT’) is a new, patented, technique for radically improving the cost-effectiveness of low head (1 to 4m) hydropower generation [1], [2]. Initial development was described in a paper presented to EWTEC 2013 [3].

This paper describes developments made in the last four years to improve hydrodynamic efficiency, to re-configure its layout for more economical use in bi-directional tidal flows, and to further establish its benign environmental characteristics.

Tidal power generators can be classified into two broad types: those that operate in effectively unconstrained flows (‘tidal streams’) and those that operate by building up a head of pressure and constraining the resulting flow through the device (‘tidal range’).

The former devices are sometimes thought of as ‘zero-head’, though some head drop is needed to develop power, even if it is imperceptible. Tidal range schemes usually use conventional turbines installed into a wall or barrage, with sluice gates holding back the water until there is sufficient head for the turbine to operate effectively.

At sites where the tidal range is limited, conventional turbines and their associated generators become very expensive: the turbine needs to handle large rates of flow for a given fluid power, and the generator is turned slowly.

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

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

Venturi-Enhanced Turbine Technology (‘VETT’) improves the cost-effectiveness of conventional hydro turbines in producing electrical power from very low head sources (1 to 4m). It can be used at sites where the tidal range is not high; it can operate over virtually the full tidal cycle, and there is no need for a major barrage structure to hold back the flow. In common with tidal current turbines water is able to pass through all the time, and yet like the conventional Ebb-Flow Barrage scheme it produces far more power per unit of flow – due to the higher Δp in the equation.

Venturi-Enhanced Turbine Technology (‘VETT’) improves the cost-effectiveness of conventional hydropower turbine schemes in three ways. Firstly, it uses a smaller turbine. Secondly, as the turbine spins faster a smaller generator is used, with no need for a gearbox. A theoretical study [4] 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. The third cost saving comes from the civil works being considerably lighter and less costly, since the overturning moment on the VETT wall is less than on a conventional Ebb-Flow Barrage wall due to the lower maximum head.

II. Operating Principles

VETT's unique feature is that the head drop across its turbine is amplified 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 a 6m 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.

The device therefore acts as a kind of 'pressure amplifier' in a manner analogous to an electrical transformer acting as a voltage amplifier, or to a gearbox as acting a torque amplifier.

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 axial turbine, while the intake side is connected in the normal way to the upstream water source.

In Fig. 1 flow is from left to right driven by a low head of pressure say, for example, 2m. The main part of the flow is accelerated in a contracting region. At the venturi, the flow pressure is very much lower, according to Bernoulli's equation. A small proportion, typically one-fifth, of the total flow is led through a turbine which discharges into 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 is recovered in increased static pressure. Exit pressure is, in this example, typically 20 kPa lower than intake, a head of 2 mWG. The turbine, however, is driven by a much larger head than that, typically 6m.

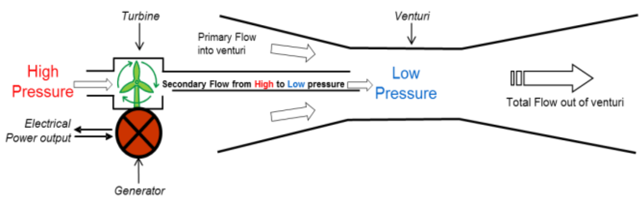


Fig. 1 Operating principle of the VETT

The turbine is of conventional, well understood design, but is smaller and runs faster than would be required without VETT.

The VETT's performance is characterised by three parameters:

Pressure ratio (PR): The pressure developed across the turbine in a VETT, compared to what it would have been if it had been installed into the site directly. A typical value of pressure ratio might be 3.

Flow rate fraction (FRF): The fraction of total flow that is taken by the turbine. A typical value of flow rate fraction might be 0.2 .

Hydrodynamic efficiency: The hydrodynamic power made available to drive the turbine as a proportion of the hydrodynamic power lost by the total flow of water.

It is straightforward to show 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 three times that corresponding to the available head, then the hydrodynamic efficiency is 60%.

B. Energy losses

For good energy conversion 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 flow separation and stall in the diverging section, be minimised. While those losses can be minimised by good design, a portion of the overall energy loss is due to the basic mechanism of energy exchange between two flows possessing different kinetic energies. That loss cannot be avoided completely. It 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. Current development programmes are targeted at a hydrodynamic efficiency of 60%; further improvements towards 70% are expected in the longer term.

III. Development

Venturi-Enhanced Turbine Technology (previously termed SMEC) was first patented by VerdErg 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. There are currently six patents granted on various aspects of the technology.

In 2012 a circular-section, coaxial design was developed from the rectangular-section VETT (Fig. 2).

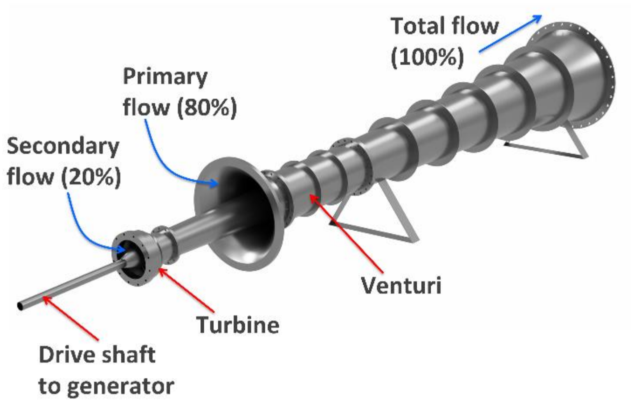


Fig. 2 The Co-axial VETT. Both the primary and secondary (turbine) paths take water from the upstream water source. The turbine discharges into the low-pressure venturi that is created in the primary path. Mixing and deceleration of the combined flow follow.

A. Physical model testing

Experiments to prove the principle started with two programmes at IFREMER in Boulogne, France [5]; and continued with three separate programmes for the rectangular section version at BHR Group, Cranfield in the UK. In all those tests the model was quite large, and for many applications might represent one module of a real VETT river installation at full scale. In 2012 and 2013 a Coaxial VETT model was constructed for a further series of trials at BHR Group. It was 8m long, and 0.5m diameter at the downstream section. Three large pumps circulated water back to a $12m^3$ header tank at flow rates of up to 500 litres per second, supplying the model with over 10kW of hydraulic power. (Fig. 3 and Fig. 4).

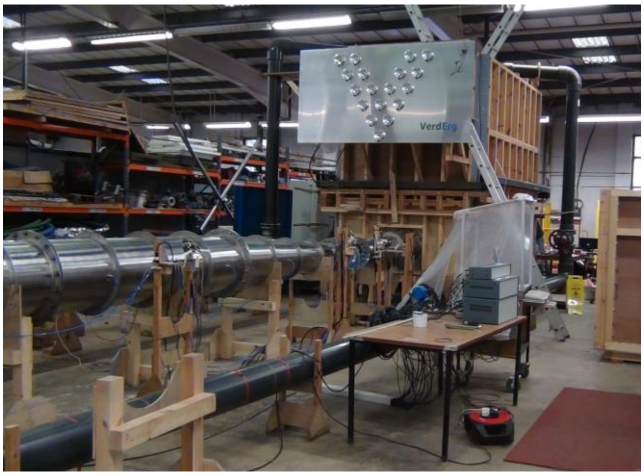


Fig. 3 A Co-axial VETT at BHR Group. The VETT model is on the left, supplied by the 3m high header tank behind. Mounted on the header tank is a bank of lights which acted as a small electrical load for demonstration purposes. Comprehensive instrumentation quantified VETT performance, and the locations of losses.

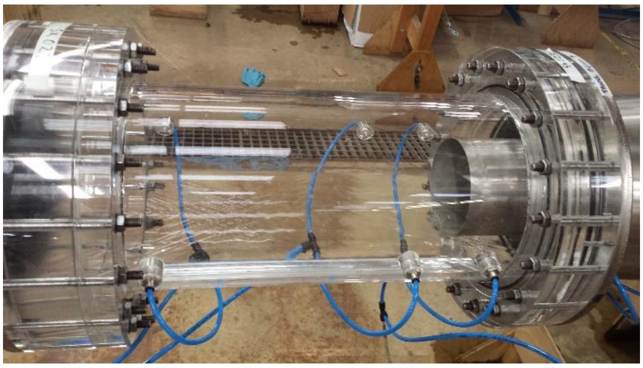


Fig. 4 The Co-axial VETT at BHR Group: the mixing section which follows the venturi (not shown). Flow is from right to left. The steel tube visible to the right is the turbine discharge. Fast primary flow emerges from the annulus around the turbine discharge tube.

The model enabled measurements to be made of the effects on efficiency of the diameter and axial location of the secondary tube and the length of the mixing section. Hydrodynamic efficiency of the optimum combination was considerably better than the rectangular-section VETT. However, it was clear from the results that an even greater length for flow mixing would have given further improvement.

In all those tests the turbine was represented by a valve – a highly controllable way of losing power. At the end of the substantive test programme a real turbine was fitted to the secondary flow path. In this configuration VETT generated electrical power for the first time on 14 January 2014.

Up to and including this stage VETT design was determined by a basic knowledge of the fluid processes involved, and by empirical data – such as the maximum divergence angle of a diffuser before separation is likely to occur. The model's centre section was transparent enabling some rudimentary flow visualisation with dye streams and bubbles, but proper measurement of velocity profiles was not possible. It was not possible, therefore, to form a good understanding of the mixing process and the role of turbulence and vorticity, nor of the effect on diffuser performance of a non-uniform entry velocity distribution.

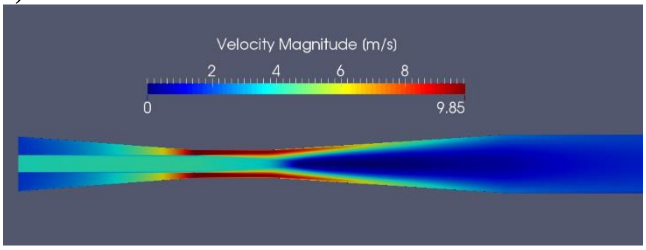
B. Computational fluid dynamics (CFD)

Several CFD studies were conducted 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. A study was also undertaken 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 at that time.

In 2011 a CFD simulation of the contracting and mixing sections of the VETT tested at BHR Group was carried out. Useful insights were obtained although some inconsistencies were observed.

a)



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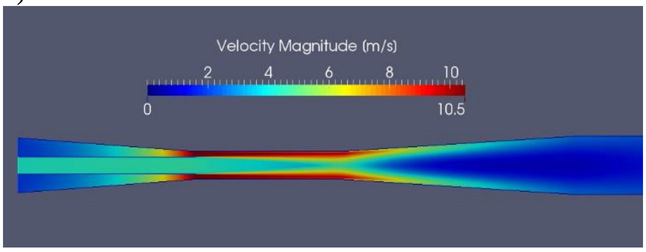

Fig. 5 CFD simulations of velocities in the VETT's mixing region. Faster main flow approaches from the left through the contracting annulus and mixes with the slower (pale blue) secondary flow from the turbine. a) short mixing section leading to excessive stall in the diffuser; b) better mixing resulting in greater pressure recovery in the diffuser.

Arup were commissioned in 2012 to study the diverging section modelled in the laboratory. This was followed by several other simulations with different geometries. The extra detail, especially velocity fields, which CFD provides compared to a set of discrete measurements taken in the laboratory was very useful.

The BHR Group Coaxial VETT trials were then also simulated by Arup; good agreement was found with measured pressures from the laboratory in most parts of the device. Subsequently, circular-section straight-sided mixers/diffuser profiles, developed from the large physical model geometry, were simulated, with the objective of optimising the length of the parallel mixing section (Fig. 5). The result was consistent with the conclusions from the laboratory model trials: the mixer needed to be longer than the longest tested to present the diffuser with a flatter velocity distribution, but not so long that skin friction losses dominated.

As part of a subsequent Innovate UK funded bi-directional VETT project [6], Arup conducted evaluations of a wide range of rectangular diffuser shapes: straight sided, and curved: the latter both flaring (like a trumpet) and turning in (like a bell). It was found that a trumpet style diffuser gave an improvement over the straight sided for most reasonable lengths, although an additional very small improvement could be obtained from a straight-sided diffuser if it were made very long.

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. The project duration was two weeks with intermittent use of the VETT. Measurements were made for comparison with those made in the lab. The measurements demonstrated near identical performance in the field on a real river flow to the laboratory. The benefits of this prototype were to show that real flows containing substantial natural debris did not impact VETT performance and to learn about the practicalities of deploying the device in a realistic environment. However, only a permanent installation will allow drawing firm long term conclusions. Permissions and approvals, in particular, were found to require considerable effort to obtain. Results from the laboratory and from the field installation at Dalston were validated as near identical by Lloyds Register [7].

D. Theoretical work

Two processes were identified as key to reducing energy losses and so to improving efficiency. Firstly, the transfer of energy from primary to secondary flow streams during mixing, and secondly, the recovery of kinetic energy in the diffuser. To make progress on these, VerdErg embarked upon a collaboration with the Mathematical Institute at Oxford University. At the time of writing the resulting three-year project is half-way through. A mathematical model for the growth of the shear layer between two flows (fundamental to mixing) has been developed and successfully validated against laboratory and CFD simulations [8]. At present it includes wall drag (using empirical data) but does not predict the shape of boundary layers or flow separation in the diffuser. The model consists of a set of ordinary differential equations which govern the continuous dependence of the velocity profile and pressure on the channel shape. The mathematical model has been coded and runs on a PC in around a second, making it very suitable for use as a forward model for automated optimisation.

In addition a laboratory model with particle image velocimetry (PIV) was developed by the Engineering Science Department at Oxford University. It consists of machined transparent Perspex sheets (for optical access) that make up an easily-modified rectangular working section. Water was seeded with neutrally buoyant tracer particles which were then illuminated from the side by a light sheet provided by a pair of pulsed Nd:Yag lasers. Mounted above the test section was a high-speed camera synchronised to take still shots in pairs at 1ms separation. PIV software computes the velocity fields associated with each image pair. Fifteen still velocity fields were produced for each second of running time. These velocity ‘maps’ can be played back as video, giving a good impression of mixing development and turbulence in the shear layer and the development of the boundary layers. Fig. 6 shows a velocity field plot averaged over a large number of individual frames, with streamlines added. It can be seen that this is a highly non-ideal profile (insufficient mixing): the diffuser is stalling. Fig. 7 shows the associated turbulent kinetic energy field for the run. A sequence of sight-tubes running down the model centreline provided measurements of pressure.

A Reynolds Averaged Navier-Stokes, k-ε turbulence, CFD model of the test section was also developed at the University, with the assistance of the Arup team.. Results for velocity distributions and pressures from these three models (mathematical, lab and CFD) were compared, and good agreement found both for a parallel sided channel and a linearly expanding one.

Having confirmed the correctness of the mathematical mixing model, it was then incorporated into an automated optimisation routine to evolve the optimum shape for the mixing and diffuser channel. The criterion for optimisation was the maximum pressure recovery, which is directly related to the minimum energy loss. The channel shape was manipulated using 500 control points, allowing for curved shapes. It is found that the optimum shape can be well approximated by a shape consisting of three straight sections.

At the time of writing work is concentrating on more efficient optimising strategies. The model's predictions for optimised shapes are suggesting new profiles, and improving the understanding of the relevant flow processes to permit further reduction of energy losses.

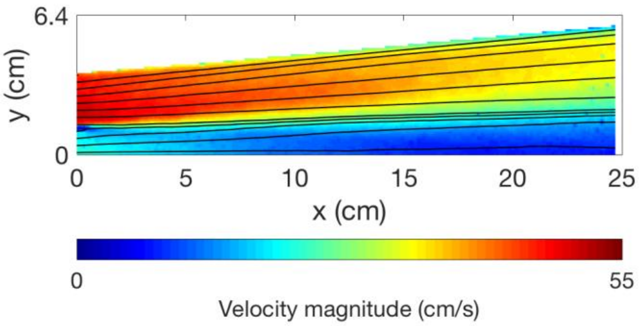

Fig. 6 Time-averaged velocity magnitude plot in a widening channel (only half the channel is shown) obtained from the lab PIV rig. Fast primary flow and slow secondary flow enter from the left. The shear layer is seen to widen: some mixing occurs but in this example not enough, and the diffuser stalls. Streamlines have been overlaid. (Taken from [8].)

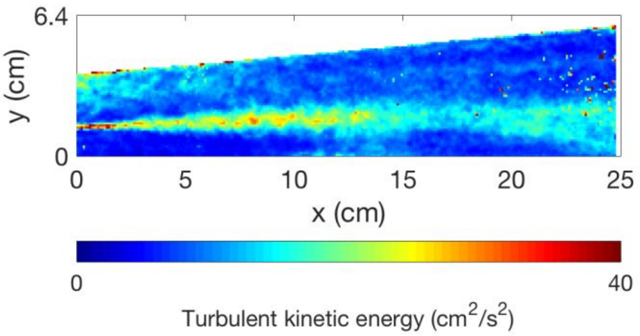

Fig. 7 Time-averaged turbulent kinetic energy k plot for the widening channel, obtained from the lab PIV rig. Vorticity generated on the surfaces of the separator plate is important to promote mixing. (Taken from [8].)

Further planned work with the Engineering Science Department at Oxford will investigate stimulating vortex generation by harmonic perturbation of the flow caused by flexible surfaces.

IV. VETT AND TIDAL POWER GENERATION

VETT was originally conceived as a marine energy convertor, although the concept can be applied just as well to rivers and other, for example industrial, water flows. The first sites will be at weirs in rivers due to the easier access and lower installation cost, but studies have been made of the use of VETT in tidal sites such as the Severn Estuary [9], [10], the Solway estuary, the Wyre estuary, and Morecambe Bay in the UK, and at Brouwersdam in The Netherlands [11].

The device described above and tested at BHR Group takes flow in one direction only. Although conventional turbine installations are also usually uni-directional, it is planned to operate VETT symmetrically, generating on both flood and ebb tides. Clearly that could be achieved by using VETTs arranged in opposing directions or by using VETTs arranged normal to the flow with the inflow direction controlled by sluice gates. However, a preferred solution is to use a genuinely bi-directional VETT. In a study funded by Innovate UK [6] VerdErg again worked with Arup to assess, by CFD, the hydrodynamic performance of a number of potential bi-directional VETT configurations. Arup's civil engineering team then undertook a review into the installation, buildability, operational and maintenance characteristics for a tidal project using three different reef types.

Five candidate geometries were proposed to accept flow in alternate directions. Inspection of VETT's geometry shows that the primary flow is inherently bi-directional. To realise that efficiently the converging section was made a mirror image of the diffuser. Reversing the secondary flow path, which includes the turbine and discharge into the fast-flowing primary, is more difficult. A method was devised for retaining VETT's simplicity by providing high-head side flow to the turbine's intake without mechanical intervention whichever direction the tide flows. However, the turbine discharge and its introduction to the primary flow did require moveable components if extra losses due to poor flow alignment were to be avoided. Theoretical analysis, later confirmed by CFD simulation, evaluated the penalty for not aligning the flows reasonably closely.

This project also enabled examination the flows in the distribution manifolds and circular-to-rectangular transition sections which featured in some of the candidate bi-directional VETT layouts.

The five candidate designs were evaluated with a weighted scoring matrix in order to identify the most promising. The key criteria and the weightings given to each are shown in Table [1].

TABLE 1
INITIAL EVALUATION CRITERIA AND ASSOCIATED WEIGHTING FACTORS

Evaluation Criteria	**Weighting Factor**
Number of Turbines	3
Number of Generators	3
Civil Cost (Estimate)	6
Manufacturability	25
Maintenance	2
Flow Control	2
Wetted Surface Area	2.5
Secondary Flow Path Simplicity	3
Secondary Flow Screening	1.25
Aesthetics	0.25

A. *Reef Options*

In order to create a useable head across a device such as VETT, and to ensure all flow passes through it rather than over the top, some sort of reef is needed. Most schemes to date have been based on the fixed, impermeable barrier, as in the La Rance scheme, the Severn Barrage, and some contemporary tidal lagoon proposals.

During the Innovate UK project the use of impermeable barriers for VETT was studied in detail, and also the application of two newer reef technologies.

1) Obermeyer Gates (Fig. 8) are movable steel gates, with the level controlled by inflating a rubber air bladder located under a steel plate. These gates have been used extensively on more traditional hydro-generation schemes in the US, Scandinavia and continental Europe, although they have not been used in the manner that is being proposed here, with gates located both in the direction of the flow and against it. The gates would typically be 3.5m to 4.5m high, located on a concrete plinth above the VETT. The plinth is required to house the air hoses and holding down bolts which resist the hydraulic forces. The gates can be lowered to facilitate navigation. They require less reinforced concrete than a fixed barrier.

However, there are some critical weaknesses for a symmetrical bi-directional scheme. Placing this type of gate opposing the direction of flow is likely to cause buffeting which might result in fatigue loading of the gate components. Debris and silt is also likely to get trapped under the gate with no way of removing or flushing it out. The gates are not designed to be fully raised and lowered on a daily basis as they would require significant energy to inflate. The mechanical and electrical equipment (compressors and air dryers and air hoses) would need to be accommodated within the plinth in a fairly complicated housing.

Fig. 8 Obermeyer Gates with a small flow overtopping

2) Water Filled Aquadams

An alternative option considered was the Aquadam (Fig. 9). Similar to the movable weir option, the Aquadam aims to offer a cheaper, more flexible alternative to a solid concrete barrier. It can be constructed much faster. The Aquadam is a water-filled rubber bladder. The bladders are designed to take load in both directions and are extremely robust; floating debris would not be an issue. The maximum length of individual units is currently 65m and the individual gates comprising the whole scheme would be divided by concrete piers. The pumps for filling the bladders could be located within the dividing piers or located at either side of the estuary.

The construction of the Aquadam is similar to the moving gates with the requirement for a concrete plinth and dividing piers. However, the design is much simplified with less onerous fixing requirements, less ducting and less mechanical and electrical equipment. The gates could be deflated in flood situations but are not intended to be deflated and inflated frequently due to the energy requirement.

Fig. 9 Aquadam installed at Azmak Hydroelectric, Turkey

From this relatively basic assessment it was found that the Aquadam was an attractive option. It was the lowest cost reef option, and also the most flexible in terms of deflation to allow for navigation and mitigation against flooding.

V. Environmental Impacts

In recent years there have been numerous studies on the impacts of hydropower on the environment with special focus on the impact to fish passage and migration [12],[13]. 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. Current technologies address this with extensive fine screening and low speed turbine blades. These in turn impact energy generation potential and project economics.

With only 20% of flow passing through the VETT's turbine the screening requirement is significantly reduced and limited to the turbine inlet. Fish strike is eliminated quite simply, and the 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 in the turbine.

80% of the water passes straight through the passive sections (and so does marine life) 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. Existing studies suggested that the magnitude and exposure of fish to pressure transients in the venturi of a VETT, and their entry acclimatisation, would not be severe enough to cause damage [14],[15].

The effect of pressure transient varies from species to species and with life stage, and also to pressure acclimatisation of the fish in the water column immediately before transit. Depending on the swim bladder type (physoclistic or physostomous) fish react differently to pressure transients.

In 2013, VerdErg performed an environmental testing programme to ascertain whether fish could safely pass through VETT's 80% primary flow. In collaboration with Vis Advies BV at their test facility in Nieuwegein, The Netherlands, VerdErg set up a fully instrumented rectangular-section VETT to recreate heads of 1 to 2 m with a maximum flow rate of 450 l/s. 827 fish comprising Atlantic salmon smolts, rainbow trout, round goby and European eel were tested using the "forced exposure method" developed by Vis et al. [16]. For all of the test scenarios no internal or external, either immediate or latent, injuries from their passage were observed. That gives the VETT a score of 1 in the methodology of Bruijn et al., [17], the maximum possible, and the classification "Outstanding" (ref). Independent Third Party Verification was conducted by Dr Billy Sinclair at the University of Cumbria [18].

It became clear whilst embarking on the commercial development of run-of-river sites that further work was required to validate VETT's fish friendly attributes for a wider operating range up to heads of 3.5m and to explore the impact on depth-acclimatised fish, physoclistic fish, and on designated species that had not previously been tested. From this, acceptable hydrodynamic thresholds for the safe passage of fish through VETT would be identified enabling environmental design criteria for future VETT schemes to be formed.

In collaboration with Fishtek Consulting Ltd a Coaxial VETT was installed at HR Wallingford's Froude Modelling Hall in 2016 (Fig. 10). Over 1200 fish were tested representing a range of physostomous, physoclistic and native coarse fish, including brook lamprey and perch. For each test the Logarithmic Ratio Pressure (*LRP*) was calculated from the peak pressure (i.e. the pressure the fish are acclimatised to prior to VETT passage) and the lowest pressure (nadir) experienced within the venturi.

$$LRP = Ln\left(\frac{acclimatisation\ pressure, abs}{nadir\ pressure, abs}\right)$$

*LRP*s of up to 1.0 were tested. The results concluded zero mortality from the VETT passage for all species and zero injuries associated with barotrauma for physostomous fish (eel, lamprey, salmon, and bream). Physoclistic fish (perch) showed some susceptibility to barotrauma injuries at high *LRP*s but still achieved a safe scheme passage rate (*SPR*) for barotrauma of above 99% at an *LRP* of 0.8. ($SPR_{\text{barotrauma}}$ quantifies any long term or permanent injuries associated with barotrauma in a VETT hydro installation). This result is of 99% safe scheme passage rate for barotrauma at an *LRP* of 0.8 is therefore considered the safe passage threshold for physoclistic species. VETT was formally approved for installation by the EA in this context in mid-April 2017

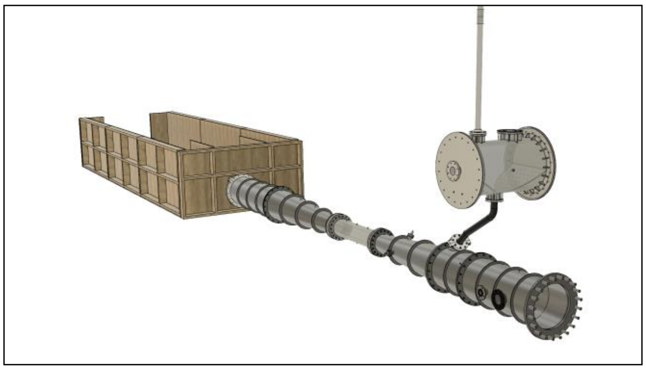

Fig. 10 The VETT installation at HR Wallingford, 2016. The model is approximately 8m long, and discharges into a sink tank from which the fish were recovered. Above the VETT is an 'acclimatisation chamber', in which fish were kept at positive pressures before transit through the VETT.

These live trials have provided auditable evidence of VETT's ability to facilitate fish passage through the primary flow path and venturi without any significant adverse effects. That is especially relevant for the Annex II designated juvenile and adult fish and their migration. This work compliments the national and international conservation initiatives such as the Water Framework Directive and Eel (England and Wales) Regulations 2009 to promote river connectivity and preserve the integrity and function of designated habitats for species who reside in them. The outcome is a hydropower technology that only requires screening of the turbine intake, which translates into a lower cost of energy.

The results of these fish trials are especially relevant to tidal locations where anadromous fish migration routes are prominent, such as in the Severn Estuary. In addition to VETT's demonstrated capacity to facilitate safe fish passage, migration pathways are maintained due to VETT's porosity. The hydrodynamic regimes which the fish are attuned to for their life cycles will be largely preserved. The impact on the integrity of designated marine sites and the species attributed to them will be minimised as a result.

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. 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') [9],[10] 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.

Fig 11 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, Fig. 12, which are available for conversion into electrical power.

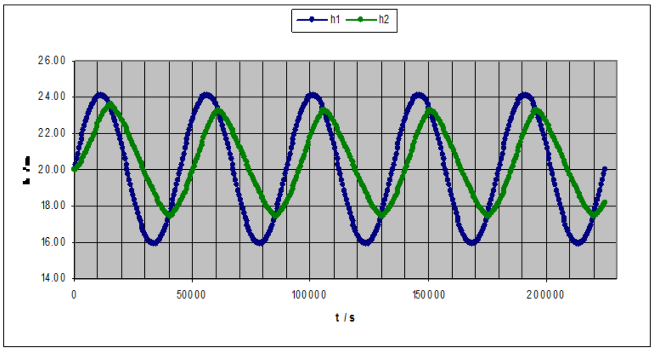

Fig. 11 Effect on Basin Levels from a VETT installation in the Severn. Blue (h1) is the seaward level, and green (h2) is the water level inside the barrage, over time. Tidal range to seaward is 8 m; range upstream is 6 m.

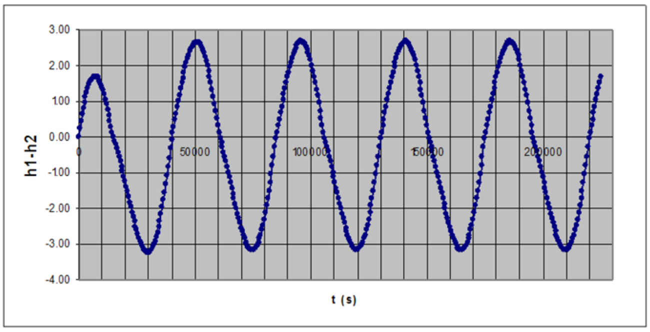

Fig. 12 Head developed across the VETTs taken from Fig. 11

It is expected that the porosity, and consequent flows at lower water levels, would also inhibit any build-up of sediment in and around the lagoon.

VI. Sites for Installation

The flow – head characteristic of the VETT is particularly well suited to tidal estuaries. Wherever a tidal estuary can permit the construction of a reef into which VETTs are installed then far more power can be extracted than with 'zero head' free stream generators [19], 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 in the UK Government's Severn Embryonic Technologies Scheme (SETS) [9],[10]. Similar benefits, on a smaller scale would be seen for tidal lagoons.

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' (Fig. 13). VETT has also been chosen as the candidate technology by Wyre Tidal Energy, a social enterprise looking to generate power from the tidal flow at the Wyre Estuary, UK. This proceeds from the project is targeted for the local community to drive economic growth and regeneration in the area.

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.

Fig. 13 Impression of a new crossing of the Solway Firth incorporating VETT units and a roadway. (Produced for Solway Energy Gateway Ltd.)

VII. Economics

A. Rivers

Conventional schemes, using technologies like the Archimedes Screw or a double regulated Kaplan turbine, are very expensive. Under the current UK subsidy regime FITs (Feed-in-Tariffs) have significantly reduced since 2016 and low head hydropower installation has come to a halt. Installation costs for conventional technologies in the low head hydro sector range around £10,000 per kW installed capacity (very project dependent) and are no longer economically feasible. Underpinned by quotes for the first river installations currently in progress it is anticipated that VETT can be installed for around £5,000 per kW, which would more than compensate the efficiency losses from the pressure amplification process and substantially improve project economics (Table 2).

B. Tidal

The cost information for VETT tidal installations (and tidal installations in general) is less advanced than for river installations and depends even more on the project location.

During the SETS [9] studies for the Severn, VETT was calculated to achieve a cost of energy of £68/MWh. It has to be acknowledged that the Severn bears the highest energy potential in the UK (nearly 12,000 GWh energy output for a VETT installation).

TABLE 2
ECONOMIC COMPARISON FOR VETT IN RIVERS

	Other tech-nologies	**VETT 1**	**VETT 2**	**VETT 3**	**VETT 4**
Installed capacity (kW)	100	80	80	80	80
Annual energy output (MWh)	438	350	350	350	350
Cost per kW installed (£)	10,000	8,000	7,000	6,000	5,000
Total cost (£000)	1,000	640	560	480	400
IRR	1.1 %	3.9 %	5.6 %	7.7 %	10.4%
Payback period (yr)	19.5	15.5	13.5	11.5	9.5
Cost of energ (£/MWh)	275	220	192	165	137

Table 2: Economic comparison for four VETT installation cost scenarios. Based on a FIT of 7.8 *p/kWh*, export tariff of 5.5 *p/kWh* and a 50% load factor.

The current Swansea Bay Lagoon project advertises 530 GWh output at a cost of £1.3bn, which translates into a cost of energy of ca. £275/MWh (by making assumptions including a forecast period of 35 years, construction period of 3 years, operation costs of 1.5% of construction costs and a discount rate of 8%).

Cost of Energy scales directly with the installation costs per unit of energy installed (a 100 MW project has the same cost of energy as a 120 MW project if both are built at £4m/MW assuming other factors remain the same). Therefore each % of cost reduction will equally reduce the cost of energy. The generating elements for VETT (turbines, generators) and the reef structure show significant cost improvements. Early work also indicates a reduction in civil work requirements but more analysis is required. Overall cost savings of at least 50% compared to conventional barrage or lagoon systems are aspired to.

VIII. Conclusions

The Venturi-Enhanced Turbine Technology (‘VETT’) energy converter is a 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 comprehensive series of physical model testing at large scale to be a cost effective way of utilising hydropower resources in the very low head (circa 2m) range. Efficiency improvements have been made through programmes of development encompassing CFD, theoretical analysis and particle image velocimetry. These are continuing.

Bi-directional versions have been devised and evaluated by CFD to further reduce the cost-of-energy of VETT in tidal applications. The installation, operation and maintenance aspects at tidal sites have been investigated by a leading civil engineering consultancy.

VETT devices have a uniquely benign impact on the environment. Two live-fish testing programmes have demonstrated those characteristics with a view to operating without power wasting and expensive fine-mesh screens.

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

VerdErg has entered into commercial arrangements and understandings with a number of site owners and partners, and work is expected to start shortly to install the first commercial units.

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