VENTURI-ENHANCED TURBINE TECHNOLOGY

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ABSTRACT

"Low head" for the purposes of this paper is considered to be where power is extracted cost-effectively from a water level difference of between 1m and 3m. These conditions are widely found onshore and at numerous tidal locations along the World's coastlines. Typical Significant Wave Heights also frequently fall within this range. Venturi-Enhanced Turbine Technology ("VETT"), the subject of this paper, was developed to economically exploit such low head renewable energy opportunities. Its development, logically, was started with small low-cost applications in onshore rivers. This initial phase of development is now advanced and commercial exploitation activity has commenced. Tidal VETT applications are under active development and the application of this technology to harnessing wave power is planned for the future.

VETT technology is a fluid step-up transformer formed by a passive venturi, through which most of the water flows to amplify the pressure drop across a turbine in the remainder of the flow. The cost savings and reduced environmental and societal impacts from using a simple, conventional, small, high-head, high-speed turbine-generator set in a low-cost passive duct is substantial when compared to the large, slow moving legacy technologies such as the waterwheel, Archimedes screw and tidal barrage type schemes

There are also a very large number of sites located worldwide for which this technology is well suited. Hence, VerdErg's VETT low head renewable energy has much potential to offer.

INTRODUCTION

This paper outlines the development and laboratory testing of VETT at the BHR Group hydraulics laboratory on Cranfield University Campus in the UK. Five major test campaigns were undertaken at BHR Group between 2009 and 2014 following initial trials at IFREMER's circulating water facility at Boulogne in France. Intensive product development including a successful full-scale field prototype was made between each series of laboratory tests, incorporating the "lessons learnt" from the previous tests.

This paper refers to the fifth and most recent tests completed at BHR in early 2014. This paper will outline the methodology used and test results, aimed at determining the optimal combination of three of VETT's characteristic geometrical parameters. The relevance of these results to future development will then be indicated.

Large-scale laboratory testing was initially undertaken in favour of computer modelling, having determined that Computational Fluid Dynamics (CFD) did not, at that time, have sufficient power to accurately model, still less to predict, the complex flow regimes found downstream of the venturi in typical VETT configurations. However, Ove Arup & Partners Ltd in London has recently been able to reproduce in a CFD model the laboratory test results discussed here. Future development work will continue to use CFD modelling techniques to examine areas of power loss and configuration improvements to the VETT although laboratory testing will still probably be needed where major changes are made.

Laboratory testing was carried out at two values for driving water head, with the aim of determining the optimum combination of the geometric parameters of cross sectional diameter of secondary flow pipe, position of secondary flow pipe and length of mixing section. The significance of these three parameters will become apparent later in the paper.

Results of laboratory testing have shown that turbine efficiency changes considerably with secondary pipe diameter and mixing tube length, with the highest turbine efficiency achieved with the largest diameter secondary pipe and longest mixing section tested. However results also suggest that the exact position of the secondary tube with respect to the mixing section has no statistically significant impact on efficiency over a range of configurations.

A graphical description of the flow through VETT is displayed in figure 1. The device consists of a large primary tube with water flowing through it, driven by a low static head upstream of the entrance to the tube. Downstream of the entrance, the primary tube consists of a venturi duct, where flow velocity increases compared to the entrance to the tube according to the continuity equation, followed by a diffuser section. Also contained within this primary tube is a secondary flow tube. This secondary tube starts at or upstream of the entrance to the primary tube. It continues, concentrically located within the primary tube, up to the venturi duct section. The pressure differential between the faster moving (hence lower pressure) flow at the downstream end of the secondary pipe just before the venturi section and the slower moving (hence higher pressure) flow at the upstream end causes a secondary flow through this secondary tube. This pressure differential driven secondary flow then drives a turbine mounted within the secondary tube to generate useable electricity.

OBJECTIVES

Previous testing of the VETT showed that the efficiency and power generated by the device was dependent on the strength of adverse pressure gradients and the amount of turbulence generated at various sections throughout the length of the primary tube. The three main sources of energy losses in the device are:

- The adverse pressure gradients caused by the contraction in cross sectional area between the inlet to the primary tube and the venturi duct of the tube.
- The dissipation of energy as unusable heat due to the mixing of primary and secondary flows at end of the secondary pipe located just upstream of the venturi duct.
- The expansion of flow as it travels from the venturi duct through to the diffuser section.

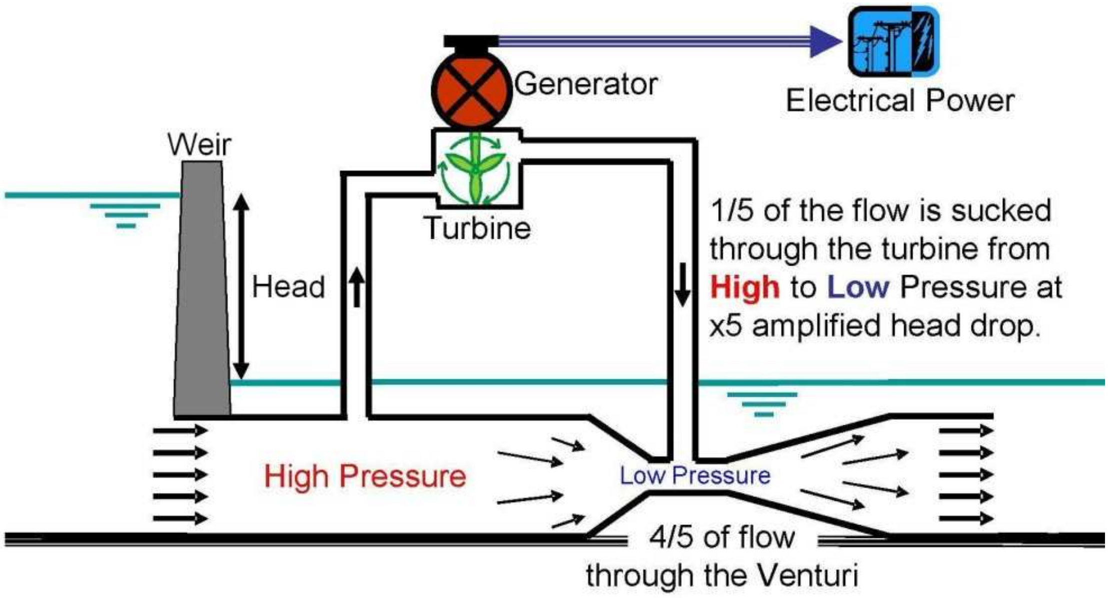

Figure 1: Diagrammatic representation of VETT

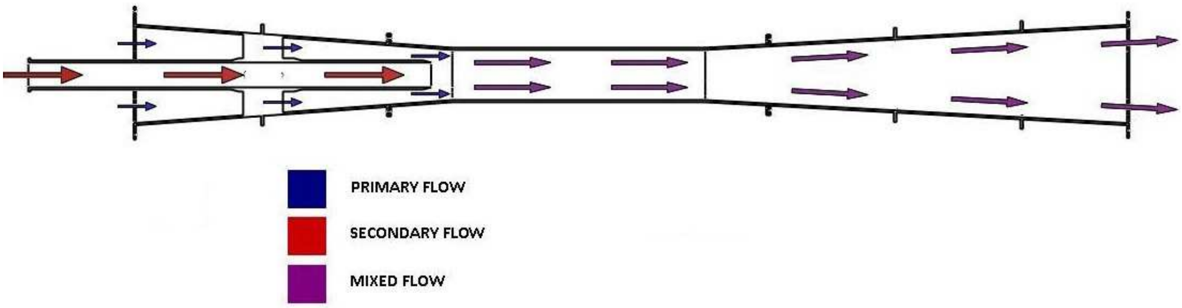

Figure 2: Areas of flow mixing in Co-axial VETT.

It is desirable that the geometry of the VETT is such as to allow as smooth as possible transitions between smaller and larger cross sectional areas as well as smooth mixing of primary and secondary flows. For the particular set of tests presented in this paper, the objective was to examine the optimum combination of the following geometric parameters:

Cross sectional diameter of the secondary flow pipe.
Position of the downstream end of the secondary flow pipe with respect to the venturi section.
Length of the venturi mixing section.

Previous testing had also showed the length of the diffuser section to be a parameter to which hydrodynamic efficiency was particularly sensitive due to the energy losses associated with expansion of flow. The optimum diffuser length found from these previous tests was used in this set of experiments, and was kept fixed throughout. Also fixed was the length of primary pipe between the inlet of the primary pipe and the start of the venturi mixing section.

The original test plan was to run each combination of the above parameters at two driving heads and four different ratios of flow through primary pipe and flow through secondary pipe. The overall hydrodynamic efficiency of each configuration at each flow condition was to be determined by recording static pressure at 20 points along the length of the VETT, and using the following relationships:

$$Pressure\ ratio = \frac{Pressure\ across\ secondary\ path}{Pressure\ across\ VETT}$$

Eqn. 1

$$Flow\ rate\ fraction = \frac{Secondary\ flow\ rate}{Total\ flow\ rate\ through\ VETT}$$

Eqn. 2

$$Hydrodynamic\ efficiency = \frac{Hydrodynamic\ power\ dissipated\ in\ secondary\ path}{Total\ hydrodynamic\ power\ dissipated\ in\ VETT}$$

Eqn. 3

$$Hydrodynamic\ efficiency = Flow\ rate\ fraction\ x\ Pressure\ ratio$$

Eqn. 4

EXPERIMENTAL SETUP

The experimental setup of the VETT test rig at the BHR Group hydraulics laboratory is shown in figures 3 and 4. The VETT converging section, venturi duct and diffuser section were mounted between a header tank upstream of the mixing section and a sink tank downstream of the diffuser section. The longest combined length of the three sections of the VETT tested was 4.7m. The upstream header tank was to simulate the driving head of water from the weir of figure 1, and had dimensions of 3.0 x 2.0 x 2.9m. The downstream sink tank represented the downstream water level, and had dimensions of 2.4 x 4.9 x 1.2m.

All along the length of the VETT, a number of tappings were inserted to allow pressure transducers to record pressure readings, which were displayed on a laboratory computer. Flow was recirculated between the header tank and sink tank and through the VETT via three 10 inch return pipes attached to two centrifugal laboratory pumps. The flow rate and driving head in the rig was controlled using control valves on the pumps and return pipes. The value for flow rates were recorded by electromagnetic flow metres on the return pipes, while driving head was recorded via a clear acrylic sight tube attached to a pressure tapping at the base of the header tank and fixed to the outside next to a Vernier scale.

The secondary flow tube was supported in the converging section of the VETT upstream of the venturi by three aerofoil shaped struts separated radially by 120 degrees. As the secondary pipes propagated back into the header tank, it also needed to be supported here. This was done via a PVC clamp flange with three struts connecting the outside of the secondary pipe to a plate on the front inside face of the header tank. The installation of instrumentation and control valve mechanisms also meant that that a section of the intake of the secondary flow pipe was required to exit and re-enter the header tank upstream of the entrance to the VETT, as shown in figure 4.

Figure 3: Header tank of experimental rig at BHR Group hydraulics laboratory

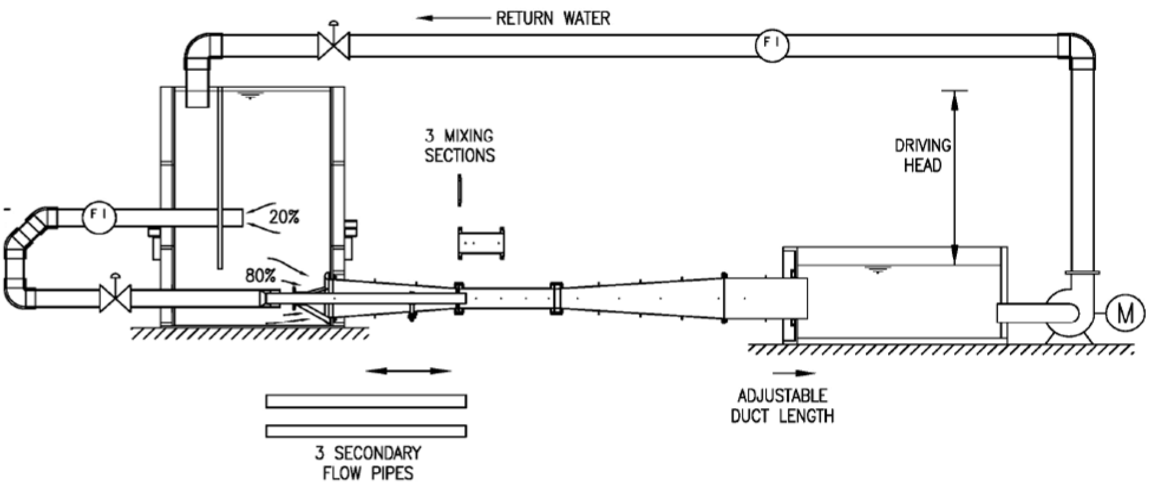

Figure 4: Schematic of experimental rig at BHR Group hydraulics laboratory.

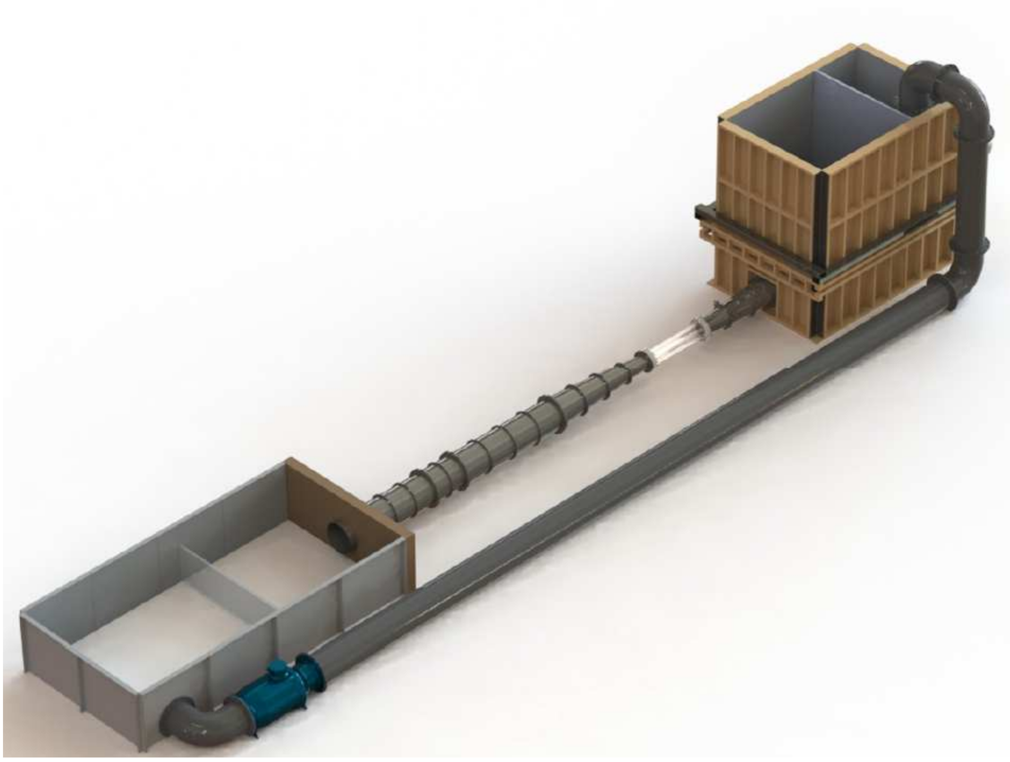

Figure 5: Representation of laboratory setup at BHR Group

The final phase of the testing was to connect a turbine (shown as “M” in Figure 4) into the secondary flow to demonstrate VETT generating electrical power to non-technical potential investors and other interested third parties. The turbine used was specified for other purposes and was not deliberately matched to the flow characteristics but nevertheless provided a good demonstration of VETT’s potential. Pressure and flow measurements were taken but these duplicated what had already been noted and provided no new insights into future design improvements.

RESULTS AND DISCUSSION

For each combination of the aforementioned geometric parameters of the VETT, driving heads of 2m and 1.3m were used. 2m was considered the largest driving head possible in experiments due to the high hydrostatic pressures associated with higher heads and the cost implications of the stronger reinforcements for the header tank which would have been required. Also for both driving heads, different ratios of flow rate distribution between primary and secondary flow tubes were sought by varying the opening of the choke valve, which was simulating the power off-take by the turbine. (See “Flow rate fraction” equation 2 above). These ratios were:

1. 85% of the total flow through the primary tube and 15% through the secondary tube.
2. 80% of the total flow through the primary tube and 20% through the secondary tube.
3. The control valve of the secondary flow tube fully open to allow maximum possible flow through it. This resulted in a flow of 362 l/s through the primary tube and 133 l/s through the secondary tube, giving a ratio of 26.9% through the secondary tube and 73.1% through the primary tube.

The potentially huge number of test results was limited to a reasonable data set by analysing trends as the tests proceeded, eliminating parameter combinations that were obviously off-optimum.

The results indicated a maximum of just over 50% for the conversion efficiency of hydraulic energy into energy available for mechanical or electrical energy. The optimal combination was the largest secondary tube diameter and longest mixing section where the secondary pipe stood back a little from the throat of the mixing section, the conversion efficiency being relatively insensitive to this latter parameter and to the driving head.

CONCLUSIONS AND FUTURE WORK

Although superficially an extremely simple concept, Venturi-Enhanced Turbine Technology is rather complex in several ways. The complexity of the turbulent flow regime in the mixing section has been mentioned. It may also be noted that there is a theoretical maximum possible energy conversion efficiency that would be less than 1.0 even in a perfect fluid with zero viscosity. The laws of Physics mandate that energy must be lost in the mixing process. This arises because conservation of momentum where two different moving masses coalesce can only be achieved with energy loss.

Practical VETT configurations have a theoretical maximum energy conversion efficiency in the 70%-75% range, typically. Allowing for viscosity in real fluids and other inescapable losses suggests that a 65% energy conversion efficiency is a realistic ultimate target.

Even at 50% efficiency, VETT economics are outstanding without reaching 65%. In a closely-supervised study conducted for the UK Government for VETT installed in a crossing of the River Severn Estuary in South-West England, the infrastructure cost compared to a conventional Ebb-Flow barrage was reduced from over £30 billion to under £10 billion, a three-fold reduction in capital costs for 75% of the annual energy output (at 50% conversion efficiency). At an 8% cost of capital, the power cost was calculated to be 6.8p/kWh.

As previously mentioned, Ove Arup & Partners Ltd conducted a CFD analysis in parallel to the tests described here, completing mid-2014. Follow-up CFD analysis is still current at the time of writing but small changes to the VETT geometry with little or no cost impact have been shown to raise the efficiency to around 55% and it is hoped to achieve and perhaps exceed this with the first full-scale commercial VETT projects currently in hand.

In practice however, VETT is a technology that can generate renewable energy at a very low cost per kWh by prioritising low cost over energy conversion efficiency. Hydraulic energy is present in the natural environment in very large quantities and if any given VETT needs to generate a greater output, it can simply be made slightly larger at little additional cost. The source energy is, after all, “quasi-infinite and free”.

An interesting analogy is available with Internal Combustion Engines. The best modern automobile engine makes available as useful mechanical energy around 25% of the energy of the gasoline it consumes. The 75% that is wasted still has to be bought, however, and the tax on that wasted fuel paid to the Government. A VETT by contrast is already twice as efficient at the start of its development as is an automobile engine in advanced technical maturity. The 50% of the incident hydraulic energy that VETT doesn’t use, moreover, costs nothing and remains harmlessly in the environment.

Perhaps even more important than its compelling economics in the future will be the environmental interaction of VETT with fish and birdlife. Having now achieved better-than-adequate energy conversion efficiency, VerdErg’s development focus has moved on to demonstrating VETT’s benign environmental footprint as regards the stewardship of fish and bird-life.

In conventional hydropower fish have to pass through the turbines unless the entire facility is fitted with fish screens, a very large cost element. All fish passing through can experience impact with the blades. Long fish such as eels and lamprey are particularly vulnerable. In a VETT, however, only 20% of the flow passes through the turbine in the secondary flow and it will always be screened off.

A second source of concern is that many fish have a swim bladder that the fish instinctively inflates and deflates to control its buoyancy. The question arises as to if the fish's swim bladder will be damaged when passing through a pressure transient such as occurs in the primary flow of a VETT. Pressure transients occur in nature when fish leap from deeper water or pass between rocks in fast-moving water and the available data suggests that the pressure transient in a VETT is of a similar order of magnitude to that known to be safe. The rather sparse known data in the literature is only indicative however, and in 2013 VerdErg commissioned tests at a specialist fish husbandry laboratory in the Netherlands to gain some reliable data. Over 800 fish of four different species passed through a VETT built in the laboratory and not one single injury or mortality was recorded. trout, salmon, gobi and eels were tested.

It is recognised that there are many other species of fish, however, and it is anticipated that one of the major elements of future work will be expanding the data base to demonstrate that VETT technology is "fish-friendly" to all species found in the various geographic locations where VETT is deployed.

Figure 6 shows the fish trials undertaken in 2013 in Utrecht. It is interesting to note that all the fish instinctively passed through the venturi backwards, keeping their heads facing the direction of flow relative to their movement.

Figure 6: Fish testing at VisAdvies, Utrecht, Holland

Regarding protecting birdlife, this is particularly relevant to VETT installation across estuaries. One of the major concerns is that a conventional Ebb-Flow barrage permanently inundates much of the inter-tidal wetland that is a nutrient-rich habitat for migratory birds. This is because by the time mean water level is reached in the lagoon on a falling tide, the water level outside the barrage is near low-water mark, given the driving head needed to turn conventional turbines. At that stage the turbines are shut down until the water level in the lagoon rises again on the incoming tide. So the water level never falls much below mean water level. For example the conventional barrage proposal for the Severn Estuary already mentioned would have reportedly lost 65% to 70% of its wetlands; these would have had to be expensively re-created elsewhere.

It is interesting to note how a VETT works in a tidal estuary. This is shown in Figure 7. The VETT structure is porous and the tide flows in and out nearly continuously except when its direction changes at high and low tide. The tidal signal inside the landward lagoon is somewhat attenuated, because of the energy extracted from each tidal cycle. The most notable feature, however, is the phase shift, typically of an hour or more, by which the tidal signal inside the crossing lags the tidal signal outside. This phase shift can be seen to be the source of the driving head, typically of 2m-3m, that is then amplified three of four-fold by the VETT and drives the much smaller, comparatively low-cost, high-speed turbines semi-continuously. An ebb-flow barrage, by contrast, drives much larger, slower, turbines for a much shorter period each tidal cycle.

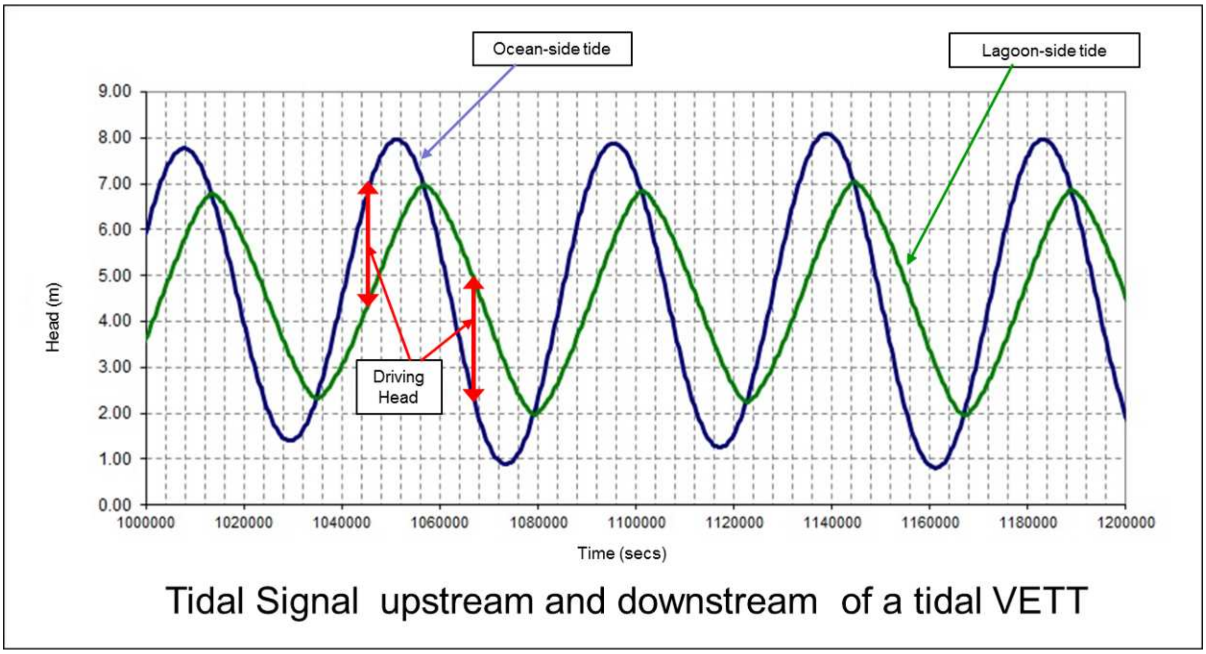

Figure 7: Tidal signal upstream and downstream of a tidal VETT.

The fact that the electrical power output is semi-continuous is an advantage in itself regarding compatibility with the electrical power transmission network but the big winner is the environment. This is because the inter-tidal wetlands are now largely preserved. In the example quoted of the Severn Estuary where an Ebb-Flow barrage would permanently flood 65% or more of this vital habitat, a VETT would permanently inundate less than 10% of the inter-tidal wetlands.

Work is already starting on deploying VETT for a crossing of the Inner Solway Firth in North-West England, shown in Figure 8. A patented bi-directional version of VETT is necessary for tidal estuaries and is already partly developed, having been tested at BHR Group laboratories at just over 40% energy conversion efficiency. This "Linear VETT" configuration features linear venturi formed between opposing hollow, aerofoil-shaped, vertical columns. Future work will draw on the CFD capability qualified and calibrated by the tests described in this paper to refine this configuration and give the tidal estuary "Linear VETT" an efficiency of 50% or better, similar to the more fully developed Co-axial version shown in Figure 2.

This "Solway Energy Gateway" installation shown in Figure 8 will be the proof-of-concept for numerous very much larger VETT-enabled tidal lagoons and estuary crossings around the World, in the more distant future.

Figure 8: Proposed “Solway Energy Gateway” from Bowness (England) to Annan (Scotland).

Beyond the commercialisation of tidal energy lies the challenge of deploying VETT offshore, for exploiting wave energy. This is much more complex although once again the principle expected to be adopted is deceptively simple. The patented concept recognises the orbital wave motion in the vertical plane. The bi-directional Linear VETT with vertical profiled tubes will therefore experience a flow between adjacent columns when placed across a wave field. A rendering of how such a VETT might look concludes this paper as shown in Figure 9.

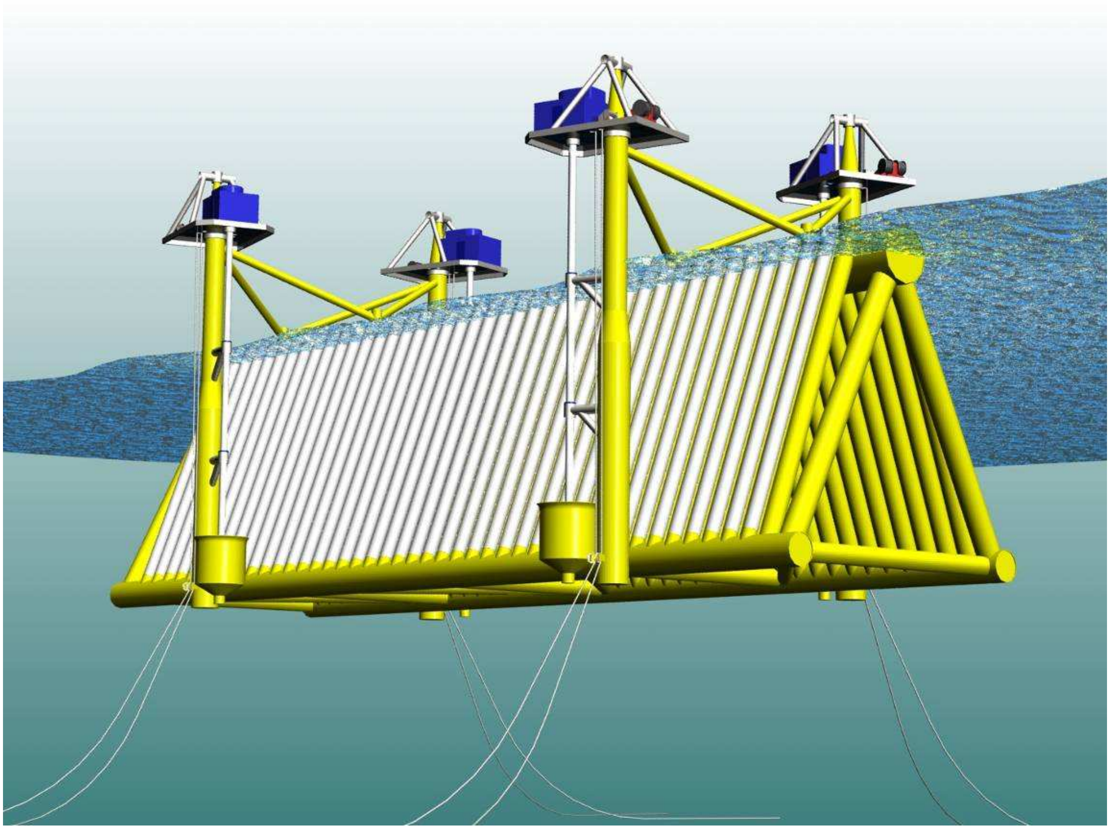

Figure 9: Conceptual rendering of wave energy VETT.