ANALYSING THE PERFORMANCE OF THE ARCHIMEDES SCREW TURBINE WITHIN TIDAL RANGE TECHNOLOGIES

MSC (BY RESEARCH) THESIS

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Declaration

The author of this thesis declares that this work has not previously been submitted for the award of a higher degree elsewhere and unless stated otherwise, is the authors own work.

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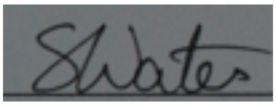

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Abstract

The UK has an enormous potential for tidal range energy. With the threat of global warming and the decline of the North Sea oil industry, national energy focus is shifting towards this form of renewable energy. Following in the footsteps of the first tidal barrage scheme in La Rance, the 320MW Swansea bay lagoon scheme has recently been given governmental approval (BBC News, 2015).

Like existing projects, this lagoon will use the bulb turbine, which has been the standard device for tidal range projects for the last 50 years. One of the reasons these have continued to be chosen is because they are a proven technology, however, since the first project in the 1960's, turbine technologies have evolved and altered in a plethora of new designs.

The aim of this research is to investigate and evaluate these new designs numerically using a marking criteria to determine their suitability. Out of the designs examined the Archimedes Screw proved the most promising for further research, due to the reduced cost, simplistic design and environmentally friendly nature.

Through the use of computational fluid dynamics (CFD), a variety of screw turbine designs were evaluated, each investigating a different geometric parameter, which affects the overall performance of the device. The trends found due to altering these values proved that the design of a screw turbine and a screw pump are fundamentally different. The designs, which both increased the volume of flow in each screw bucket and decreased the surface area of the turbine in contact with the flow proved the best.

This device in tidal lagoons offers; superior pumping ability; longer operational per tide cycle and can perform well in water with a high silt content (which is expected in tidal lagoons). However, it is necessary to perform further research and model testing to fully analyse the power potential of a full sized device.

Keywords

Renewable Energy; Tidal Range; Turbine; Archimedes Screw; Bulb Turbine; Swansea Bay Lagoon; Computational Fluid Dynamics; Optimisation

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Academic Achievements

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Journal Publications

1. Over 2,000 years in review: Revival of the Archimedes Screw from Pump to Turbine. *Renewable and Sustainable Energy Reviews* (Elsevier), June 2015

2. A World First: Swansea Bay Tidal Lagoon in Review. *Renewable and Sustainable Energy Reviews* (Elsevier), [Under Review]

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Presentations

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Nomenclature

A	Area	[m^2]
D	Outer Diameter	[m]
d	Inner Diameter	[m]
E	Energy	[J]
G	Thickness of Spiral Profile	[m]
g	Acceleration due to gravity	[m/s^2]
h	Head difference	[m]
h_1	Inlet head	[m]
h_2	Outlet head	[m]
L	Length of screw	[m]
N	Number of flights	[-]
n	Rotational Speed	[rev/min]
n_b	Number of Buckets	[-]
P	Pitch	[m]
Q	Flow rate	[m^3/s]
Q_c	Volume flow rate passing through clearance gap	[m^3/s]
Q_i	Volume flow rate through inlet	[m^3/s]
Q_T	Volume flow rate through turbine	[m^3/s]
τ	Torque	[N.m]
V_b	Bucket volume	[m^3]

Acronyms

CAD	Computer Aided Design
CEL	CFX Expressions
CFD	Computational Fluid Dynamics
FEA	Finite Element Analysis
GUI	Graphical User Interface
NTUA	National Technological University of Athens
RPM	Revolutions Per Minute
SST	Shear Stress Transport

1 Introduction

Our blue planet, with over 70% of its surface covered by oceans, offers a multitude of renewable power options. The main three being used to this date are solar, wind and hydro/tidal energy. The first two have a distinct disadvantage – they are weather dependant. A wind turbine cannot generate electricity when there is no wind and the same principal is also valid for solar energy. This makes the output unpredictable and the energy it produces cannot be relied upon. Reliability is something tidal power excels at, as in depth information regarding tidal levels can be calculated and known years in advance. Although tidal power cannot produce electricity 24 hours a day at a single location it does have a known output on any given day of operation.

There are many ways to harness energy in the ocean, and the main methods can be split into three sections: wave, tidal stream and tidal range.

Wave energy is exploited when the wind acts on the surface of the sea creating waves and uses the height difference between the peaks and troughs of these waves to generate electricity. Wave energy turbines are usually semi submerged and the output is dependent on the size and velocity of the waves entering the device.

Tidal stream devices take advantage of the kinetic energy in the ocean due to currents or tidal flows.

However, both of these types are only able to generate relatively low amounts of power, in the region of a few megawatts (MW). Tidal range power generation takes advantages of the height (head) difference created between high and low tides. By doing this, a single tidal range plant can produce hundreds of MW. For this reason, tidal range production is viewed largely as the leading method of tidal power generation and shall be discussed in length during this project.

1.1 Why Tidal Energy is needed in the UK

The UK has the greatest potential for tidal power energy in the world, with a large variety of locations that are optimal for all types of tidal energy. It has been shown that over 20% of the UK's energy supply could be met through exploiting the natural energy available in tidal streams and estuaries around the UK (McGrath, 2013).

It is vitally important the UK begins to exploit as much of its natural, renewable energy as possible. Not only to help offset carbon emissions for the sake of global warming, but also to meet legally binding obligations. As a member state of the EU, the UK is locked into various environmental laws. One of these requires the UK to meet 20% of its nations electricity demand directly from renewable sources (European Commission, 2014).

There is also a requirement to achieve an 80% reduction in carbon emissions by the year 2050 (Deparment of Energy and Climate Change, 2008). It is very important that the UK reduce carbon emissions, not solely for the reasons stated above, but for the health of its citizens and for the economy. The WHO has announced that air pollution is now the main cause of preventable death, resulting in 7 million deaths worldwide in 2012 (WHO, 2014). This is an important and expensive issue that puts a large amount of strain on the NHS with the costs of air pollution in the UK surmounting to approximately £15bn (Fig. 1) (Mayor of London, 2010). Addressing this issue before 2050 would be very beneficial and also difficult without the inclusion of a vast amount of renewable energy.

Figure 1 - Air Pollution in London (Dearden, 2014)

Furthermore, a large increase in the amount of electricity generated through renewable sources would help towards achieving energy independence, giving the UK greater control of its energy supply. With the rapid decline of the North Sea oil and gas industry, the UK is more reliant than ever on foreign imports of fossil fuel sources. Having greater control on the nation's energy supply would mean prices could be regulated and kept stable without being influenced by worldwide politics, inflation and oil prices.

There has also been an alarming decrease in spare electricity from the National Grid during winter, with the amount available this year falling from 17% in 2011-2012 to roughly 4% for 2014 (BBC News, 2014a). This is a direct result of generator failures and reductions (BBC News, 2014a). Although the UK is unlikely to have blackouts, the extra measures needed to prevent these blackouts will put strain on an already complicated and struggling system (BBC News, 2014a). Various UK coal, oil and nuclear power plants are also planned for closure in the coming years, further exacerbating this problem (Gosden, 2015) (Energy UK, 2015). Introducing a tidal power project would be able to offer a guaranteed amount of power accessible that is independent of fuel availability.

1.2 Project Aims and Objectives

As detailed above, it can be seen that the UK's stance on power generation needs to adapt and tidal range energy provides the perform way of doing it. This research plans to evaluate both the methods of producing energy through tidal range principal and also investigate the turbines used or could potentially be used. The overall aim of the project is to design and create a new device for tidal range power generation which could offer unique advantages to investors and governmental bodies to increase the likelihood of an increased number of tidal range projects in and around the UK.

As Swansea bay is a much discussed, state of the art project at the moment, this site location will be used throughout the project as a case study to both design the new device and eventually compare performance data to.

2 Tidal Range Power Generation

Tidal range power is generated through the creation of a head difference. A wall combined with turbines is used to disrupt the natural tidal flow. As the tide comes in the wall blocks the tidal flow, creating a difference in height between the seaward side of the wall and the basin of water trapped on the other side of the wall. When this difference is great enough, the water is allowed to pass through the turbines in the wall and into the basin. As this happens, energy is created. When the tide begins to flow back out to sea, the water in the basin is trapped at high tide level, and the water on the seaward side of the wall recedes. This again, creates a height (head) difference and eventually the water is allowed to flow back through the turbines, creating energy once more. This method is only an introduction to one of the various methods tidal range generation can employ and will be discussed in more detail (see section 3.5).

2.1 Tidal Barrage

Tidal barrages are the first and most common form of tidal range power generation. The barrage wall is used to completely block the river or estuary it is located within. Using the principal of tidal range power, the barrage has turbines located within the wall, combined with sluice gates (Wyre Tidal Energy, 2015a).

The barrage wall is often created through the use of pre cast cassions, which are created in sections on shore, then moved into place and sunk.

The section of the wall, which contains the turbines, is constructed with the use of cofferdams. These involve the creation of a secondary, circular wall or dam, situated around where the turbines will be placed. Once constructed, the water inside the cofferdam is then drained, creating a dry workspace for the construction and placement of the complicated turbines and turbine housing (British Hydro, 2009).

As the power potential of a location is heavily dependent on a large difference between the heights of low and high tides respectively, choice locations are hard to come by. This coupled with the need for strong grid connections to be available nearby, further reduce the number of suitable locations. However, in spite of this, there are various tidal barrages dotted around the globe, in locations such as Canada, France, China South Korea and Russia.

2.1.1 Existing Locations

2.1.1.1 France – La Rance

Figure 2 - La Rance tidal barrage (Aggidis, 2010)

The most well known tidal barrage plant is located in Brittany, northern France (Fig. 2). The La Rance barrage is the first of its kind to be operations and is acknowledged to have been an outstanding success (Aggidis, 2010, Charlier, 2007).

Construction of the barrage began in 1961 and became fully operational in 1967, creating a yearly rated output of 480GWh through 24, 10MW bulb turbines (Aggidis, 2010). Since this time, the barrage turbines have operated very successfully, with a downtime of less than 6.5%, and requiring only minor maintenance (Andre, 1976, Chaineux & Charlier, 2008).

La Rance generates electricity four time per day; both during flood and ebb tides (bidirectionally) and uses the turbines as pumps during the slack tide to increase the head difference between the two sides of the barrage wall, as this increase the amount of power available during each tidal cycle (Kerr, 2007, Rourke, et al., 2010).

2.1.1.2 South Korea – Lake Sihwa

Figure 3 - Lake Sihwa tidal barrage (Aggidis, 2010)

Lake Sihwa (Fig. 3) was originally created in 1994 as a freshwater storage lake for agricultural purposes (Bae, et al., 2010). However, due to repeated pollution leaks into the lake from nearby industries, the freshwater became too contaminated for its intended use.

Therefore, in order to help improve the cleanliness of the water inside Lake Sihwa, the dam that was used to create the lake was modified into a tidal range plant. 10 bulb turbines (the same type as La Rance) were placed inside the dam, giving the barrage a rated output of 254MW with an annual generation of 552.7GWh (Daewood E&C, 2015). By doing this, large volumes of fresh seawater would be able to pass into the lake, as well as allowing the polluted water to pass out into the sea. The modification from dam to barrage cost approximately $335 million (Daewood E&C, 2015).

Unlike the La Rance barrage, the Lake Sihwa barrage only operates during the flood tide. The reason for this is to keep areas of agricultural land permanently above sea level (Bae, et al., 2010). Operating in any other method would reduce the amount of land available for farming and other purposes.

The success of this project has increased interest and paved the way for further tidal range in South Korea with additional locations already planned in Incheon and Gerolim (Bae, et al., 2010, Daewood E&C, 2015).

2.1.1.3 Russia, Kislaya Guba

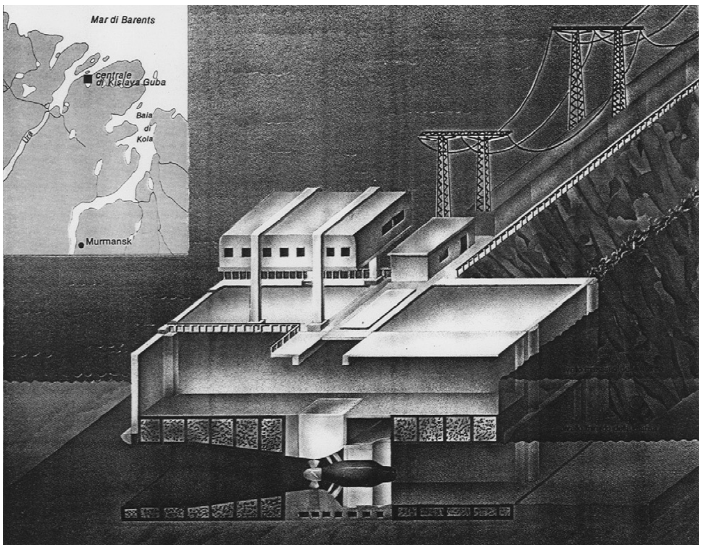

Figure 4 - Kislaya Guba tidal barrage (Chaineux & Charlier, 2008)

Russia's first tidal range project (Fig. 4) was originally funded by the USSR and was completed in 1968 (Bernshtien, 1970). This small scale project, with a rated output of 1.5MW was mainly seen as Russia exploring alternative power methods to its traditional oil and gas (Aggidis, 2010).

Built around the same time, Kislaya Guba has many similarities to La Rance, for example they both use the same style turbine (bulb). However, there are many differences; mainly as a direct result of the harsh environment it is located. The very cold temperatures seen in Murmansk meant that the concrete used had to be frost resistant, and the whole construction was fitted together with use of pre-cast concrete caissons (Chaineux & Charlier, 2008).

2.1.1.4 Canada, Annapolis

Figure 5 - Annapolis Tidal Barrage plant (Annapolis Valley Vacation, n.d.)

The tidal range plant within the bay of Funday (Fig. 5) was built in 1984 and contains the largest tidal range found anywhere in the world, with peak values reaching as much as 16m (Etemadi, et al., 2011, Pelc & Fujita, 2002).

Unlike the other operational tidal range plants around the world, this project does not use the far more common Bulb turbine. Instead it uses one very large Straflo device. This turbine (the largest in the world) is able to produce a rated output of 20MW alone (Nova Scotia Power, 2015). However, it is only operational during the ebb tide, twice per day (Electrical Line Magazine, 2002).

This project also acts as a bridge like structure, providing an important transport link, as well as acting as a successful flood defence (Power Technology, 2014).

2.1.1.5 China

Figure 6 - Jiangxia tidal barrage (Maritime Tidal Energy, 2010)

Although not often associated with renewable energy, China boasts the most tidal range projects in the world. The largest in China and most well known project is in Jiangxia port, Wenling (Fig. 6).

Using bulb turbines, Jiangxia produces 3.9MW and produces energy both as the tide comes in and when it goes out (Shanghai Investigation, Design & Research Institute Co., 2015) (Chuankun, 2009, Simas, 2012). China was able to design and manufacture everything that was required to build the project (Chuankun, 2009).

It is claimed that through introduction of the tidal barrage, the local fishing economy has improved greatly due to increased numbers (Bernshtein, 1995).

Many of China's other barrage plants were decommissioned only a few years after they were completed. This was mainly due to a lack of understanding, poor locations and inefficient turbine designs (Chuankun, 2009). Table 1 contains information on China's lesser known tidal barrage projects.

Table 1 - Tidal range plants in China (Chuankun, 2009)

Tide Power Station	Average Tidal Range (m)	Power (kW)	Operating Conditions	Run Time
Baishakou	2.48	960	Single reservoir with single direction turbines	1978-
Liuhe	2.5	150	Single reservoir with bidirectional turbines	1976-1998
Yuepu	3.6	150	Single reservoir with single direction turbines	1971-1987
Shashan	5.08	40	Single reservoir with single direction turbines	1959-1992
Haishan	4.91	250	Two reservoirs, with single direction turbines	1975
Shoudong	3.78	40	Single reservoir with single direction turbines	1959-1985
Guozishan	2.0	40	Single reservoir with single direction turbines	1977-1985

Due to the ability to create everything in China itself, a large government push in the way of tidal range energy could improve the country's economy.

2.1.2 Potential Locations

Although there are many places around the world with large tidal ranges, potential locations need to take into account other aspects such as accessibility and protected environmental areas. For many locations the tidal range may be just a little too low for the project to be profitable in a relatively short timescale. This has limited the potential locations for tidal barrages significantly. A list of sites feasible for development is outlined in Table 2. As can be seen in the list, there are significant amount of locations available in the UK.

Table 2 - Possible tidal barrage locations around the world (Hammons, 1993)

Country	Site	Mean tidal range (m)	Basin Area (Km^2)	Installed Capacity (MW)	Approx. annual output (TWh)	Annual plan load factor
Argentina	San Jose	5.9		6800	20.0	
Australia	Secure Bay 1	10.9			2.4	
	Secure Bay 2	10.9			5.4	
Canada	Cobequid	12.4	240	5339	14.0	0.30
	Cumberland	10.9	90	1400	3.4	0.28
	Shepody	10.0	115	1800	4.8	0.30
India	Gulf of Kutch	5.3	170	900	1.7	0.22
	Gulf of Cambay	6.8	1970	7000	15.0	0.24
Korea	Garolim	4.7	100	480	0.53	0.13
	Cheonsu	4.5			1.2	
Mexico	Rio Colorado	6-7			5.4	
	Tiburon	-			-	
UK	Severn	7.0	520	8640	17.0	0.22
	Mersey	6.5	61	700	1.5	0.24
	Wyre	6.0	5.8	47	0.09	0.22
	Conwy	5.2	5.5	33	0.06	0.21
US	Passamquoddy	5.5				
	Knik Arm	7.5		2900	7.4	0.29

	Turnagain Arm	7.5		6500	16.6	0.29
Former Soviet Union	Mezen	9.1	2300	15000	50.0	0.38
	Tugur	-		10000	27.0	0.31
	Penzhinskaya	6.0		50000	200.0	0.45
	Cauba	-				

2.1.3 Environmental Issues

Issues revolving around the negative effects to the environment have made it difficult for tidal range projects to gain the appropriate planning permission and local support required for construction to commence. This has been seen with the repeated rebuttals of the Severn Estuary barrage, which is a project that has been considered several times throughout the past one hundred years. Each proposal however, was turned down due to a combination of high initial costs and environmental concerns.

However, the truth regarding the effect on the surrounding areas of these projects can be very different. In fact with the lake Sihwa project, by adapting the original structure into a tidal range power plant, the inclusion of turbines has improved the water quality inside the basin, although it should be noted that the prior to the tidal range plant being created, the water inside the basin was severely polluted. One of the main reasons for its construction was to improve water quality.

Unfortunately, there was no comprehensive environmental study carried out on the Rance River prior to the creation of the tidal barrage. It is known that during the 3 years of construction, various marine fauna disappeared, mainly due to variations in water salinity and increased sediment in the basin (British Hydro, 2009). There has also been a noticeable reduction in various marine life in the area such as sand-eels (Wyre Tidal Energy, 2015b). However, since its construction a new, healthy ecosystem has been created. The same species of bird life in the area is largely the same, having adapted to the new environment, through finding food in nearby mudflats. As well as this, there is now a well-established range of fish eating birds living in area. Marine life has also adapted to the new environment, with scallops and oysters being introduced. A study undertaken in 1980, showed over 70 fish species, 110 varieties of worm and 47 kinds of crustacean were all living in the La Rance estuary (British Hydro, 2009).

This seems to prove that although the barrage has modified the marine environment significantly, life finds a way to adapt, and after a transition period a new environment is able to become well established and thrive. However, for areas in which protected or rare species are reliant upon the environmental stability of the surroundings, this can be make it nigh on impossible to achieve the necessary planning permission, government permits and local support required.

2.2 Tidal Barrage Adaptations

Aside from the environmental concerns attached to barrage projects, there is another key issue that has held back large scale deployment of tidal barrages around the world: cost.

As the barrage arrangement requires a large wall spanning the width of whichever estuary or river it is situated in, construction costs are very high. Although the structure has a long lifetime of at least 120 years, the large initial costs required to fund the construction, combined with the time required before the project pays back these costs to become profitable discourages potential investors.

Due to these two major issues, a variety of new methods have arisen, each of which is able to generate power through the basic tidal range principals. The successful utilisation and development of these new adaptions means that locations that are not currently suitable for a tidal barrage could still be constructed and would revitalise the tidal power industry around the globe.

2.2.1 Tidal Fence

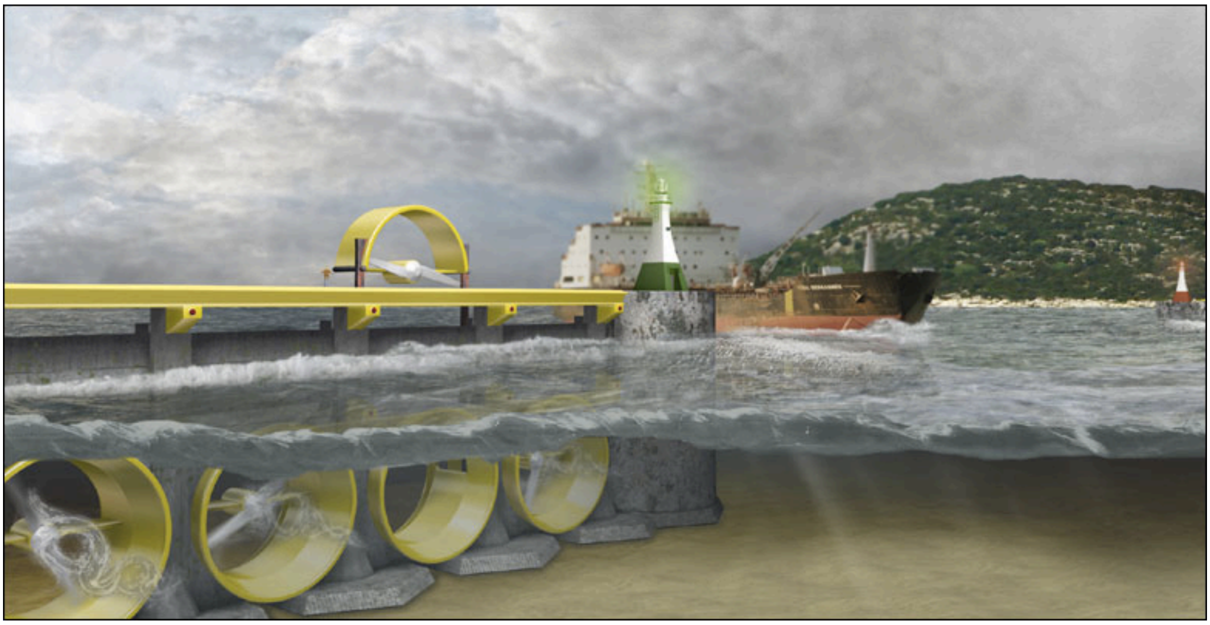

Figure 7 - Artists impression of a tidal fence project in the Servern estuary (BBC News, 2008)

Tidal Fences (Fig 7) are a theoretical design, with no projects currently in progress at this time; however, they are attracting a lot of attention due to the wide range of potential locations (Pelc & Fujita, 2002). These projects mainly generate power due to tidal currents close to land. The turbines are placed constantly below the waterline and use venturi technology to increase the water velocity through the turbines in order to improve the power output (Blue Energy, 2015). These turbines, using tidal currents, can be placed in locations with tidal flows of above 2m/s (Pelc & Fujita, 2002). This value is quite low, which means a wide range of locations are feasible.

Marc Paish (Severn Tidal Fence Group) believes that a tidal fence project located in the Severn estuary would be able to produce 1.3GW, which would be greater than the output of Sizewell B nuclear power plant (BBC News, 2008).

As the tidal fence does not require the water to be blocked by a solid wall (as a barrage does) they could be produced at a much lower cost. This, mixed with the ability to easily combine the project with required infrastructure, means future projects such as bridges/roads could be used to generate renewable energy. It would also be able to guarantee that shipping would be able to pass easily, keeping vital ports operating at peak values (BBC News, 2008).

Due to the lack of solid wall holding back water to create a large head difference, tidal cycles are disrupted as little as possible, meaning environmental effects are kept to a minimum

(Blue Energy, 2015). However, the full environmental effects of a tidal fence spanning the full width of an estuary are currently unknown and could possibly be damaging (Aggidis, 2010).

2.2.2 Tidal Reef

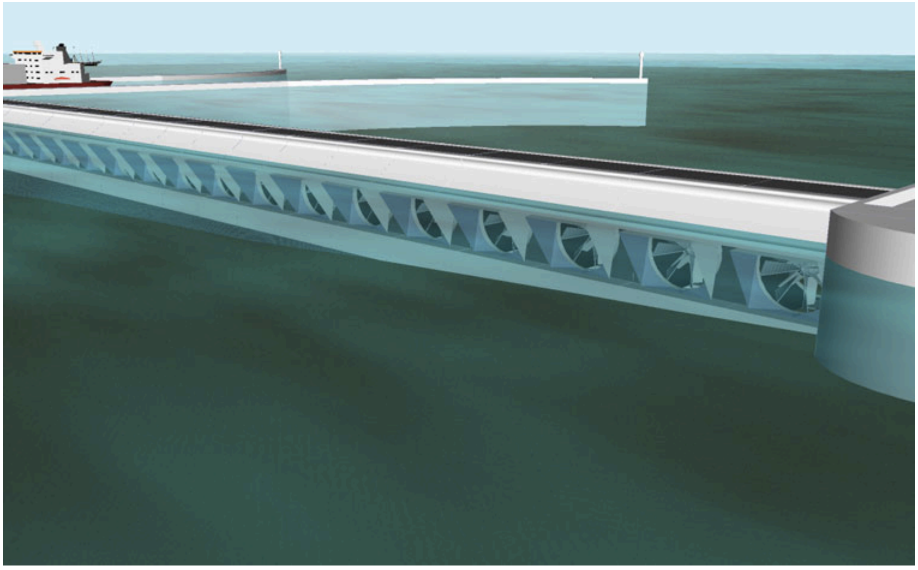

Figure 8 - Prototype Tidal Reef Project (Evans Engineering & Power Company, 2015a)

A tidal reef (Fig. 8) can also offer reduced environmental affects compared to the barrage method. Through the use of ultra low head turbines, a head difference of approximately 2m is created and kept constant. As only a small head difference is required this means the energy created is generated over a much longer time period during each tidal cycle (Evans Engineering & Power Company, 2015b). Although this reef method is comfortably able to generate more energy than a normal tidal stream turbine, it is only able to generate a fraction of what a tidal barrage would be able to (Aggidis, 2010).

However it is much safer for passing marine life, as the pressures encountered in only a 2m head drop are not significant enough to cause harm as they are within limits fish would be subjected to during normal environments.

Although there are no tidal reef projects in the UK, the Severn estuary has been touted as a potential location (Evans Engineering & Power Company, 2015b). If situated in this location, a tidal reef may be able to adequately protect delicate mudflats and saltmarshes in the area, unlike a barrage project (Gray, 2008).

2.2.3 Tidal Lagoons

Figure 9 - Onshore lagoon project outline - (Kelsey, 2015) **Figure 10 – Offshore lagoon (Tidal Electric, 2015a)**

A tidal lagoon is the adaptation that is most like the conventional barrage and is currently generating international interest. The main difference between the two is that a lagoon does not fully span the estuary or river it is located within.

The lagoon wall can be formed in one of two methods. It can either be an onshore lagoon, created in a horseshoe shape, with the coastline forming the last section to complete the circle (Fig. 9) (Tidal Lagoon Swansea Bay, 2015b). This would allow for direct connection to nearby national grid through underground cables. Or the wall alone can form the full circle, with the lagoon situated fully offshore (Fig. 10) (Tidal Electric, 2015b). This would require the power to be transmitted through a series of cables under the seabed connecting the lagoon to the mainland (Tidal Electric, 2015b).

Due to not fully spanning the estuary, tidal lagoons pose a much lower risk environmentally. This is because it does not fully block the tide cycle, meaning there would be a greatly reduced change in the tidal patterns when compared with a barrage. Through not fully blocking the estuary, this also reduces the likelihood and chances of damage due to river debris as the majority will be able to bypass the lagoon structure. However, there is a possibility of a build of silt occurring around the wall of the lagoon and at the sluice gates, potentially causing damage over time.

3 Swansea Bay Tidal Lagoon

Swansea Bay, situated within the Severn estuary has been the most discussed location in the UK for tidal range energy. First discussed in the 1920's, the idea for a Severn barrage has been repeatedly proposed, and each time dismissed under the grounds of the high costs associated with the project and environmental concerns (Harvey, 2013, Aggidis, 2008, Brammer, et al., 2014).

The main reason this site has been at the centre of attention for so long is due to the incredible tidal ranges of this area, which are the largest available within the EU, achieving values as high as 10.5m (Parsons Brinckerhoff Ltd , 2010, Tidal Lagoon Swansea Bay, 2015c).

The project has gained a lot of support, with backing from the government, investment companies and even the surrounding population. With governmental backing coming from the prime minister, the project was given the official go ahead, with all relevant planning permission accepted (BBC News, 2015). During the planning stages, over 195,000 questionnaires were posted to local residents, asking for their thoughts and opinions about the tidal lagoon, while educating people on the aims and methods of the project. The response was overwhelmingly positive, with over 86% of people giving their support to the project, compared to 4% who were against it (Tidal Lagoon Swansea Bay PLC, 2014).

3.1 Cost

As previously stated, one of the reasons against building a Severn tidal barrage was the costs involved. It was previously estimated that the barrage project would cost approximately £34bn (Department of Energy and Climate Change, 2010a). In comparison, the Swansea Bay tidal lagoon is much cheaper, at approximately £1bn, however it does produce much less energy (Harrabin, 2015).

Unlike the proposals for the Severn barrage, the initial costs for the tidal lagoon have been met through a plethora of private investor companies, such as InfraRed and Prudential (South West Wales, 2015, South West Wales, 2014a). Through these investments, the £1bn target for the construction of the lagoon has been reached without the need for government funding or excess debt. Raising funds in this way for a tidal barrage would have been much more difficult due to the amounts involved.

Despite no government involvement with the initial funding stage, the government do provide incentives for renewable energy projects in the form of a "Feed in Tariff Contract for Difference" (Department for Energy & Climate Change, 2012). This involves the government increasing the amount each megawatt is sold for to a pre-arranged 'strike price'. The reason for doing this is to make the project profitable for investors throughout the time where the construction costs are being paid off. The strike price required for the Swansea Bay Lagoon will be necessary for 35 years after it becomes operations at the value of £168/MWh (Pöyry, 2014). This figure is higher and required for longer than what would normally be necessary for wind and solar projects (Pöyry, 2014). This strike price is no cheaper than what would be required for a Severn barrage, although subsequent tidal lagoon projects such as Cardiff are projected to require a much reduced value (Pöyry, 2014). However a tidal lagoon project has the largest operational lifespan of any renewable energy source (120 years), which vastly outlives the 20-25 year predicted lifetime of an offshore wind farm, and is even double the average span of a nuclear power plant (Pöyry, 2014). Therefore, the lagoon is able to produce profitable, cheap and clean energy for 85 years after the strike price ends.

3.2 Construction

The construction timeline set out in Table 3 comes directly from the creators from Swansea Bay lagoon, however other reports have suggested the project is in fact ahead of schedule, with construction set to start in March 2016 (BBC News, 2015). This is largely due to the success the project has had with achieving the necessary planning permissions and government permits.

Table 3 - Swansea Bay tidal lagoon construction timeline (Tidal Lagoon Swansea Bay, 2015d)

Construction Timeline	
2010-2012	Feasibility investigations and project scoping. Optimising construction and engaging with consultees.
2012	Continued engineering and design. Informal consultation on proposals with broad stakeholder audience.
Oct 2012	Submission of Environmental Impact Assessment. Scoping report to the Planning Inspectorate.
Dec 2012	Environmental Impact Assessment commence.
July 2013	Formal consultation (minimum 28 days).
Feb 2014	Submission of application for Development Consent Order to the Planning Inspectorate for determination by the Secretary of State for Energy and Climate Change. Submission of application for a marine license to Natural Resources Wales on behalf of the Welsh Government.
Mid 2015	Planning and marine licence decisions expected.
Late 2015	Construction and installation could commence.
Early 2019	**Earliest connection and first generation into the Grid.**

The construction phase will take approximately 36 months, as long as there are no unforeseen setbacks (Tidal Lagoon Power, 2015a). The wall of the lagoon will be constructed in two major phases. The first will involve the use of high strength, durable plastic Geotubes. This cost cutting method has proved very successful on a large scale, when used for the lake Shiwa project in South Korea (TenCate, 2015). The tubes will be filled with sand, which has been dredged nearby from within the basin area and combined with water. The Geotubes will be carefully placed with the help of divers, and stacked to form the beginning of the wall. The area in between the stacks will be filled with more sand as seen in (Fig. 11).

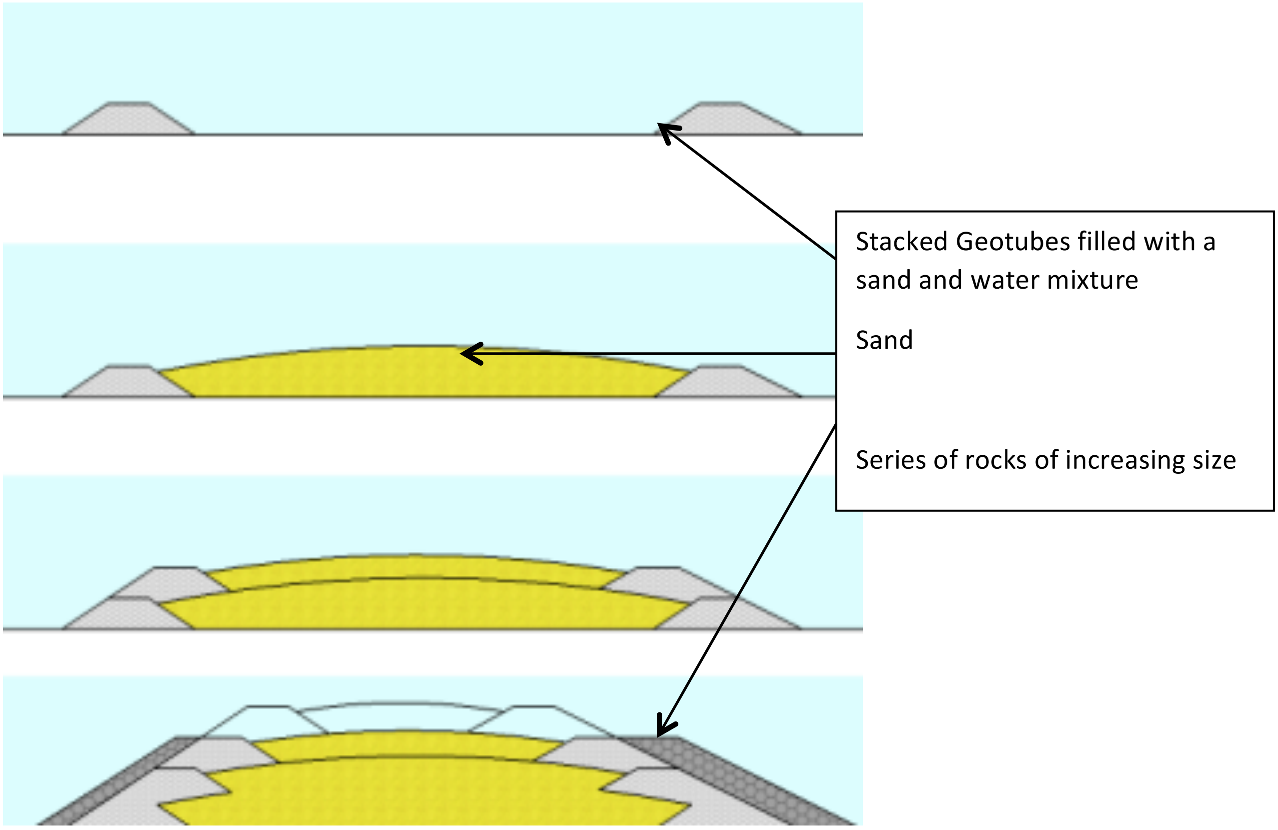

Figure 11 - Cross section of the lagoon wall (Tidal Lagoon Swansea Bay, n.d.)

To protect the Geotubes, a series of high density rocks will be arranged alongside them ranging from small rocks directly next to the tubes, to large rock armour on the outside face of the wall. The rock used will be gabbro, mined from Cornwall and shipped to location via a barge. The rock will allow the lagoon to last its rated lifetime of 120 years and withstand 500 year storms, even when considering the influences of climate change (Shorrock, 2014).

The turbine house section will be created much in the same way as La Rance, through the use of cofferdams (Nemati, 2007). This means a second, circular damn will be needed to drain the water within to create the 500m long turbine house (Charlier, 2007).

The main alterations between the construction of Swansea bay and La Rance are within this turbine house. The turbines will be built in a more modular fashion where they can be constructed in just 4 stages, instead of the 17 that were required previously (Shorrock, 2014). By being able to construct the turbines in fewer steps it means that any costly delay with construction will have a much lower knock on effect, meaning the project is more likely to stay on schedule.

3.3 Environment

Previous tidal range projects based in the Severn estuary have been scrapped due to the environmental concerns associated with a barrage. The two key areas of concern were of fish safety and mortality, combined with the possible destruction of the flood plains in the estuary. These important mud flats provide a vital source of food for a variety of migrating birds and therefore, it was critical that these were sufficiently protected (The Wildlife Trusts, 2010). Unlike a barrage scheme (which would heavily damage and reduce the size of these mud flats), the lagoon is able to adequately protect them (Xia, et al., 2010a). As the lagoon will not completely block the estuary, instead of radically modifying the tide cycle, it delays a portion, allowing the tidal pattern to closely mirror the natural cycle.

In recent times, the bulb turbines that shall be used during the project have also gone through a development phase, intended to improve fish safety. This was mainly achieved through reducing the number of runner blades on the turbine. These modifications, combined with the careful placement of the lagoon wall and turbine housings have managed to improve fish safety enough to satisfy environmental organisations and the local government. The location of the lagoon was chosen specifically to avoid the natural migratory path fish take; therefore the majority of fish naturally pass around the structure, instead of through it (Baker & Leach, 2006). Through complex and extensive fish passage computer modelling, the amount of fish actually harmed could be accurately quantified. It is estimated that there would be approximately a 3.6% mortality rate for both smolts and salmon, both of which are common in the surrounding areas (Tidal Lagoon Swansea Bay, 2015e). This figure was seen to be low enough for the project to continue.

However, the lagoon project has large plans for the area, not just in terms of power generation, but also to reintroduce the once native oyster as well as lobster and kelp to the bay, inside a specially designed 10km reef (Tidal Lagoon Swansea Bay, 2015f).

The lagoon will also provide a platform for a wide range of recreational activities. For example, the lagoon wall can be used as a running or cycling track (Tidal Lagoon Swansea Bay, 2015c). Inside the lagoon, the calm waters will be perfect for both swimming and sailing.

Although 642,000 tonnes of CO_2 (Carbon dioxide) will be produced during the construction of the lagoon, the project will save 236,000 tonnes of CO_2 per year, therefore becoming carbon neutral after only four years (Tidal Lagoon Swansea Bay, 2015c, Tidal Lagoon Swansea Bay, 2015g). This is a considerable carbon offset, and a vital step towards reducing air pollution and tackling climate change.

3.4 Silting Issues

Silt is a combination of both sand and clay sediment carried in the water flow and is very common in tidal estuaries. The build up and deposition of this silt has been a difficult and unpredictable engineering problem for a long time. These issues are made increasingly worse with the fully enclosed tidal lagoon. Previous silt management projects have proved highly unsuccessful. Royal Portbury Dock was created with a built in water pond which was created as specified area within the Dock where the water was able to settle and deposit silt, reducing the levels in more important areas (Western Daily Press, 2015). This process, although theoretically sound did not work in practice. The cooling reservoir for Oldbury nuclear plant also contained a high level of silt, rending almost 90% of the reservoir unusable, despite preventative measures. For the Watchet Harbour project, a substantial amount of time and money was spent on researching silt management techniques, however they were not included in the final construction because of the very expensive nature of the designs (Western Daily Press, 2015). The only effective method of managing sediment levels has been through extensive dredging (which was eventually used for all of these projects).

Currently the large amounts of silt carried into the estuary out of the river Tawe is managed naturally in the area of the Swansea bay lagoon through both the anti clockwise tidal currents in the area and the turbidity caused by the waves (Keith-Lucas, 2013). Both of these prevent the silt from becoming stagnant and depositing on the seabed. The introduction of a tidal lagoon in the area will disrupt both of these by altering the natural anti clockwise current direction and lowering the turbidity. Furthermore, recent and extensive erosion damage to the Severn inter tidal area has resulted in an increased amount of fine sediment in the estuary by a rate of approximately 4 million tonnes per year (Western Daily Press, 2015).

The company behind the Swansea bay lagoon have conducted a range of computational modelling to understand how the project will affect the deposition of sediment in the area. The results of the modelling suggested that there would be no increase in sediment layers below the Tawe barrage, but would increase siltation within the Tawe river channel (Keith-Lucas, 2013). They did not comment regarding the sediment levels inside of the lagoon.

However, the accuracy of these computational tests is in doubt. Dr Graham Dabron is a researcher in Canada who has worked on a variety of projects including the Bay of Funday tidal barrage, the Miramichi, Humber and Severn Estuaries and has done extensive work to understand silting (Hickman, 2012). He believes that the different particles that make up the sediment behave in different ways and not the same as is assumed during computational modelling. Their research has also shown that settling rate is heavily dependent of a wide variety of different aspects including particle size, water salinity, temperature, mineral and organic content, water velocities, turbulence, wave height and more (Hickman, 2012). It is not believed that all of this information required was sourced or available for the modelling therefore bringing the accuracy of these results into question. One silting expert expressed both his and his colleges views on the subject saying how the project would be "plagued" by a build up of silt which would end up dumped at an unknown location (Booker, 2015). If this is true, it will also affect the marine life within the lagoon, potentially destroying the planned sea reef and oyster beds.

3.5 Operating Methods

All tidal range projects are able to generate power during a minimum of one tidal phase (flood or ebb generation), however, like the barrage; there are a number of operating combinations a tidal lagoon can operate with.

There are three different operating methods that can be used when generating power with a tidal range plant: ebb; flood and two-way generation. All three of these methods involve a combination of: filling the basin; holding (closing the sluice gates to keep a constant level of water inside the basin) and a generation phase where water is allowed to pass through the turbines to create electricity. Each of the operating methods can be seen in (Fig. 12) although it should be noted that the thinner line representing the lagoon should be horizontal representing a stable water level during the holding phases.

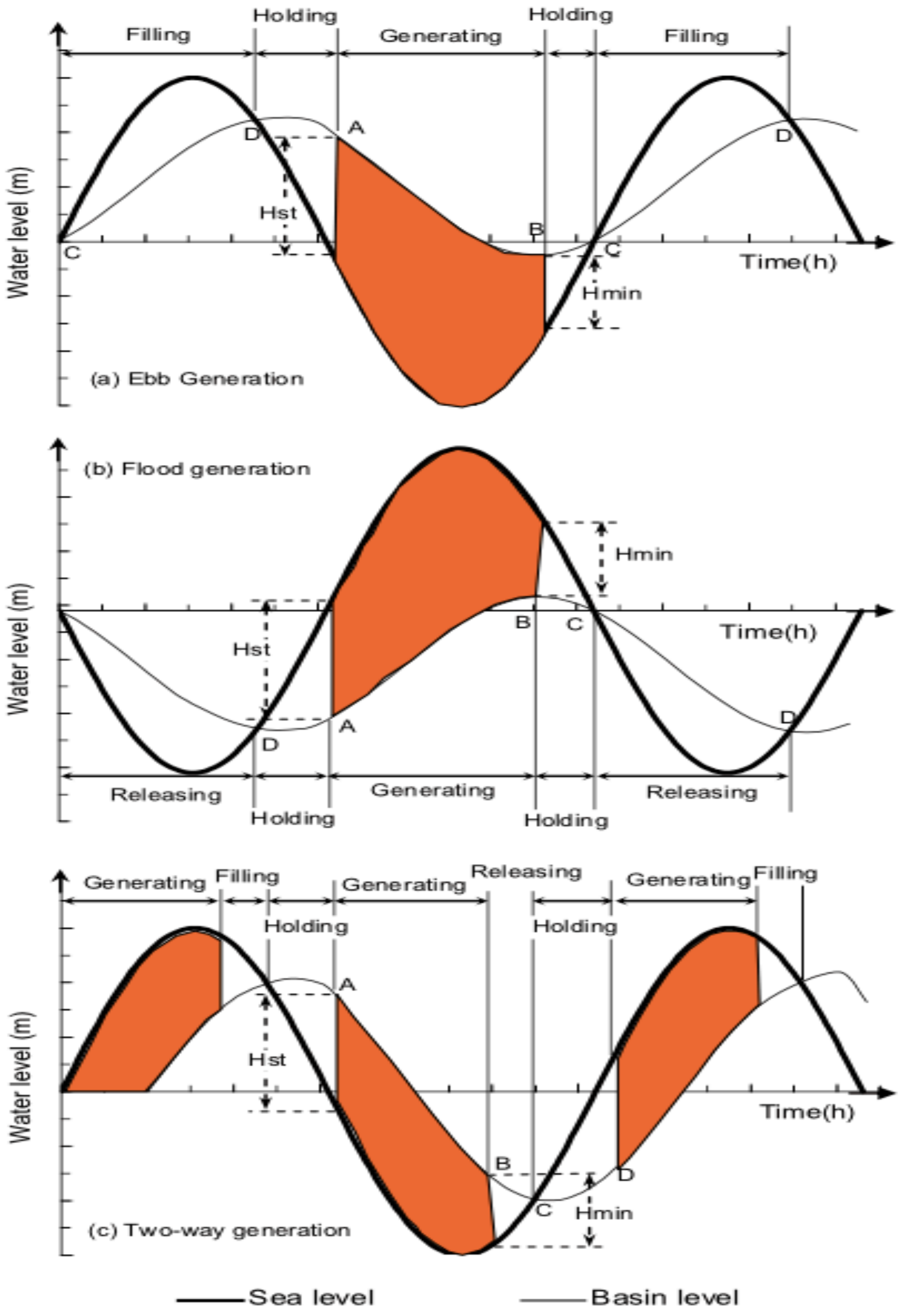

Figure 12 - The different operating methods available for tidal range projects (Xia, et al., 2010b)

3.5.1 Ebb Generation (a)

Ebb generation generates electricity, twice per day, when the tide flows out to sea. During the flood tide, sluice gates, which allow water to pass through, into the lagoon, are left open, and the turbines allowed to freewheel, therefore filling the lagoon basin (Xia, et al., 2010b). Once the basin is adequately filled, the sluice gates are shut as the tide begins to recede. As the tide begins to go out, and the head difference between the sea and the lagoon has reached the minimum operating head for the turbines, the gates are opened again to allow to the water within the lagoon to flow back out to sea. During this process, the turbines become operational, generating electricity. When the head difference between the sea and lagoon becomes too small for the turbines to continue to operate the turbines stop generating electricity and the sluice gates are shut once more, ready for the next tide cycle.

3.5.2 Flood Generation (b)

Flood generation works exactly the same as ebb; however, it produces electricity during the flood tide instead of ebb, twice per day. As the tide comes in, the sluice gates are opened, allowing the water to pass through, turning the turbines and generating electricity. As the tide flows back out of the basin, the turbines freewheel and do not generate electricity.

However, this is a less efficient method when compared to other modes. This reduction of efficiency is due to the volume of water involved. In realistic operating conditions, the basin can never be fully emptied or fully filled while operating (Jones, et al., 1993). Furthermore, due to the bathymetry of the basin, the volumes of water contained in the higher section where ebb generation operates are larger than the volume of water in the lower section used for Flood generation (Xia, et al., 2010b, Aggidis, 2010).

3.5.3 Bidirectional generation (c)

Two way generation is the most complicated method, and is the method that will be used for the Swansea bay lagoon. The turbines are in use both during the flood and ebb tides, therefore producing electricity four times per day. As the tide comes in, the sluice gates are opened when there is a large enough head difference for the turbines to operate, producing energy. During slack water, when the head difference between the basin and sea is too small, the sluice gates are shut. When the tide goes back out and the operational head is created once again, the gates are opened causing the water to flow out of the basin towards the sea and the turbines produce energy again (Aggidis, 2010).

Two way generation produces the largest amount of energy when compared to the other two types. However, the complexity of this method requires more carefully designed turbines so they are able to operate at high efficiencies in both directions.

3.5.4 Pumping

Both tidal lagoons and barrage projects have the ability to incorporate pumping as an extra operating aspect. During the slack tide when the turbines can not produce electricity, they are run in reverse to work as pumps. The pumping is able to increase the head difference between the lagoon basin and the sea. For two way generation, water is first pumped out of the lagoon to lower the basin height as much as possible before operating in flood mode. Then after the flood cycle, water is pumped inside the lagoon to raise the basin height ready to operate in ebb mode.

This process can be very beneficial, as the amount of power available for a tidal range project is heavily dependent on the head difference between the lagoon and sea. This relationship can be seen in equation 1

$E = \frac{1}{2} A \rho g h^2$ (1) (Tousif & Taslim, 2011)

h = operating head difference

ρ = density of water

A = lagoon basin area

Using Eqn. 1, (based on the potential energy) it can be seen that the energy available within a tidal range project is based on a square relationship with the tidal range (head difference) available. Therefore, although pumping does use energy, by increasing the operational head difference the energy used is more than repaid (Hammons, 1993).

3.6 Economy

As with the tidal barrage project, the lagoon is not just a project designed to generate electricity, there are many other benefits to the surrounding area. Over 2,000 construction jobs will be required during the construction of the lagoon, and once completed there will be at least 80 permanent jobs on site (BBC News, 2014b, Tidal Lagoon Swansea Bay, 2015c).

The parts required for construction will also help not only the local, but national economy, with 65% of the construction cost staying in the UK (Tidal Lagoon Power, 2015a). These costs will include the complete construction of the generators, as well as a large amount of the turbine parts (Tidal Lagoon Power, 2015a). The project will use locally sourced materials and rock for the construction of the lagoon wall.

La Rance is also seen as a tourist destination, with approximately 70,000 tourists visiting per year. It is expected that the world's first lagoon project will also attract substantial interest. It is estimated that the lagoon will provide the Welsh economy with approximately £76 million each year (Tidal Lagoon Swansea Bay, 2015).

3.7 Future

After the completion of the Swansea Bay lagoon, there are five more potential lagoons sites around the UK that will be developed (Fig. 13) along the west coast, with an additional lagoon situated in Cardiff, rated with an estimated 1800-2800MW (Tidal Lagoon Cardiff, 2014).

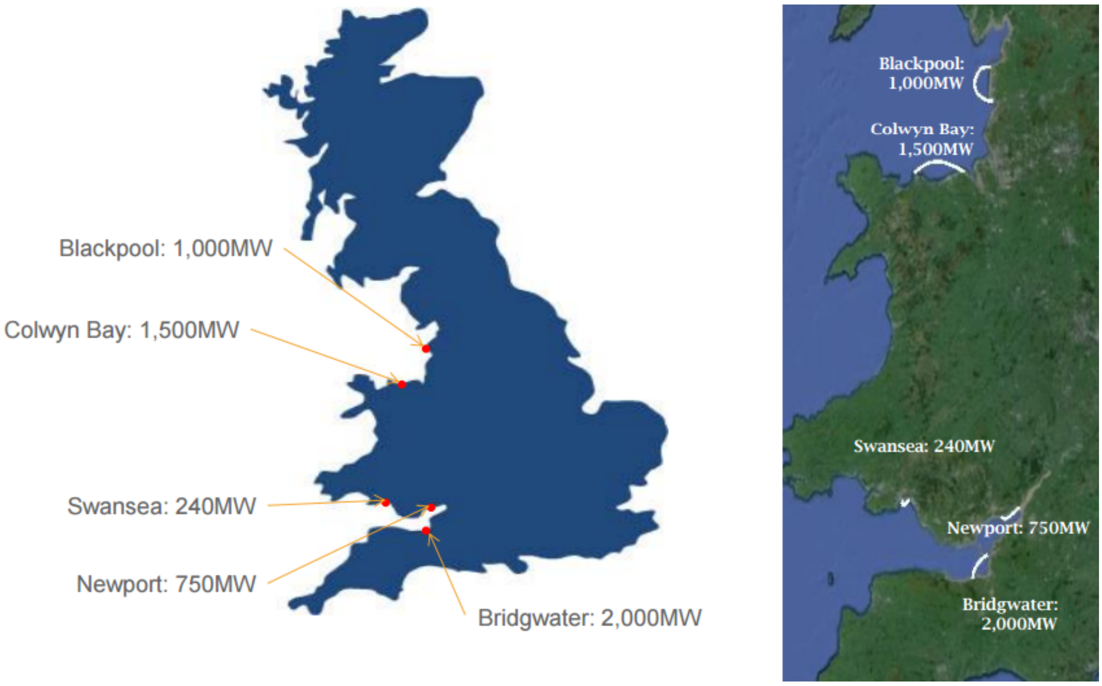

Figure 13 - Future tidal lagoon projects (Tidal Lagoon Swansea Bay, 2015a)

These larger projects would have the advantage of producing more energy at a lower cost. The strike price for these projects falls to £92/MWh, which is cheaper than wind power and in line with costs from nuclear power. However, these projects will have twice the lifetime of a nuclear plant and will not be subject to decommissioning costs (Pöyry, 2014).

The subsequent lagoons will be able to produce more energy because they will have both a larger lagoon basin area, combined with a larger tidal range so the head difference between the sea and lagoon is greater.

The Swansea Bay site was chosen for the first lagoon, as it is the smallest of all sites that were debated. Therefore, as the smallest, it requires the least initial investment and overall costs. Therefore, any cost saving methods that can be found through the experience of creating Swansea Bay lagoon can be used to greater effect on the larger projects. Also, it is a very convenient location, with very simple grid connection making it the easiest and cheapest to connect to the national grid. Although the projects come with a combined £30bn price tag, they would be able to meet 8% of the nation's electricity (Harrabin, 2015, South West Wales, 2014b). When compared to the current percentage met through renewable energy (3.2%) this would almost triple the amount and would put the UK back on track to meet EU targets (Tidal Lagoon Swansea Bay, 2015a).

Even after the production of the first 6 lagoon projects that have already been planned out, the UK has the potential for even more. Various locations around the east and south east coast (Fig. 14) are also suitable for tidal lagoon projects.

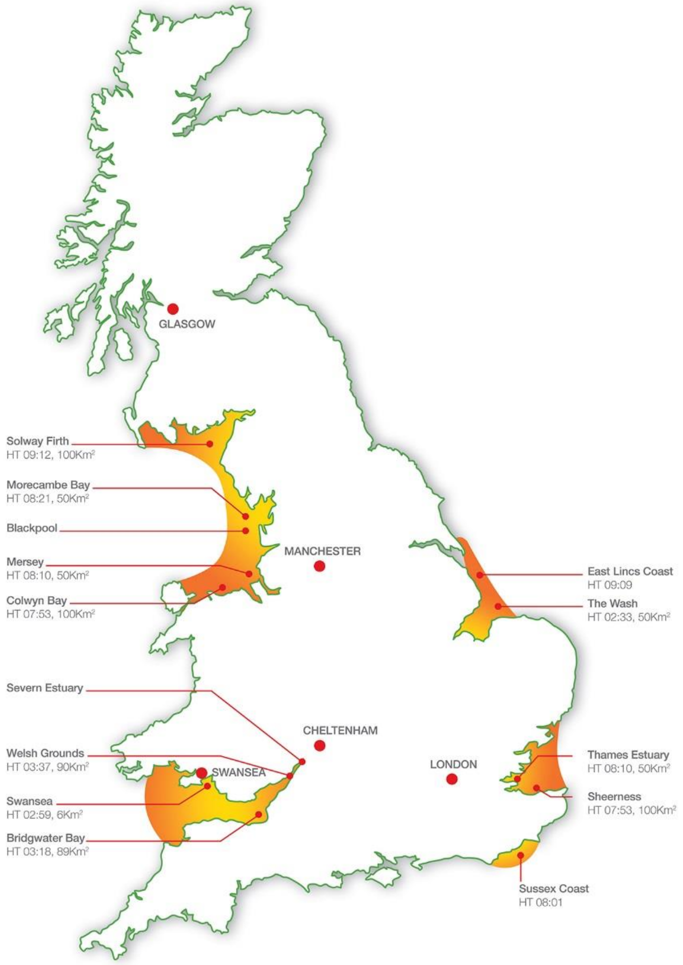

Figure 14 Potential tidal lagoon projects around the UK (Tidal Lagoon Swansea Bay, 2015a)

If all of these projects were to be constructed, it would open up the possibility for the national grid to be able to provide a base layer of electricity through tidal energy (Shorrock, 2014). This may be possible, as the tide times for these potential lagoons would overlap therefore potentially producing constant tidal range electricity by carefully holding and generating. Currently renewable energy is not able to provide a base layer due to the unpredictable nature of the renewables currently in use (wind and solar).

With the increased, ever present threat of global warming tidal range projects could become just as vital as a front line front defence system for numerous coastal populations. Somerset is a prime example of this, with frequent and extensive flooding. A leading researcher a Cardiff university, Professor Roger Falconer understands that a lagoon or barrage project situated in Bridgewater bay would act as a superior flood defence when compared to the current method of dredging (Science Media Centre, 2014). Similarly, flooding could be mitigated in the Solway estuary in the same way, as a tidal range project would be able to cope with the increase in tide high when flooding would usually occur (Howard, et al., 2007).

Although these projects would cost significantly more than conventional flood defence options such as dredging recent flooding in the area has caused damage on a large scale costing millions of pounds. They would also operate effectively for over 100 years and the added benefit of creating energy and other advantages make the idea appealing.

Tidal lagoons currently have the world's attention due to their plethora of advantages, with countries such as the United States, China, Mexico, India and Korea all interested and are monitoring the progress of Swansea bay lagoon closely (Tidal Electric, 2015a).

4 Turbine Selection

There has been continuous evolution in turbine designs aimed for both wave energy and tidal stream energy. The reason for this is not just because optimal turbine design is location dependant. A large reason is because the turbines are cheap to create and relatively simple to test. These two important aspects makes these devices attractive to investors and breeds innovation and creativity. Tidal range projects have not been so lucky. With the vastly increased construction costs that come with the creation of a tidal barrage or lagoon, full scale testing in a real world situation are both difficult and expensive.

Therefore many new projects such as the Swansea Bay tidal lagoon choose to follow on from the work of existing projects such as the La Rance barrage by using the Bulb turbine to generate the electricity.

There are many positive reasons for doing exactly this. For example the bulb turbine has already been a resounding success in the field, as shown in the previous projects. This success is enticing for potential investors as it is a proven, reliable technology. The high expenses involved with tidal range projects mean investors want to have as little risk involved as possible. By using the same style turbine, with only minor changes and improvements, years of performance data can be used to calculate accurate outputs and there will be a minimum amount of teething problems. This also allows for downtime to be predicated in advance and planned maintenance can be introduced and carried out after an accurately known amount of time for maximum effectiveness and minimise cost.

All of these points are obviously very useful and valuable aspects to have, however, by mainly following on from an existing technology made famous in the 1960's, new technologies are being overlooked. In comparison with wind energy, tidal is relatively new and has not had the same level of research time invested.

However in the past 50 years there have been many different turbine designs created that are suitable for tidal energy (as seen with tidal stream power). Although introducing a new turbine design does have many caveats, thorough research into whether the designs are being chosen just to follow on, or are the best currently available is important. It is possible that new and innovative designs that could be better suited for certain tidal range projects are being overlooked.

To fully evaluate both the current tidal range turbines that are in use today and a range of potential devices that could theoretically be used in these situations, a marking criteria was developed. The aim of this criterion was to evaluate a wide range of turbines, analysing the key aspects that should be considered to make the turbine a success. The important characteristics that were identified to be used in the criteria were:

1. Environmental aspects
2. Efficiency
3. Initial Costs
4. Maintenance requirements

This criterion was based on a mixture of the important aspects any power generation plant requires, but also on the issues that have held back the creation of these types of projects. As the theoretical devices will not have been tested in a tidal range situation prior to this comparison, the power generated by the turbines and the price per Mw/h during operation in this way is not known. Therefore, the efficiency each device has been able to achieve will be taken into account. As the Swansea bay site and other potential UK lagoons are planning to use two way generation, the efficiency will be investigated both during flood and ebb tides and over a wide range of head and flow values which will be seen in this location. The ability and potential for including pumping will also be taken into account.

As tidal range projects have repeatedly been declined due to cost and environmental concerns, these are two important issues that will be investigated. As the project hopes to not only produce a turbine suitable for tidal range power generation, but also to improve the usability of tidal range projects, it is hoped to find a device that can reduce both of these aspects.

Comparing the theoretical designs in this manner and assigning a numerical value based on ability for each section, would mean the device with the greatest potential for tidal range projects could be found.

5 Existing Tidal Barrage Turbines

Despite the wide range of locations and tidal range values, there are only two different turbines currently in use for the existing tidal barrage projects.

5.1 Straflo Turbine

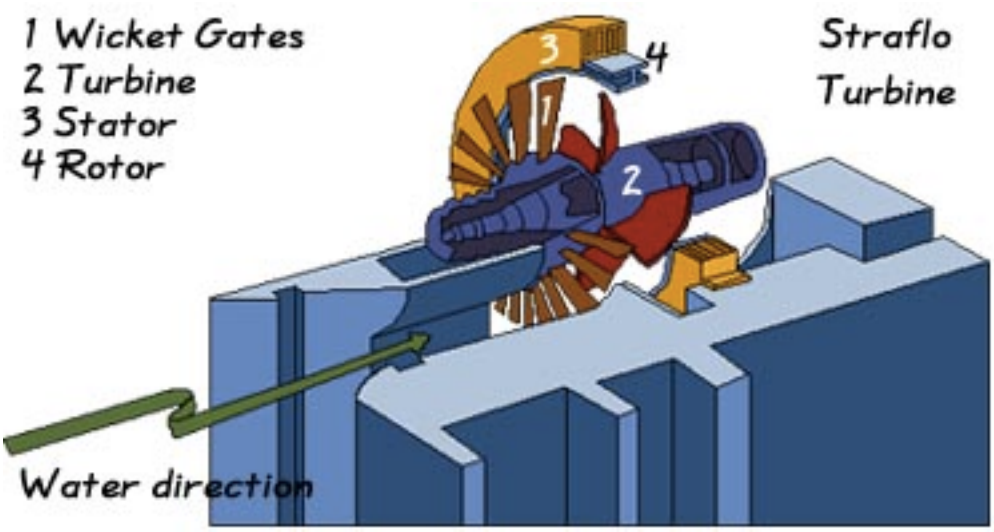

Figure 15 - Straflo Turbine design (West Nova Eco Site, 1997)

The Straflo device (Fig. 15) is an axial turbine first designed in 1919. The main difference between this device and the bulb turbines is the generator. Unlike the bulb, where it is housed in the nose, it is situated out of the flow, around the edge of the runner blades in the form of numerous electromagnets (Rivers Project, 2014, Recharge, 2010).

5.1.1 Environment

As with other existing tidal range devices, the Straflo turbine has significant issues with fish friendliness. The mortality rate for fish passing through the device can be as large as 30%; however, this large value is only present during a small amount of the operating range, with the mortality rate dropping to approximately 5% for the majority of the time (Collins, 1984).

In addition to this, a large amount of turbulence is formed at the point where the rotor blades meet the turbine housing. In some cases this can be harmful, but the large size of the device means there is a larger area for the water to flow through, reducing the chance of marine life being harmed through either cavitation or large pressure changes (Collins, 1984).

The fixed wicket gates pose a threat through impact related injuries, which could be reduced by using adjustable pitch blades (Collins, 1984).

5.1.2 Efficiency

The operational efficiency of the device does not reach the same maximum values as the bulb turbine, and is subject to larger fluctuations, as there are no adjustable guide vanes to direct the flow onto the runner blades in the best position for the various head and flow combinations. For the majority of operating conditions, the device located in Annapolis is able to achieve values varying between 78 – 89% (Collins, 1984). This figure does fall rapidly when the head values fall below 2m. As the angle for the runner blades is set, the device is only able to operate efficiently in one direction, therefore any project using the device must use a single generation operating method (flood or ebb) (Balls, 1988).

As the rim of the device rotates in the opposite direction to the runner blades (in order to generate electricity), this forms extra friction between the rim and the water flowing through the turbine, further lowering the efficiency (Miller & Wyss, 1974).

5.1.3 Cost

The physical construction of the device itself is able to lower the costs associated with constructing the turbine housing, as the generator rotor is able to be supported by the runner blades (Rivers Project, 2014). As it is situated around the runner blades, the generator is placed out the water flow meaning lower insulation costs and easier access.

There are no other highly complex components such as adjustable guide vanes or runner blades, both of which are very expensive. Although it is possible to incorporate these into the design, the added cost to do so would be too great (Collins, 1984).

When directly compared to the costs of a bulb turbine, substantial cost reductions could be achieved by using Straflo devices instead (Balls, 1988).

5.1.4 Maintenance

As used in La Rance, cathodic protection of the runner blades has been successful for the Annapolis project (Balls, 1988) (Rice & Baker, 1987). The single device in Annapolis has been rather trouble free, with approximately 98% availability (Rice & Baker, 1987).

The majority of the maintenance issues are with the generator. Although it is automatically cooled as the water naturally flows through the gap created between the rotor and stator components, the salinity of the sea water over works the filtering system (Rivers Project,

2014) (Rice & Baker, 1987). Also the rubber seals required to insulate parts of the generator require regular maintenance to prevent water damage (Balls, 1988).

Debris screens are also required to prevent costly damage which has already been seen in Annapolis where there have been several instances of unplanned downtime due to tree trunks causing damage to the wicket gates (Balls, 1988).

5.2 Bulb Turbine

Bulb turbines have become the logical and usual choice of turbines for all low head tidal projects, starting with La Rance. This is to be the same for the Swansea Bay Lagoon project and other planned lagoon projects around the UK.

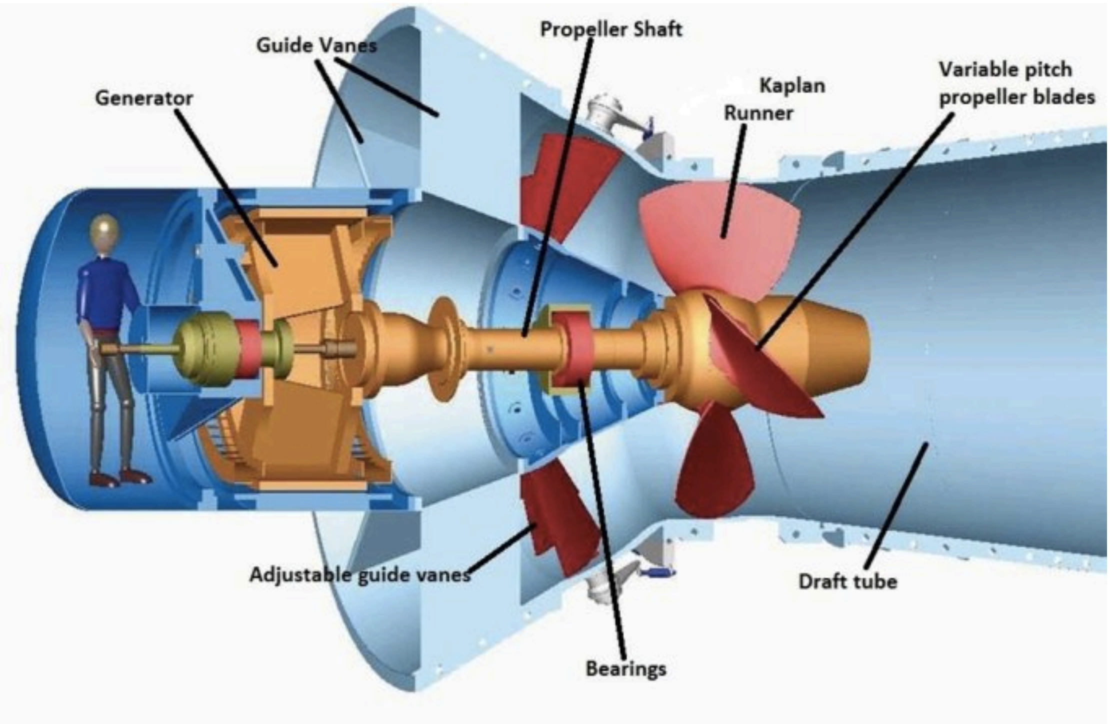

Figure 16 - diagram of a typical bulb turbine (Tidal Lagoon Swansea Bay, 2014)

Bulb turbines (Fig. 16) have all but replaced the vertical Kaplan devices created in 1913 (Hansson, 2015). They offer a more compact design, which requires less building works to house the device safely. Also, due to the design of the bulb turbine, less head is lost, as the bulb turbine can be placed closer to the sea/river bed. They are seen as the optimum choice for tidal range projects.

The basic operating process of the bulb turbine can be split into three different actions (Karpov, 1933):

1. Water flowing through the inlet of the device and interacting with the guide vanes. The guide vanes are used in order to direct the water flow onto the runner blades at the best angle for maximum power generation.

2. The water acting upon the runner blades, which like the guide vanes are able to alter their position as to interact with the water in a way to produce the maximum power output.

3. Finally the water exits the turbine via the draft tube. Although this section is after the runner blades, it is vitally important and can affect the overall efficiency of the device by a few per cent (Benigni & Jaberg, 2007).

5.2.1 Environment

Despite the continued use of these turbines in existing projects there are a variety of environmental issues that are present. The major problem is the direct effect on fish and marine life. Due to the operational nature of the turbine, they can cause harm in a variety of forms, such as “rapid and extreme pressure changes, cavitation, strike, grinding, turbulence, and shear stress” (Cada, et al., 2006). During a breakdown of injury or mortality to fish from the Wanapum Dam Kaplan turbines, 43% were due to mechanical injury, 23% through cavitation, 10% were shear stress related and the rest were through a variety of causes (Francois, et al., 2000).

During the tests at Wanapum Dam, the effects on coho salmon were investigated. Throughout the course of the test, 1278 passed through the turbine 21 were found to sustain mortal injuries and 33 were assumed dead but could not be found (Cada, et al., 2006).

When investigating shear stress there are four locations where excessive amounts, which can be dangerous to fish, are found. These are: close to the surface of the runner blades; the gap created by the runner blades and the outer case; at the point the blades are attached to the turbine hub and downstream of the device as a result of the wakes created from the blades (Cada, et al., 2006).

However, turbine manufacturers are trying to make these bulb turbines more environmentally friendly. For example modifications have made it possible to use water instead of oil as the operating lubricant (Department of Energy and Climate Change, 2010b).

In addition, through the development of devices with fewer but longer blades, (thereby reducing the solidity of the turbine) results in a reduction in the likelihood of a collision (Department of Energy and Climate Change, 2010b). Another design alteration that can be introduced is to reduce the gaps in-between the blades and the hub, which causes approximately 25% of all mechanical injuries (Francois, et al., 2000). One final method is based around diverting or preventing fish from entering areas where they could be harmed. This is done with a variety of diversion screens and fish ladders. However, any screen can become blocked reducing efficiency and be also expensive to clean (Loiseau, et al., 2006).

The actual fish-friendliness of these physically modified turbines is still in the theoretical stage. Even if they are successful, the operating nature (such as turbulence, cavitation, and rapid pressure changes) of the devices themselves means that there will still be a certain level of fish mortality.

Damage caused by silt present in the water flow can both irreparably damage, and reduced efficiency of Bulb turbines. This damage can be costly to repair and can occur in a variety of places on the turbine. There are three main types of silt and sediment erosion damage – micro, accelerated and secondary flow erosion (Neopane, et al., 2011).

As the first point of contact for incoming flows, the guide vanes are highly affected. Turbulence causes the silt particles to rotate and cause damage as they come in contact with them. Secondary flow as the flow separates at the edge of the guide vanes causes a horseshoe shaped erosion pattern. As the flow separates, large particles are removed from the main flow path and impact with the guide vanes, which is the greatest cause of damage (Neopane, et al., 2011).

It is possible that the runner blades will be even more susceptible to damage than the guide vanes for the bi directional generation used by the Swansea bay project. In normal, one way generating turbines, the runner blades have damage due to a combination of turbulence erosion and micro impact erosion due to the small silt and sand particles (Neopane, et al., 2011). Due to the operating nature of the device and the rotational speeds of the runner blades, there will be certain areas of the runner blades, which are more susceptible to erosion damage than others.

5.2.2 Efficiency

Bulb turbines are known for having a very high efficiency with values around 92.5% (Andre, 1976). Through the use of variable pitch blades and guide vanes, high efficiencies can be achieved for a wide range of different flow rates and head values, thereby creating a relatively flat efficiency curve (Karpov, 1933). This is done by continuously altering the positions of the runner blades/guide vanes into an optimum position available with the head and flow rates at any given time.

However, even with the adjustable parts of the turbine, these high values of efficiency can only be achieved for flow in one direction. For example, a bulb turbine with a single set of guide vanes that was able achieve a maximum efficiency of 90.49% in one direction, but was only able to achieve a peak value of 71.55% in the reverse direction (Yang, et al., 2013).

Bulb turbines can cope with a wide range of flow velocities and head values, while being able to operate at a very high efficiency throughout. However, with the majority of planned and existing tidal power plants (La Rance, Swansea Bay) using bidirectional power, the large reduction in efficiency in the opposite direction leaves room for improvement and perhaps better suited designs.

5.2.3 Cost

Due to the highly intricate design of a bulb turbine, the costs are very high. The adjustable guide vanes and runner blades are especially expensive. Cost savings of up to 20-25% for large devices and up to 50% for small, can be made by removing the ability to adjust the positions of these parts (Department of Energy and Climate Change, 2010b). However, with the constantly changing tides and therefore varying head and flow values, doing this would compromise the efficiency by creating an efficiency curve that decreases rapidly when head and flow values are not optimum. Unlike the relatively flat efficiency curve for the adjustable bulb turbine, which can keep high values over a wide range of inputs. As the range of head and flow values constantly varies the initial cost saving would not benefit due to the loss of power being generated during the turbines operational lifetime.

Another knock on effect related to the complexity of bulb turbines is the requirement for an assembly facility near to the site of the lagoon. This facility would be used for welding, heat treatment and the final assembly of the turbines. During a report aimed towards developing a barrage on the Severn estuary, it was verified that such a facility would be required at an expense of approximately €10 million (Department of Energy and Climate Change, 2010b).

Due to environmental issues with bulb turbines, fish screens and ladders are often a requirement to protect marine life, which become an added cost.

However, due to housing the generator inside the turbine, the construction of the barrage can be simpler and cheaper. This is because there are no construction requirements for an external generator (Aggidis & Feather, 2012). However, to achieve the high efficiencies required, both the inlet and outlet sections of the turbine have to be optimised and created accurately (Motycak, et al., 2010).

Although they are cheaper than vertical Kaplan devices, it is estimated that approximately 25% of the overall cost of a tidal lagoon will be required for the turbines.

5.2.4 Maintenance

The bulb turbines operational in La Rance have operated well, with relatively little maintenance required. Reports directly from La Rance have been positive where the use of cathodic protection has kept the runner blades in good condition despite being under water for over 70,000 hours (Andre, 1976). As La Rance is the only tidal barrage using bulb turbines that have been in operation for a large amount of time, their experiences with maintenance are the most useful and reliable.

Initially there were 'teething problems', with many issues focused around electrical faults in the rotor. These came in the forms of: electro-erosion, reduced insulation strength and moisture, but once the causes were discovered, it was possible to rectify them (Andre, 1976). As these are problems, which have been solved, any subsequent devices should not encounter these. Downtime with bulb turbines is considered good at fewer than 6.5%, giving them a reputation of reliability (Andre, 1976).

However, there will always be a variety of maintenance issues and even the physical aspects of the turbine can make this difficult. For example accessing the bulb in order to carry out repairs is more difficult that other devices and the cramped space inside has resulted in maintenance staff damaging the insulation (Andre, 1976).

One of the main issues is with cavitation and this issue is currently limiting the different applications of these turbines. Cavitation causes 'pitting' which needs to be repaired quickly as the cavitation process happens quicker when there is an area of non-uniformity present (Karpov, 1933). It occurs due to the necessary pressure gradients required to achieve the high levels of efficiency bulb turbines are known for; therefore to remove cavitation completely would require a significant drop in efficiency. Another issue can be seen in the shaft seals, where the rapid variation in pressure causes damage and requires a lot of maintenance because if they are to fail the consequences can be very costly (Andre, 1976).

Debris flow through the device has the potential to cause a large amount of damage, largely by causing stud failures in the guide vanes through impact (Andre, 1976). Excessive damage in this manner to the guide vanes or runner blades can both be costly and reduce efficiency if not monitored carefully.

Due to the complexity, any major repairs are often very costly and if they are unplanned, the lead times required to create the parts can be lengthy.

Bulb turbines are estimated to have a lifetime of around 40 years, but only if there are major repairs carried out after approximately 20 years (Department of Energy and Climate Change, 2010b).

6 Theoretical tidal range turbines

The following devices outlined in this section have been selected as they have the potential for tidal range power generation. Although they are all established turbines, none of these have been developed for this use and therefore all information is based upon normal operation as a normal hydro turbine, combined with accurate, academic predictions on performance.

6.1 Modified Bulb Turbine

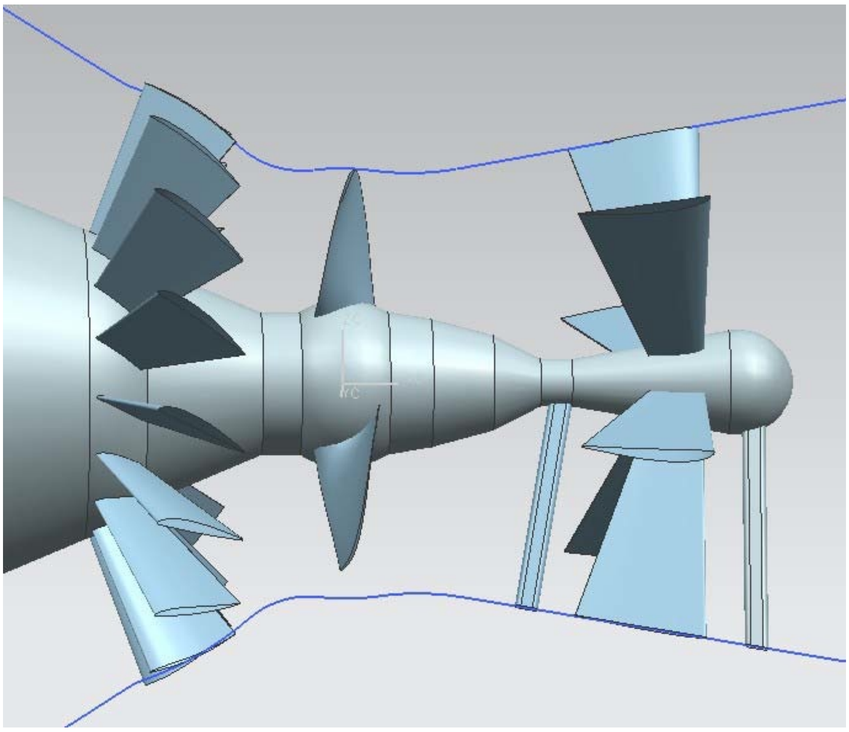

Figure 17 - Theoretical image of the modified bulb turbine (Zheng, et al., 2013)

The bulb and modified bulb turbines are very similar with the latter being a variant of the first (Fig. 17). However, this device includes an extra set of guide vanes after the runner blades. This variation has been made in order to make the Bulb turbine become more efficient in the reverse direction of the flow (which will also be used in the power production of Swansea Bay). The added guide vanes will do this by directing the flow onto the runner blades in the optimal direction for both flood and ebb tides. It utilises all of the positive aspects of the original bulb turbine: adjustable guide vanes; adjustable runner blades and compact structure with the generator housed inside the nose section.

6.1.1 Environment

With the necessity for bidirectional flow to be used already established regardless of which device is being used, the modified bulb presents even more of an environmental issue than the normal bulb unit. This is due to the extra set of guide vanes, which can cause added shear stress and more mechanical points of impact for fish. An analysis on the Kaplan turbines at Wanapum Dam showed that any values of shear stress above 1600Pa would harm or kill any fish that are subjected to them. Values above this threshold were consistently found in the flow after interaction with the guide vanes (Cada, et al., 2006). The guide vanes also provide a larger number of surfaces for impact related injuries.

6.1.2 Efficiency

The main aim of the modified unit was to minimise the difference in efficiency during both ebb and flood phases by increasing the reverse flow. Theoretical results have shown that with the extra set of guide vanes this is achieved because the flow passing back through the device is being guided onto the runner blades at the optimum angle. However, the inclusion of the extra guide vanes results in part of the efficiency in the initial direction being lost. One theoretical test saw a loss of 2.62%, however the turbine had a much improved flow pattern through the device (Zheng, et al., 2013).

Testing a model bulb turbine with double guide vanes increased the efficiency of the reverse direction by approximately 10% (from 69.64% without the extra guide vanes, to 80.12%) (Yang, et al., 2013). However, it also caused a drop in the efficiency in the forward direction from 84.03% to 80.12% (Yang, et al., 2013). Although, even with this reduction the increase in the reverse direction combined with the improved internal flow results in an overall better performing turbine when operating in both directions.

6.1.3 Cost

Cost for the modified bulb turbine will even higher than for the normal bulb turbine. This is because of the increased complexity involved by adding an extra set of guide vanes.

6.1.4 Maintenance

Following the same trend, maintenance and operational costs will be greater with the modified version. Again due to the added complexity involved with the extra set of guide vanes, which will result in increased routine maintenance and repair in order to stay functional.

6.2 Archimedes Screw

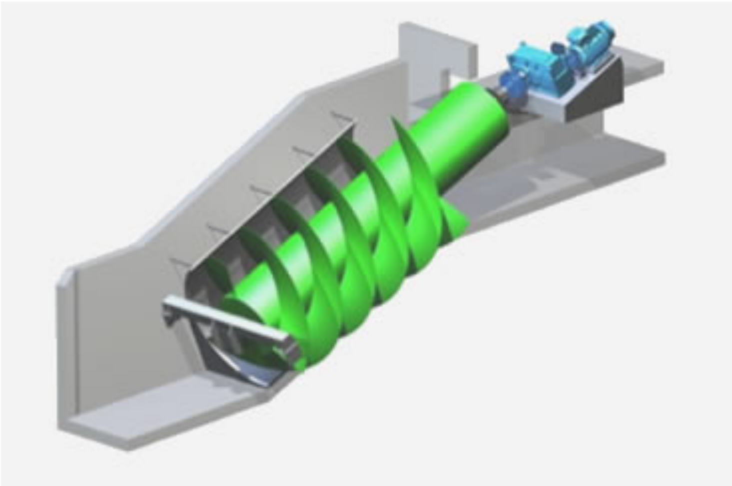

Figure 18 - Archimedes screw turbine (New England Hydropower Company, 2015)

Already an established pumping device in use for over 2,000 years, operating it in reverse to form an Archimedes screw turbine is relatively new (Fig. 18). Most commonly the device operates partially filled while inclined at an angle.

6.2.1 Environment

Screw turbines are considered to be the most fish friendly design available. Part of the reason for this is because of the low rotational speeds the device operates at. Furthermore, due to its method of operation, there are no large variations of shear stress or pressure that could be harmful (Fishtek Consulting, 2008). The shear stresses, pressure and turbulence present with the device are within safety factors and are levels which the fish have to cope with during normal environments (Waters & Aggidis, 2015).

Live fish trails were conducted by Fishtek Consulting to confirm this. The test carried out was created in conjunction with the environmental agency, which made sure the tests were stringent enough. A variety of fish were passed through an Archimedean screw device, multiple times. Of 220 fish that were used, there was no long lasting damage found (Fishtek Consulting, 2008). These tests included a variety of sizes and fish, trout's (up to 63cm long), smolts, salmon and even eels which are often very susceptible to damage when passing through turbines. Of the smolts used, a maximum of 1.4% used suffered minor, repairable scale damage. Fish above 25cm, suffered no scale damage at all.

After passing through the turbine, the fish were held for 48 hours to assess any lasting effects on them, such as listing or disorientation. Either of these things could increase the chances of being caught by predators, however neither of these signs was found. There are two reasons for this, one because once the fish have entered the device, they stay with the same section of water until exiting the device and the other due to the level of turbulence created by this type of turbine is very low and similar to levels sometimes experienced in normal circumstances (Fishtek Consulting, 2008).

There were mortalities during start up, where the leading edge was 'pinching'. Once the problem was identified, aligning the edge of the screw with the trough and fixing a rubber extrusion to the leading edge rectified it. This rubber extrusion both stopped the pinching and also protected the exposed leading edge from being sharpened/damaged by debris (Fishtek Consulting, 2008).

A second test, conducted in Holland, directly comparing the Archimedes screw and a propeller type device found that the screw turbine was able to vastly reduce the mortality rate for adult eels (Buysse, et al., 2014).

The Archimedes Screw turbine however will not suffer the same damage due to excessive silt. Much in the way that that it is immune to all but the largest debris, the robust device operating at low RPM values is not affected by even the most silt heavy water (Tiger Green, 2010). In fact there have been many instances where the Archimedes screw pump has been used as a dredging device in highly sensitive environments to reduce the amount of silt from a river or canal where conventional dredging devices could not be used, proving its relative immunity to silt damage or corrosion (The Construction Index, 2013) (Dredging Today, 2013).

It has also been seen that when using the Archimedes screw as a turbine, it can have a secondary use by allowing the silt to pass easily through the device and in the case of the lagoon, it has the potential to help regulate the sediment levels within. This method has been researched and tested for the River Dart Totnes Weir project, where the Archimedes Screw would help the progression of silt (of all sizes) down stream (Mann Power, 2011).

Therefore, in the presence of highly silted water, the Archimedes screw is able to both last longer; as it will not suffer the same level of damage, it will also not suffer a drop in efficiency due to blade erosion. Maintenance requirements will be even lower, and the lifetime even greater. The screw turbine would also offer the chance to reduce the high levels of silt within the lagoon, lowering the need for frequent dredging and help keep a more natural flow.

6.2.2 Efficiency

Although, the peak efficiency does not exceed that of a bulb turbine, it does offer continuity for both forward and reverse direction if placed horizontally, due to the symmetrical nature of the design. This method of operation mainly uses the velocity of the water to turn the device. The efficiency of the device does not change excessively when the flow rate deviate from the optimum value (Nuernbergk & Rorres, 2013). The efficiency

In 1999, an in depth analysis undertaken in Germany on existing, inclined Archimedes screw turbines found the peak efficiencies of devices in the country were approximately 80% (Brada, 1999). Since then, the efficiencies achievable have ranged from 78% to 83% (Papadopoulou & Coronopoulos, 2011). However, Andritz Hydro claims their screw turbine is able to achieve peak value of 92% (Andritz, 2015).

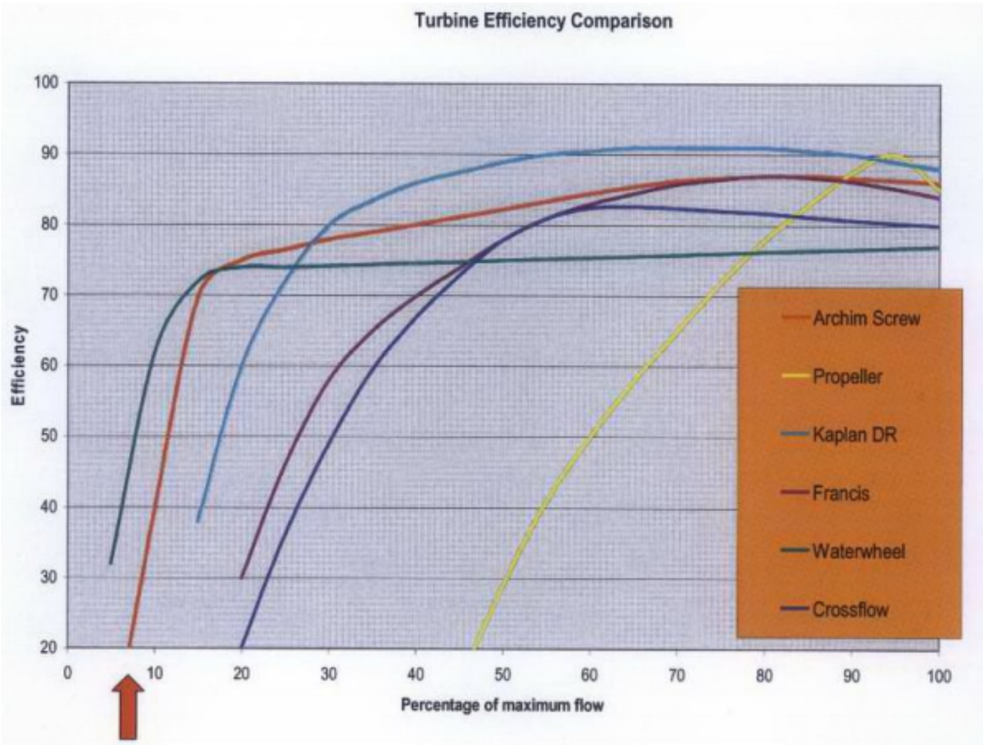

Figure 19 - efficiency of various turbines over a wide range of flow values (Mann, 2010) (Waters & Aggidis, 2015)

The device is also able to achieve high values of efficiency over a wide range of flow values as seen in (Fig. 19). It is even able to produce energy with lower flows than the Kaplan device. This is very important with tidal range as the head and flow values vary constantly.

Currently the horizontal Archimedes turbine is still in theoretical design phase, so no operational data on efficiency is currently available.

One possibility to increase the output from the lagoon is through pumping. This is where Archimedes screw turbines excel. By pumping, the tidal range can be increased, thus increasing the output.

6.2.3 Cost

The simplicity of the design itself helps to reduce costs. This is because costly and complex parts such as adjustable guide vanes or runner blades are not required.

Advances in composites and manufacturing methods mean that unlike other turbine designs, the screw device can be built in one single structure (Aquatic Control Engineering, 2012). Being able to do this not only lowers cost, but also reduces the likelihood of failure (Aquatic Control Engineering, 2015). Furthermore, this means a highly complex assembly facility is not required to connect numerous turbine parts.

The turbine is also very successful when it comes to withstanding damage from debris; therefore stringent debris screens are not required.

6.2.4 Maintenance

The lack of adjustable parts with the potential to go wrong and the robustness of the design mean that maintenance costs are low. Re-tipping is required after approximately 20 years with an overall lifetime estimated at over 30 years. (Renewables First, 2014)

As the device does not require excessive debris screening, this helps reduce maintenance as these can often become blocked and need regular cleaning. Slow rotational speed and the large gaps in-between flights of the screw mean that even relatively large debris does not cause damage to the device (Renewables First, 2014). If the rubber extrusion is added to the leading edge of the device, it can further protect it from debris, as this is the first point of contact. Therefore physical damage to the device is not a frequent issue.

By having a low rotational speed and only small pressure variations, there is no chance of cavitation damage. However, this low rotation is the cause of the only significant maintenance issue. A complex gearbox is required to increase the speed for the successful connection to a generator.

However, as the turbine has never been used in a tidal range situation, there may be unforeseen difficulties such as a reduction in lifetime through corrosion.

6.3 Gyro

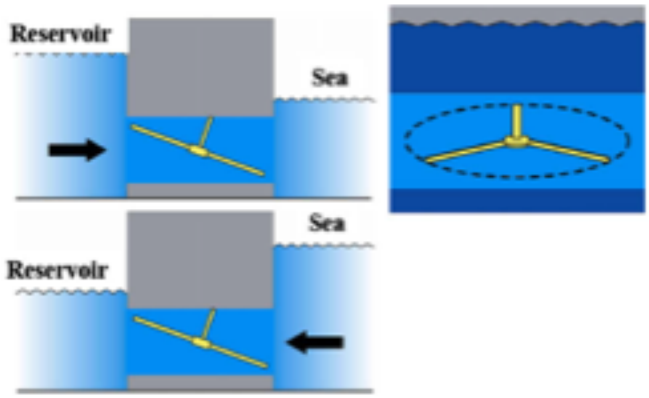

Figure 20 - Gyro style turbine design (Kanemoto, 2010a)

The gyro style turbine (Fig. 20) is an established device and has been previously used with both wind and tidal stream energy. This modification, housing it within a channel means it can be incorporated within a tidal range situation.

6.3.1 Environment

The low levels of solidity in the turbine rotors allow fish to pass through easier than in bulb turbines. There are also no areas that can cause pinching like on the other devices. The faster rotation rate means that there will be a certain degree of damage due to turbulence.

However, this has only been created theoretically and no live fish trails have been carried out.

6.3.2 Efficiency

One of the advantages of this turbine is the ability to modify the angle of the turbine so it is not perpendicular to the flow, so the diameter of the device can be created larger than the width of the channel (Kanemoto, 2010a). For example, with a channel 5m long and 1m wide, the output of the gyro turbine compared with a normal non-adjustable propeller turbine (with the same efficiency) is approximately 5 times greater (Kanemoto, 2010a). This means that the actual efficiency values for the gyro device can be much lower than propeller turbines, while still producing a similar output.

However, without having adjustable blades, the turbine efficiency will drop when the constantly varying head and flow rate values differ from the optimum.

There is also no ability for pumping, which can increase the output of a lagoon/barrage and is planned for use for all UK based tidal lagoon projects.

6.3.3 Cost

The simplicity of the design, without the need for complex adjustable parts helps to keep costs to a minimum. Without the need for expensive parts such as guide vanes means that when compared to the bulb turbines this is a low cost option.

Additionally, by having the ability to keep the generator out of the tidal flow, means that there is much less insulation required, further reducing costs.

6.3.4 Maintenance

Once again, the simplicity helps to keep maintenance costs low. With the generator placed out of the tidal flow, means any repairs or routine maintenance is much easier to carry out meaning there is less likelihood of any accidental damage like seen with La Rance.

6.4 Counter Rotating

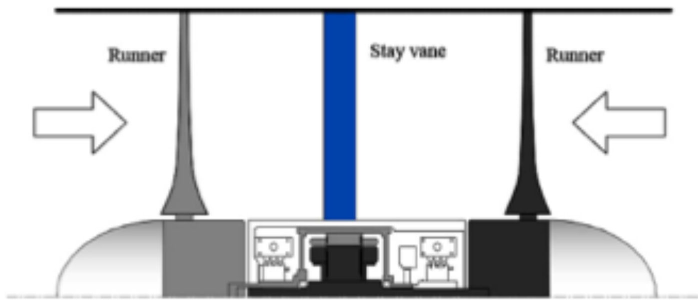

Figure 21 - Counter rotating turbine design (Kanemoto, 2010a)

This device (Fig. 21) uses two runners which operate in tandem with a counter-rotating permanent magnet synchronous AC generator containing double rotation armatures which allows both sets of blades to create electricity simultaneously (Kanemoto, 2010a). The two runners are each connected to a single armature of the generator, with each runner turning in opposite directions (Kanemoto, 2001, Kanemoto, et al., 2000).

The counter rotating turbine is able to extract energy from the water twice. Firstly, the water enters the device in the axial direction, which rotates the front-runner. The water exits with a circumferential, swirling velocity, which causes the second runner to rotate in the opposite direction. As the water leaves the second runner, it exits once more with an axial velocity and because of this; the device operates with equal efficiency in either direction (Kanemoto, 2010a).

6.4.1 Environment

The device works best with a low number of blades, meaning a low solidity to allow fish to pass through. Also, there are no guide vanes, which can cause both mechanical damage and damaging shear stress. However, the impacts of flow in the wake of the turbine have not been investigated. (Clarke, et al., 2007)

It is also possible to create the device with a central, longitudinal hole through the middle of the device to create a safe fish passage (Williams, 2004, Grillos, et al., 2008).

On the other hand, the turbulence created when converting the flow from axial to radial could both damage and cause disorientation to fish. Also, by having two sets of blades, there is more likelihood of mechanical damage.

6.4.2 Efficiency

As turbine blades can be created with the same profile shape, mixed with the general method of operation the contra rotating turbine is able to operate just as efficiently in either direction, which is important for the bi directional Swansea Bay location (Kanemoto, 2010a). However, with the lack of adjustable blades, when the flow and head values differ from the optimum, efficiency will be lost rapidly. With constantly altering head and flow values, this presents an important performance issue.

With the blades rotating in the opposite direction, the each set of turbine blades can reach large rotational speeds relative to the other (Clarke, et al., 2007). The maximum efficiencies are achieved at high values of flow discharge, which is promoted by having fewer turbine blades (Kanemoto & Suzuki, 2010b). Existing turbines used within tidal stream energy have achieved coefficients of power of approximately 0.457; however this is subject to the Betz limit as this was for an un-shrouded device (Lee, et al., 2015). As the device would be housed within a lagoon wall (shrouded), the efficiency would not be constrained to this value.

There is potential to increase the power output of the turbine by reducing or eliminating the swirling velocity of the flow in the wake of the device, however any possible improvement is currently unknown at this time (Clarke, et al., 2007).

6.4.3 Cost

With the relative rotational speed reached by each set of counter rotating blades, the output voltage can be high enough so a gearbox is not required. (Kanemoto & Suzuki, 2010b) There is also almost no torque forces on the structure as a result of the natural counter balancing of the unit, meaning that the turbine housing structure is not required to be as rigid (Clarke, et al., 2007, Grillos, et al., 2008).

There is no need for expensive adjustable guide vanes and it is possible to place the generator out of the flow, meaning less insulation is required (Kanemoto, 2010a).

6.4.4 Maintenance

Although there is no need for potentially high-risk objects such as guide vanes and gearbox, there are added maintenance requirements with the extra set of runner blades. However, through having no adjustable parts or gearbox a large portion of maintenance requirements is not necessary.

With slow individual runner speeds, the effects of cavitation are low and not troublesome (Kanemoto, 2010a). There is also an added benefit to having the generator out of the tidal flow for ease of access.

6.5 Marking Criteria

The results of the marking criteria are set out in Table 4. As the theoretical devices have not been fully evaluated in the appropriate tidal range situation, the values used within the table are based on the information gathered throughout this section. The results were set out in this way because a direct comparison of the values would not be fully representative, for example some of the devices have previously only been used as tidal stream devices, where the values of efficiency are subject to the Betz limit. Therefore, comparing the efficiency values directly would not be a fair comparison against those turbines not limited to this value.

The results of the marking criteria are not fully representative of how the device will operate, but an educated estimation only in order to find the device with the greatest potential.

Table 4 - Marking criteria of both existing and theoretical tidal range turbines

Turbine	Environment	Efficiency	Cost	Maintenance	Total	Comments
Bulb	6	8	3	6	23	Used in the majority of existing tidal range projects. Highly efficient with peak values over 90% Downsides are issues with fish mortality, environment and cost
Straflo	5	7	5	3	20	Usually very large devices, producing high outputs Difficult to maintain and costly
Modified Bulb	3	9	2	4	18	Bulb turbine optimised for bi directional generation schemes Higher costs and greater environmental effects
Archimedes Screw	9	5	8	8	30	Ancient pump changed into a modern turbine Not quite as efficient as Straflo and bulb turbines Very fish and environmentally friendly
Gyro	7	1	8	8	24	Simple design, with low costs. Low efficiency over wide range of flow. No pumping ability
Counter Rotating	6	4	6	6	23	Lower construction costs. Not suitable for flows too far from optimum

The table is set out so each device's performance can be measured both numerically and visually, with:

Red - a very poor performance

Yellow – neither very good nor very bad

Green – a strong performance

As seen from the results of the marking criteria, the Archimedes screw turbine provides the greatest potential in regards to both the aspects investigated as part of the marking criteria and in terms of being a new and innovative design. In addition, the aspects it rates highly in the criteria (environmental effects and cost) represent significant improvement compared to current operational tidal range turbines. These two issues have frequently been quoted by governments as the major deciding factors in deciding against a tidal range project. Therefore this device could have the potential to unlock a wide range of further barrage or lagoon locations around the world.

However, as previously stated, much of the information used for the marking criteria was based on each device's normal operating conditions and not how it operates in a tidal range situation. To clarify if the Archimedes screw device is able to perform well as a tidal range turbine further research needs to be under taken to fully understand how it will operate fully submerged with a pressure head. The next steps will be to analyse the turbine using computational fluid dynamics followed with scale model testing.

The theoretical aspect of this additional research will be carried out at length in Lancaster University, with the scale model testing being conducted in collaboration with the National Technological University of Athens (NTUA), using the facilities available in Greece.

7 Archimedes Screw

7.1 History

First created over 2,000 years ago as a pump to remove water from the bottom of ships, the invention of the device is credited to the famous Greek Archimedes of Syracuse. However, some historians believe it was created in Egypt before he was even born and was merely made famous and adapted for general use as an irrigation pump by Archimedes (Koetsier & Blauwendraat, 2004). Following on from Archimedes, during the first century BC the Roman Vitruvius wrote extensively about the development and creation of the screw pump in De Architechtura (Virtruvius, circa first century BC).

7.2 Pump Operation

To this day the screw pump is still in use. The reliable and robust nature of the device has meant it has lasted all of this time, becoming one of the oldest pieces of engineering technology still in use today (Spans Babcock, 2015). Instead of newer technologies overtaking the device, in recent times the screw pump has found a plethora of new applications to add to an already impressive repertoire.

7.2.1 Land Reclamation

Used to pump water out of sub sea level areas to create useable land (otherwise known as polders). They operate by carefully monitoring the water level and maintaining it through the use of multiple locks and fixed stations where the screw pumps are located to transport the excess water back towards the sea (The Scene of Land and Water, 2015) (Buysse, et al., 2014). This process is most used in the Netherlands where over 50% of the land mass is below sea level and a large percentage of this reclaimed land is used for agricultural purposes (Buysse, et al., 2014) (Green, 2010).

7.2.2 Injection Moulding

An Archimedes screw also has uses in modern production methods where it is used to move the material used to the mould being produced. The screw can operate well at very low rotation rates, meaning that the fibres in the material are not damaged whilst passing through the device (Bunsell & Renard, 2005).

7.2.3 Heart Valve Replacement

The screw device also has uses within the medical industry, in the form of a mechanical heart valve. Heart failure has directly resulted in the deaths of over 600,000 US citizens every year. The pumping technology behind the Archimedes screw has been used since the 1980's to simulate the process of the left ventricle by continually rotating to pump blood at a continuous rate (Butz, 2013). The technology has so far been used to save the lives of over 20,000 people operating as a temporary heart, until an appropriate replacement donor was found (Stix, 2013). A single device can currently last for approximately 10 years, hopefully giving sufficient time for the permanent donor (Lepage-Monette, 2007). However, the technology is continuously advancing, with Cohn and Frazier leading the way to providing a permanent screw heart, with successful animal and human trails, where a terminally ill person had their lifespan lengthened due to the device (Butz, 2013).

7.2.4 Fish Ladders

Due to the exceptional fish friendliness of the device, it has been used and trusted in numerous locations to actually transport or divert fish safely from one area to another. This is often used to direct migrating fish or manoeuvre them away from man made obstructions that could be potentially harmful (National Oceanic and Atmospheric Administation, 2015).

7.2.5 Tower of Pisa (Italy)

Dubbed the leaning tower of Pisa, this building has had structural issues for a very long time mainly because of the compressible soils beneath result in weak foundations. Due to this, every so often, work needs to be carried out to stabilise it. As this is a very delicate project, usual methods to improve foundations could not be used, as they were too intrusive, potentially damaging the protected building, therefore an Archimedes screw was developed by John Burland tasked with reducing the lean angle. The screw was able to remove soil from the foundations therefore reducing the angle by 0.5 degrees, without causing any damage because the screw was able to operate without causing disturbance to the surrounding soil (Burland, 2001).

7.3 Archimedes Screw Turbine

The idea of using the Archimedes screw pump in reverse as a turbine is a new technology. The first operational device was deployed in Europe in 1994 and was not used in the UK until 10 years later (Western Renewable Energy, 2015) (Mann Power, 2015). The reason it was not used in this way until so recently was due to the highly advanced gearbox the device requires was not available (Nuernbergk & Rorres, 2013). As the La Rance barrage was developed and constructed during the 1960's, it was not possible for this turbine to even be considered during the research and development phase.

From the creation of the first screw turbine there have been a number of variations in design, with each set up used to generate electricity in a slightly different way (See Appendix A). Since operating the device as a turbine is a relatively new idea, the understanding behind how to achieve the most power from the device is still in the initial stages, with few in depth analyses carried on the subject. To find the optimum geometries required further understanding and research is necessary.

7.3.1 Inclined Axis Turbine

The inclined Archimedes screw turbine looks very similar to the pump version of the device, and in some cases the same geometry has been used though, doing this is not ideal, as the operational aim of the two devices differ significantly. The role of the pump is to transport the greatest volume of material or fluid with each rotation, whereas the turbine is required to capture the maximum possible amount of energy from the flow per rotation.

Theoretically, the Archimedes screw turbine would be 100% efficient only if it is assumed there are no losses and that the weight of the water within the turbine acts upon the blades, however these conditions are unattainable in real world situations, where friction, among other detrimental forces will always be present (Fiardi, 2014). When analysing how exactly the device generates power, the weight of the water is usually neglected as the majority of the fluid in fact acts upon the fixed trough the screw is housed within, therefore not on the rotating screw. The inclined screw turbine uses two different methods to produce the torque necessary to create energy.

The first method is through the creation of a hydrostatic force (Müller & Senior, 2009). This force is produced because of the difference in head between each inclined screw bucket. The difference in height creates different pressures (with the larger height producing the greater value), which acts on both sides of the blades and therefore producing a higher and lower value of hydrostatic force (Fig. 22).

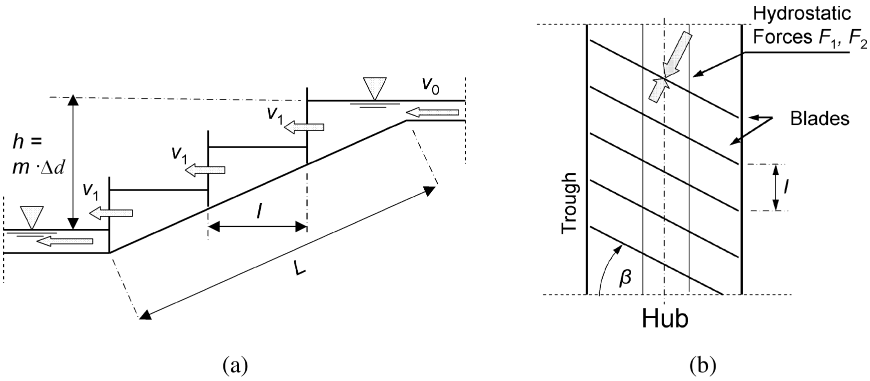

Figure 22 - Outline of how the Inclined Archimedes Screw turbine produces hydrostatic force (Müller & Senior, 2009)

The larger component acts in the useful direction, cancelling out the opposing value and producing the torque component. The second method of generating torque is through the velocity of the water itself as it passes through the turbine, causing the blades to rotate.

The torque is transmitted to the required gearbox where the low values of RPM are stepped up for the generator to convert to useable electricity.

This is currently the only one of the three types of Archimedes screw turbine that has been fully deployed around the world.

7.3.2 Submerged Tidal Turbine

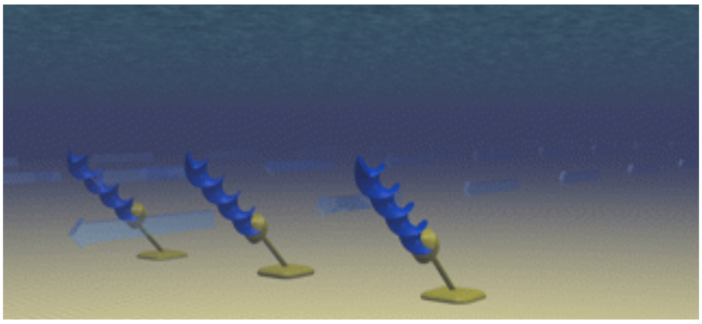

Figure 23 - Archimedes screw tidal stream device (European Marine Energy Centre, 2011)

The Archimedes screw is one of the innovative designs developed in the field of tidal stream energy (Fig. 23). Although there are no full scale projects operational this time, a Norwegian company called Flumill are currently in the process of developing a device (Flumill, 2015a). The device in development uses a pair of screw geometries with symmetrical blades with a top fin, which is used to alter the angle of inclination (Fig. 24).

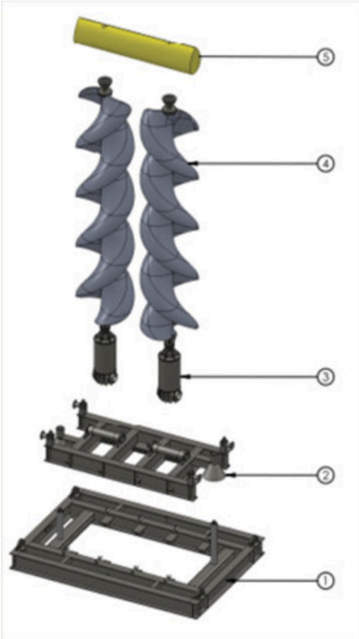

Figure 24 - Flumill screw turbine (Flumill, 2015a)

It is permanently fixed to the bottom of the sea, on a rotating pivot which allows the device to alter the angle and direction it comes in contact with the flow to maximise the output. Water flows up through the buckets of the device, causing the blades to rotate therefore creating a useful output with the help of an attached gearbox and generator.

The design is theoretically sound, with multiple computational analyses already carried out. With the Norwegian government behind the project offering financial backing, full scale tests are due to commence shortly in Tromsoe (Flumill, 2015b, Flumill, 2015a). It is thought that the device will operate well with even very low flow velocities of 1m/s, which many other tidal stream devices are unable to do (Solbakken, 2014).

7.3.3 Horizontal Screw Turbine

Figure 25 - Horizontal Archimedes screw turbine (Stergiopoulou , et al., 2011)

The horizontal device takes aspects from both the inclined device and the tidal stream version. The screw design itself is identical to the inclined version; however like the tidal stream device it does not include an enclosure or trough. As seen in (Fig. 25) the device would be located on the surface of the water, partially submerged, meaning it is very easy to access for maintenance. Created with a symmetrical design, each device would be able to operate using flows in either direction with the same efficiency.

It is designed to operate in near zero head locations such as rivers (Stergiopoulou & Stergiopoulos, 2013a, Stergiopoulou, et al., 2013b). The device uses the velocity component in either tidal or river currents and the kinetic energy within these to create the torque necessary to energy production (Stergiopoulou, et al., 2013c, Stergiopoulou, et al., 2013d). As there is no incline, no hydrostatic force is created to add to this torque value.

This design is very much in the infancy stage, currently in the initial stages of research, with no in depth computational or physical analysis conducted. However, the technology is available and the design idea is promising.

7.4 Design Criteria

An extensive study on the performance criteria of the Archimedes screw turbine by Muller and Senior found that the maximum efficiency the device is able to achieve is limited by a combination of the turbine geometry and the mechanical losses within the system (Müller & Senior, 2009). In addition to this, the optimum design of any turbine is always a trade off between the theoretical optimum and the cost needed to create it.

There are two sets of design aspects, which affect the overall geometry of the device, in the form of internal and external parameters. The internal identities are values, which can be modified and changed during the design phase. External identities are the parameters set by the site the device is to be located in and the designer cannot easily change maximum values. Therefore, the statement from Muller and Senior can be modified into: the maximum efficiency the device is able to achieve is limited by the external geometry and mechanical losses in the system.

Each device must have the optimum values for the internal parameters for the specific set of external. This can be known as the designers' problem (Waters & Aggidis, 2015). The main geometrical identities that are chosen and modified during research and construction are outlined in (Fig. 26) and Table 5.

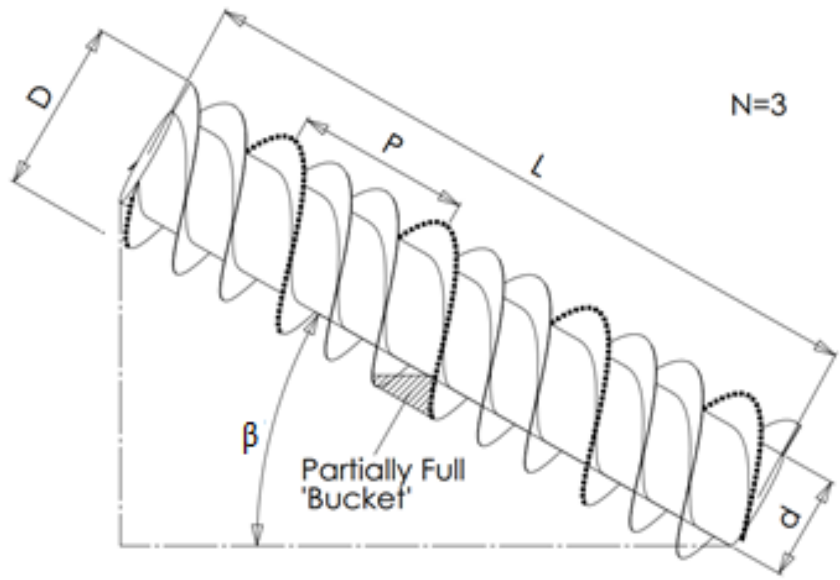

Figure 26 - Geometrical details of Archimedes Screw Turbine (Lyons & Lubitz, 2013)

Table 5 - Geometric parameters of Archimedes Screw Turbine (Waters & Aggidis, 2015)

Symbol	Name	Internal (I)/External (E)
D	Outer Diameter	E
d	Inner Diameter	I
P	Pitch	I
L	Length of screw	E
θ	Angle of Inclination	E
N	Number of flights	I
G	Thickness of Spiral Profile	I
n	Rotational Speed	
Q	Flow rate	E
H	Head	E
ω	Rotation rate	

The method behind optimising any turbine often combines various key parameters that are linked to each other, meaning when one changes it affects the other as well as the overall performance of the device. These links are otherwise known as design ratios and are important to understand in order to optimise the geometry effectively. The design ratios which are valid for the Archimedes screw turbine are set out in Table 6.

Table 6 - Design ratios for the Archimedes Screw Turbine (Waters & Aggidis, 2015, Lyons, 2014)

Name	Ratio/Relationship
Diameter ratio	$\delta = d/D$
Pitch ratio	$Pr = P/D$
Length ratio	$Lr = L/D$
Profile ratio	$\varphi = G/d$

7.5 Internal Design Parameters

7.5.1 Pitch Ratio (Pr)

Much of the literature on the subject believes there is a strong link between performance and the pitch ratio (Rorres, 2000, Nagel, 1968). Laboratory testing of a variety of different geometries, each with different pitch ratios is able to confirm this link. During the testing, the larger pitch ratio values corresponded to an increased value for efficiency and power.

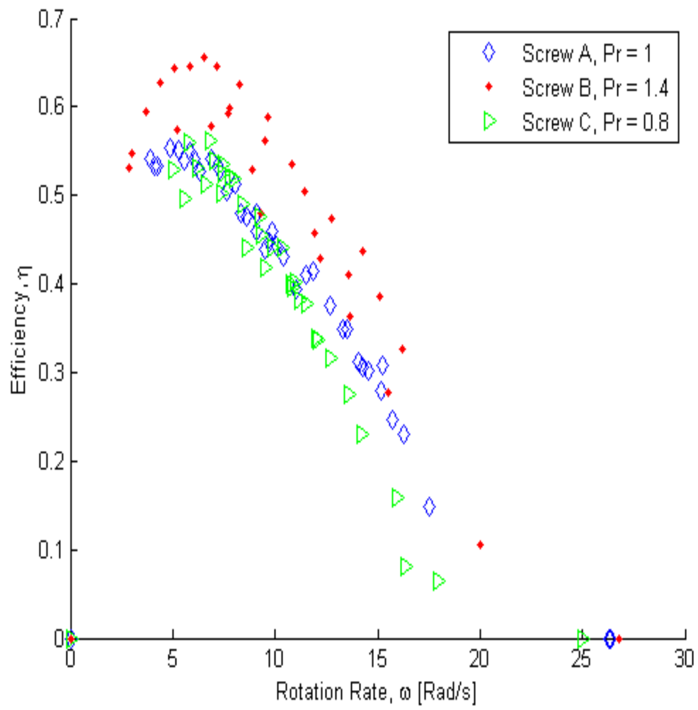

Figure 27 - How varying pitch ratio affects performance (Lyons, 2014)

Increasing the pitch decreases the amount of buckets for a given length, but increases the volume of water within each bucket. The number of buckets on an Archimedes screw turbine can be calculated using (Eqn. 2) (Lyons, 2014).

$$n_b = \frac{Lr\ N}{Pr} \qquad (2)$$

This increase of water in each bucket means there is a greater hydrostatic force created acting on the walls of the turbine blades to produce a higher amount of torque. Therefore, as the graphs prove (Fig. 27), it is more important to increase the volume of water within the buckets, than it is to have more buckets.

However, it has been predicted that by decreasing the pitch, there are less leakage losses created by water effectively spilling out of the buckets and therefore not contributing to the creation of torque, reducing efficiency (Lyons, 2014). This means there will be a limiting point where increasing the pitch ratio becomes detrimental to performance.

7.5.2 Revolutions per minute (RPM)

Understanding the rotation rate for a turbine instead of a pump are two very different things. For the pump setup the amount of liquid being pumped through the device is increased with an increase in rotation rate (Rorres, 2000). However, when operating as a turbine it is not as simple as increasing the RPM to increase the output.

There are many advantages to operating at low rotational speeds, as doing so causes less turbulence to the fluid within the turbine, which helps to minimise losses (Lyons, 2014). Low rotation speeds also help to reduce the losses due to the friction (Nuernbergk & Rorres, 2013). However, low speeds mean a complex gearbox is required.

Through scale model testing (Lyons, 2014) believes the optimum efficiencies are reached slightly before the RPM stall point for each individual device because just before the device would stall, the buckets will contain an optimum fill to produce the highest amount of torque possible.

7.5.3 Number of turbine blades (N)

An Archimedes screw turbine has the option to have a large number of turbine blades or helices. (Müller & Senior, 2009) and (Fiardi, 2014) believe that higher efficiencies can be attained when using a greater number of blades as each blade will produce an equal amount of power, the power equation can be modified into (Eqn. 3)

$P = N \times P_{Blade}$ (Fiardi, 2014) (3)

7.5.4 Diameter ratio

The link between the diameter and performance is perhaps the most documented, with multiple references discussing the relationship between this and the increased water level possible with increasing diameter ratios (Stergiopoulou, et al., 2011, Stergiopoulou & Kalkani, 2013e, Stergiopoulou & Stergiopoulos, 2012, Müller & Senior, 2009, Stergiopoulou, et al., 2013f). It is thought that by increasing the diameter ratio, more power and torque can be achieved to a point before the ratio becomes too skewed and any further increase has a negative impact.

The maximum diameter of any screw device has always been constricted by the diameter possible for construction. This maximum value has previously been set at 4m, however with more advanced manufacturing methods and especially the ability to use composite materials such as the vinyl ester based composite, this maximum value could be increased (Aquatic Control Engineering, 2015, Raza, et al., 2013).

7.5.5 Clearance Space

The gap between the edges of the turbine blades and the enclosure or trough surrounding the turbine is called the clearance gap. While this is necessary to have a gap, so the turbine is able to rotate within the enclosure, it is important to try and keep this as small as possible to make sure as much of the flow as possible is interacting with the turbine blades rather than passing through this gap and not contributing to the production of torque (Raza, et al., 2013).

7.5.6 Rotating or Stationary Trough

It is common for the trough situated around the screw, holding the liquid in place, to be fixed in stationary position. However, research conducted by (Hawle, et al., 2012b), compared the performance of this set up with one where the trough rotated around the screw. The results found that the stationary version performed better, achieving higher efficiencies and was also able to operate well over a broader range of flow values. However, another company believes that a rotating trough is able to optimise performance as water is unable to pass through the clearance gap (Aquatic Control Engineering, 2015). However, the value of efficiency this turbine was able to achieve was still approximately 80%, which is also a common figure with stationary trough devices.

For the use of the project, a rotating trough would not be practical due to the size of the turbine and the ready made, stationary hole in the lagoon wall to house the turbine can also form the enclosure/trough. Therefore, only the stationary trough method will be considered throughout the project.

7.5.7 Variable or Fixed Speed

Although the Archimedes Screw Turbine is able to operate well over a range of flow values, being able to operate with variable speed increases this ability (Lyons & Lubitz, 2013, Hawle, et al., 2012b). It also increases performance with efficiencies around 80-85% attainable over a wider range than fixed speed (Aquatic Control Engineering, 2015).

7.6 External Design Parameters

7.6.1 Volume Flow Rate

Current Archimedes screw turbines are able to operate well with flows ranging from 0.1 to 50m^3/s (Stergiopoulou, et al., 2011). Furthermore, even when flow rates exceed this range, the device can still be used, as it is possible to connect numerous turbines next to each other to adequately extract energy from higher flow rates. This ability to handle a variety of flow values is useful for tidal situations due to the large and constant tidal flow fluctuations.

Model testing found that as expected, increasing the volume flow rate resulted in increased power and efficiency (Fig. 28). The model used was small, with an outer diameter of 0.15m and a length of 0.6m.

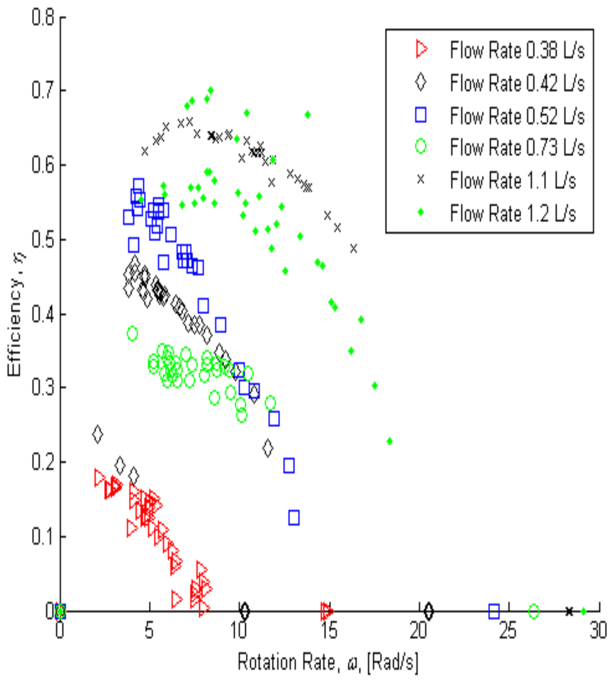

Figure 28 - How varying the flow rate affects efficiency (Lyons, 2014)

In (Fig. 28) it can be seen that although the increased flow rates improve performance, there is a maximum limit for this, which is reached between 1.1 and 1.2L/s. Any flow above 1.1L/s results in a drop in the performance.

This trend is well documented with a second experiment conducted in Ontario, Canada also showed this correlation of increasing flow rate and increasing power (Fig. 29).

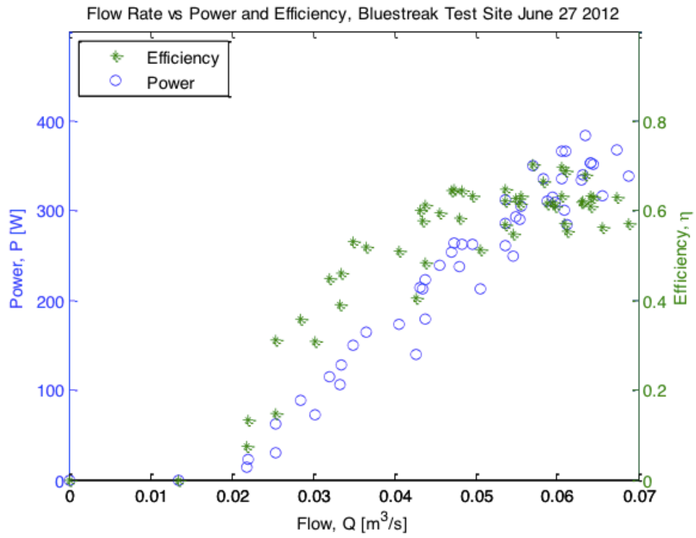

Figure 29 - Varying flow rate for model tests in Ontario (Lyons, 2014)

This can also be seen during tests from (Hawle, et al., 2012b), where the increased flow has improved performance (Fig. 30), however the limit was not found during these tests.

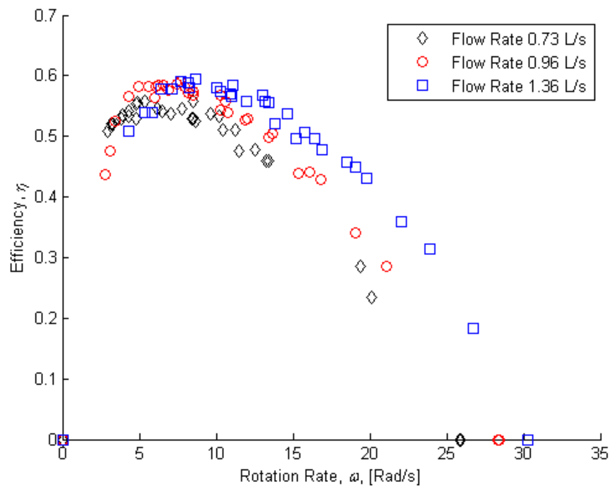

Figure 30 - The relationship between flow rate and performance (Hawle, et al., 2012b)

For all of these tests, the reduced efficiencies at lower flow rates are caused because the losses, which are created in the system, do not reduce in proportion to the reducing flow rate (Lyons, 2014). Therefore as the flow rate increases the losses (although present) do not increase as much, resulting in a greater power output. The point where the efficiency begins to decrease even when the flow rate is larger is because these losses begin to have a greater effect due to the water filling the turbine buckets above the optimum value and the increased rotation causing an increased amount of sloshing.

7.6.2 Angle of Inclination

Although the angle possible is partially location dependant, it may be possible to modify the angle of the device by changing the length. The effectiveness of changing the angle is disputed, with (Müller & Senior, 2009) believe that higher efficiencies can be reached with a reduced angle of inclination (Fig. 31)

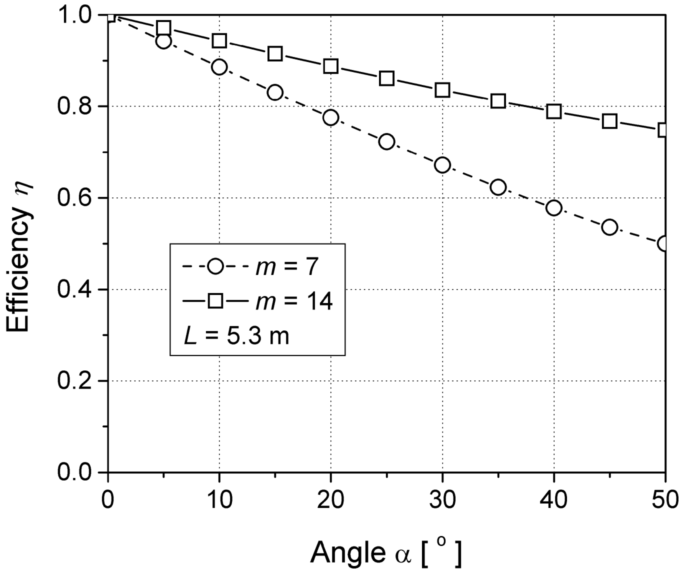

Figure 31 - How inclination angle and number of buckets alters efficiency (Müller & Senior, 2009)

However, others ((Lyons, 2014) and (Raza, et al., 2013)) believe the opposite and that higher efficiency can be achieved with an increasing value of inclination. Experimental testing, where the angle of the same model was modified shows this to be true (Fig. 32). However, it must be noted that these tests, did not factor that for a specific site, if the inclination angle is modified the length would also change and that a shallower angle with an increased length may provide better results.

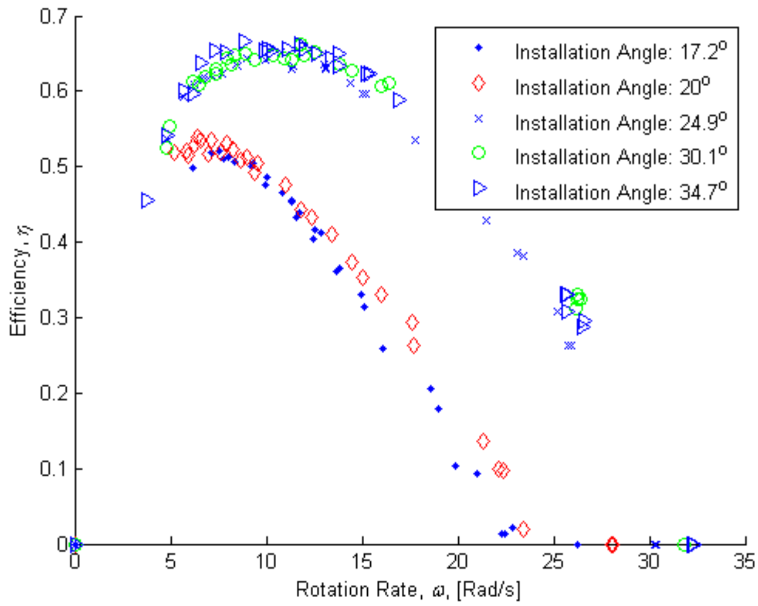

Figure 32 - Increasing inclination angle and efficiency (Lyons, 2014)

In (Fig. 32) it can be seen that there is a limit to how far the angle of inclination can be increased before there is no benefit towards the overall efficiency of the device. This trend was also seen during research carried out by (Shimomura & Takano, 2014).

If the angle of incline at a specific site is too large, it is theoretically possible to connect various slightly inclined devices in series almost in a step like formation.

7.6.3 Length

Although the maximum length is site dependant, it could still be possible for the designer to choose a smaller value. This ability to modify the length to a certain amount results in the fluid coming into contact with greater or fewer number of buckets for the given pitch value. With greater length, the turbine is able to extract more energy out of the fluid flow (Webber, 2013). However, this will only occur to a point, when increased length will result in a negative way.

7.7 Design Criteria Conclusions

The trends and values found in literature were all for partially submerged screw turbines or for screw pumps. As the operating conditions for tidal range will be different; with full submergence combined with a pressure head, the trends found cannot be automatically assumed to be correct. Therefore, it is necessary to determine which design trends are or are not valid for an Archimedes screw turbine which shall be used in a unique tidal range method.

As there is no existing information on this subject, computational modelling was undertaken to identify and evaluate the design trends found.

8 Computational Fluid Dynamics (CFD)

8.1 Introduction to CFD

Computational fluid dynamics (CFD) was first developed during the 1960's, however, it was many years before the field was advanced enough and computer processing power was great enough for it to begin to be useful for various industries (CHAM, 2015). During this time, NASA were very keen to develop the computational know how to understand the flow over and around a blunt body at supersonic speeds as part of its space program. Understanding the shock wave in front of the nose was one of the most difficult aerospace engineering problems at the time (Anderson, 1995). Through the use of developing CFD the problem was finally solved by Moretti and Abbett (Moretti & Abbett, 1966). Through the rapid development of computer software and understanding, this worldwide problem is now used as a homework assignment for students (Schleicher, 2012).

Nowadays CFD offers an extra approach in addition to theory and experimental analysis, when it comes to solving fluid problems, and is an important tool that should be used alongside these, but not replacing them (Anderson , 1995). Currently it is a valuable tool used extensively in both industry and academia due to its ability to accurately predict and model complex fluid flow interactions.

There are two different mathematical methods used to model the movement of fluids or gasses: Lagrangian or Eulerain.

The Lagrangian method follows and tracks the individual fluid particles as they move per time step (Zhang & Chen, 2007). This is the less common method and is used when the physical spread of the flow is important, for example the movement of medical dye through a patients veins or the drifting of buoys in the sea (MIT Mathematics, 2015). For the Eulerian method the governing equations are solved with fixed coordinates inside a control volume (Zhang & Chen, 2007, MIT Mathematics, 2015). The fluid flow is treated as a continuum, where the properties are set out in both space and time, and can be described as working within the laboratory frame (Universita Di Pavia, 2015, MIT Mathematics, 2015). As it suits the nature of the research, an Eulerian based approach with be used throughout the project.

8.1.1 Governing Equations

There are a very large number of CFD codes and programs available, as well as the possibility of creating a new one for a specific purpose. However, each and every program is based on three sets of principals that govern physics behind the flow interaction:

1. The conservation of mass (Eqn. 4)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) = 0 \tag{4}$$

2. Newton's second law of motion (F = ma) (Eqn. 5)

$$\begin{aligned}
&\text{x-component}: \quad \frac{\partial(\rho u)}{\partial t} + \nabla \cdot (\rho u \vec{V}) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + \rho f_x \\
&\text{y-component}: \quad \frac{\partial(\rho v)}{\partial t} + \nabla \cdot (\rho v \vec{V}) = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + \rho f_y \\
&\text{z-component}: \quad \frac{\partial(\rho w)}{\partial t} + \nabla \cdot (\rho w \vec{V}) = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} + \rho f_z
\end{aligned} \tag{5}$$

3. Energy conservation (otherwise known as Newton's 1st law of thermodynamics (Jha, 2013)) (Eqn. 6)

$$\begin{aligned}
&\frac{\partial}{\partial t}\left[\rho\left(e + \frac{V^2}{2}\right)\right] + \nabla \cdot \left[\rho\left(e + \frac{V^2}{2}\vec{V}\right)\right] \\
&= \rho \dot{q} + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) \\
&+ \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) - \frac{\partial(up)}{\partial x} - \frac{\partial(vp)}{\partial y} - \frac{\partial(wp)}{\partial z} + \frac{\partial(u\tau_{xx})}{\partial x} \\
&+ \frac{\partial(u\tau_{yx})}{\partial y} + \frac{\partial(u\tau_{zx})}{\partial z} + \frac{\partial(v\tau_{xy})}{\partial x} + \frac{\partial(v\tau_{yy})}{\partial y} \\
&+ \frac{\partial(v\tau_{zy})}{\partial z} + \frac{\partial(w\tau_{xz})}{\partial x} + \frac{\partial(w\tau_{yz})}{\partial y} + \frac{\partial(w\tau_{zz})}{\partial z} + \rho \vec{f} \cdot \vec{V}
\end{aligned} \tag{6}$$

The different sets of equations are the conservation form of the Navier Stokes Equations for viscous flow as set out in (Anderson , 1995). These are the fundamental equations that allow CFD programs to numerically analyse and predict the fluid flow and include important aspects such as friction and thermal conduction.

8.1.2 Pros and Cons of CFD

There are many advantages to using CFD, for example it can be approximately 40% cheaper to use CFD compared to physically modelling (Linfield & Mudry, 2008). This also allows for quicker and easier optimisation of the model, as a new physical device does not have to be created for every variation. The computational tests themselves can be run quicker than it would take to set up and monitor a physical counterpart (in many cases). Expensive and large laboratories can also be replaced with a single computer unit.

However, there are some limitations, mainly focussed around the computer itself. Complete accuracy is not a given, as a percentage error will always be present, however this has improved vastly in the last 40 years and as CFD was never intended to replace scale model testing, small errors are acceptable as they are still able to provide an accurate guide. Most of the disadvantages rest on the computer itself, with a large amount of processing power and speed required to cope with the computational programs necessary. The user not setting the program up correctly, with poorly defined boundary conditions can easily create inaccuracies. A badly constructed mesh may not capture all of the flow physics or phenomena. Therefore extensive training is necessary for those using the software. CFD programs are still lacking when it comes to modelling turbulence, with this causing inaccuracies both near and away from walls.

The CFD software also assumes that the device and water is at a constant temperature, whereas in real situations this will not be true, with the fluid having constant temperature fluctuations. It is also assumed that the turbine geometry is 100% accurate, made out of a perfect material, both of which, in real circumstances will not be the case. The water used will also contain imperfections that will not be considered for example silt content.

It is easy to understand how and why CFD has become an integral part of engineering problems, aiding in the rapid development and advancement of a wide range of areas. Therefore it will form a large part of this project, where a reference model will be analysed computationally to understand how the Archimedes screw turbine will operate fully submerged with a large head difference between the inlet and outlet. Once this is understood, CFD will be used again to optimise the performance of the turbine.

To do this, the geometry of the reference turbine CAD model will be altered and re run, comparing the outputted results to understand how different geometrical identities affect key performance values.

8.2 ANSYS CFX

CFX is a Eulerain based model, which is used extensively both commercially and academically. It is widely accepted that it is able to achieve a high level of accuracy for a wide range of fluid flow types, and is able to capture almost all fluid flow phenomena (Židonis & Aggidis, 2015, ANSYS, 2015a).

This product is a proven technology, with a strong user base and many years of operating experience. The integrated workbench platform gives access to the diverse range of other computational modelling modules ANSYS offer, which is often necessary for a thorough analysis. There are five key modules necessary to be able to set up and complete the computational fluid analysis.

1. Geometry creation using Computer Aided Design (CAD)
2. Mesh creation – splitting the geometry into smaller grid like sections
3. Physical set up – setting the boundary conditions reflecting the testing environment
4. Running the solver – where the mathematics is computed using the governing equations to numerically solve the fluid problem
5. Post processing – viewing the results of the solver through moving animations, graphs and still images of the fluid flow

Throughout the project the latest version of ANSYS (16.1) will be used. There are other codes available that have been used for evaluating the Archimedes screw turbine in the past such as Flow3D, however, this has only been for partially submerged devices and would not be as suitable for the application necessary for this research (full submergence with a pressure head) (Haselbauer, 2015).

8.3 Geometry Creation

The screw geometries were created using a combination of two CAD software packages – Solidworks and ANSYS Design Modeller. The geometry creation can be split into three major sections:

8.3.1 Creating the Turbine

Firstly and most importantly Solidworks was used to create the initial turbine geometry. Initially a pair of helices or spirals with identical values of pitch and height was created. One helix would have an outer diameter value equal to outer diameter of the turbine, and the other matched the inner value.

To create the inner diameter section which the blade (or blades) are attached to, a cylinder with a matching point of origin as the two helices was created with a diameter matching the inner. The two bodies were then mated to one another so they rotate as a singular device. The full turbine geometry can be seen in (Fig. 33).

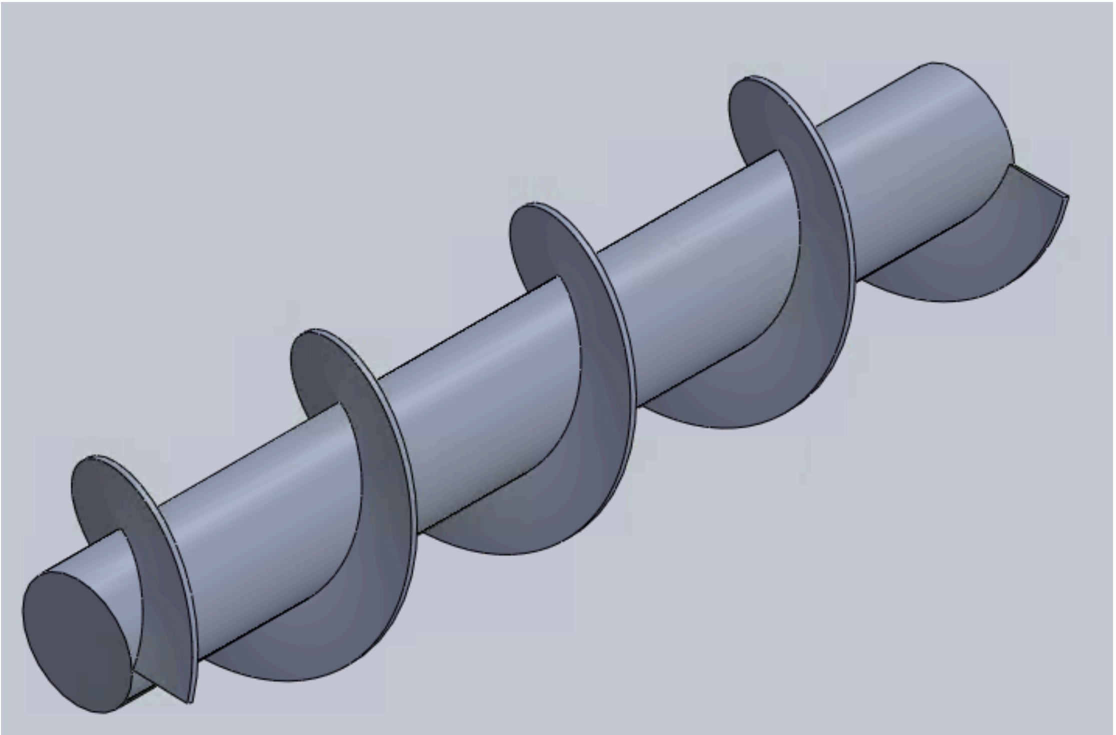

Figure 33 - CAD model of turbine geometry

The complete turbine file was imported into ANSYS Design modeller for the next steps.

8.3.2 Inlet and Outlet sections

To simulate the flow heading into and out of the turbine a cylinder section was created using ANSYS Design Modeller. The cylinder was formed in three parts, with the initial section creating a shroud around the 0.8m long, 0.2m diameter turbine using the enclosure tool, leaving a 0.01m clearance gap, which would be necessary to simulate real world conditions. This enclosure part will form the rotating section of the whole simulation.

The other two sections were created with the extrude tool, creating a large 5m inlet and outlet section. These sections were created longer than they would be during physical testing so the flow entering the device would have time to fully develop and also so the flow exiting the device can be seen and examined.

The inlet and outlet sections can be seen below (Fig. 34)

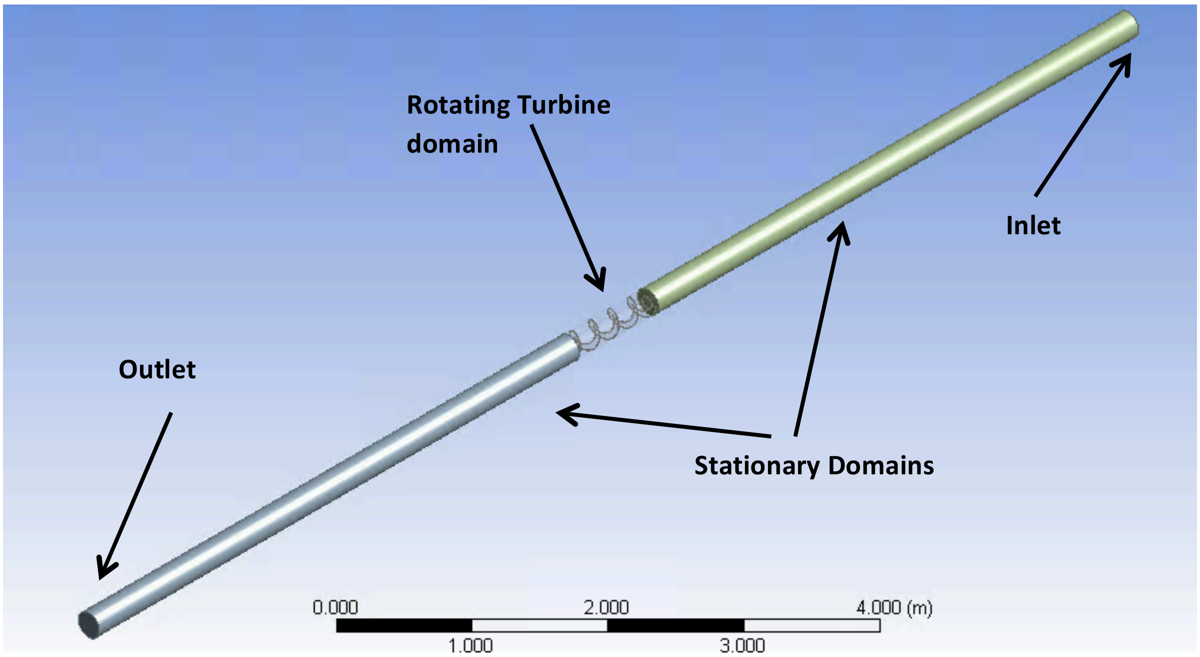

Figure 34 - Inlet and outlet sections of geometry

8.3.3 Subtracting the Turbine Geometry

The final phase used to prepare the geometry was to effectively delete the turbine from the enclosure. This was carried out using the Boolean subtract feature. By doing this, it effectively creates an empty space or cavity within the geometry. The imprint left from the deleted geometry formed a named selection and will later be used to represent the turbine model. As the 'filled' space represents the fluid, the empty section will be treated as the rotating turbine wall.

8.4 Mesh Creation

The construction of a good quality mesh is vital for successful and accurate CFD analysis. The role of the mesh is to decompose the geometry into small control volumes called cells and elements, in a process called discretization (Kuzmin, 2015). CFX uses a cell vertex method where the vertices of the elements are nodes.

The governing equations are solved iteratively at the nodes or elements until convergence is reached to numerically solve the fluid flow. Convergence is achieved when the governing equations as well as the mass, momentum and energy residuals have been solved to the required tolerance (Kuzmin, 2015). The quality of the mesh controls how well the project will converge and how long it will take. It is also important as a poor mesh will result in inaccurate results or possibly will not produce any results at all (Bakker, 2006).

ANSYS CFX uses a patch conforming meshing approach, where all of the faces, edges and vertices are captured for a part, with de-featuring only used for very small features (ANSYS Inc, 2009). For the purposes of analysing a turbine, this feature capturing method is very useful and appropriate.

8.4.1 Mesh Quality

Although there are many different ways of determining the mesh quality, the skewness and orthogonal quality statistics give a good overview of how well the mesh will work.

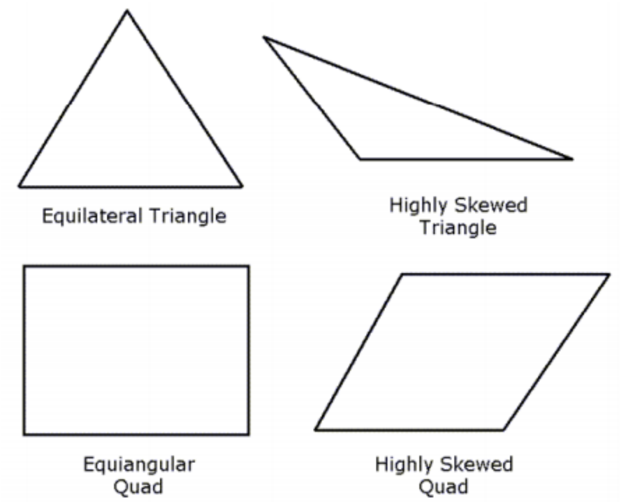

Figure 35 - Perfectly equilateral and highly skewed shapes (ANSYS Inc, 2009)

Skewness is a measure of how close the face of the cells are to the optimum. As seen in (Fig. 35), the shapes on the left represent the ideal, with a skewness of 0, and the corresponding images on the right are highly skewed. To maintain a good mesh, highly skewed cells should not be present and therefore the maximum value should not exceed 0.9 (ANSYS Inc, 2009).

Orthogonal quality is computed based on the combination of the face normal vector and the vectors from entre of the element in question to the centre and faces of the surrounding elements (ANSYS, 2013). The scale spans from 0 – 1 with 0 being the best and 1 the worst. The minimum value should not fall below 0.1 to preserve mesh quality.

Another very important feature that is required to capture the fluid flow is inflation. Large variations in velocity often occur near the wall boundary in the normal direction (Fig. 36).

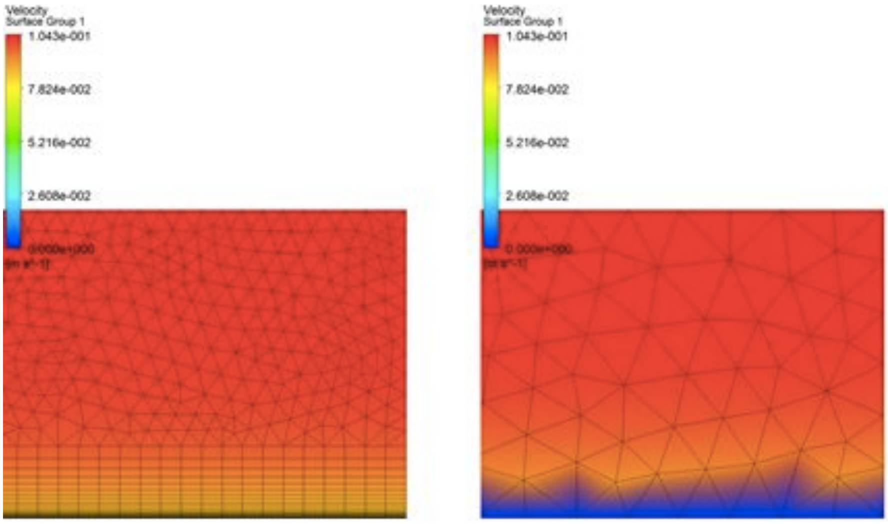

Figure 36 - Velocity gradient captured with inflation layers (left) and without (right) (SimuTech Group, 2015)

The right side of the image contains no inflation layers; therefore not capturing the velocity variation correctly as there is a large jump in the values. On the left where inflation layers are included, the velocity changes smoothly and is captured fully.

8.4.2 Rotating Domain Mesh

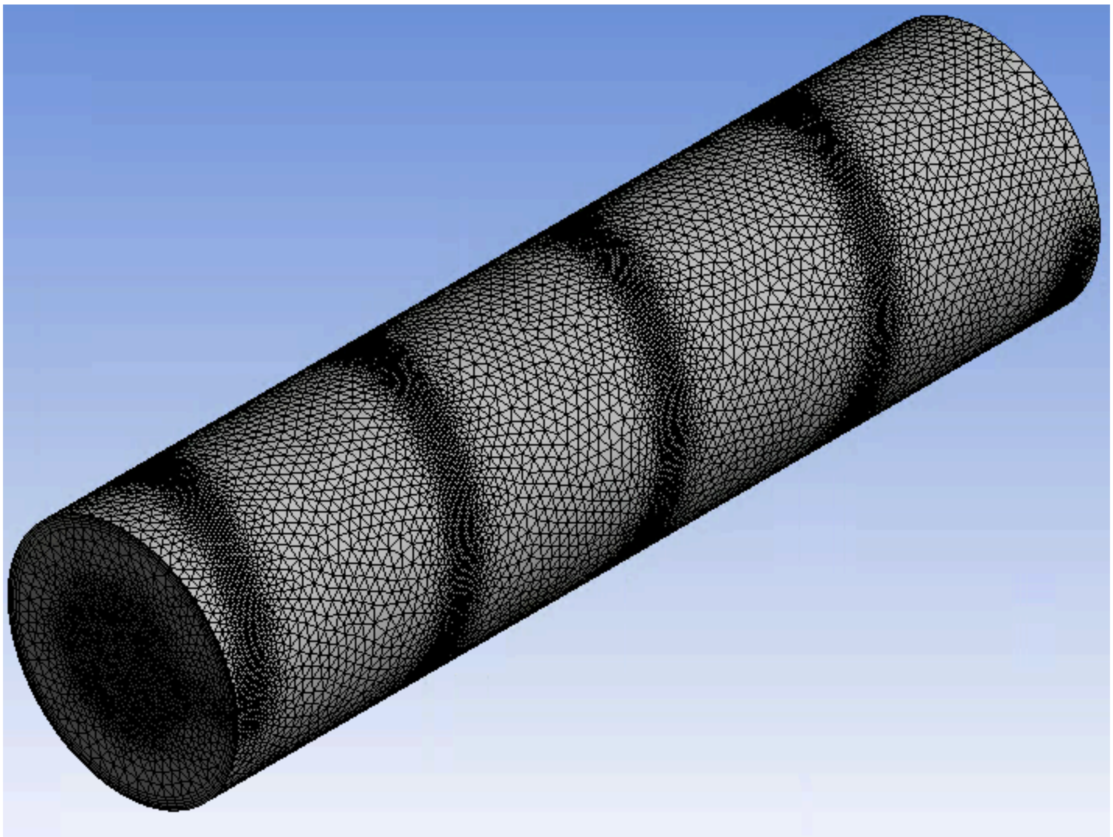

Figure 37 - Rotating domain mesh

The rotating domain is comprised of the turbine cavity and the enclosure around it. This was meshed using a patch conforming tetrahedral mesh and was chosen as it produces a fine, high quality unstructured mesh by creating the surface mesh before the volume mesh, therefore capturing the shape of the turbine walls very well (ANSYS, 2015b). This domain is the most important and therefore contains the smallest elements to fully understand how to flow interacts with the turbine.

Inflation layers were incorporated into the mesh at the areas of interest, both at the wall and where the surfaces of the turbine inner diameter cylinder and blades interact with the fluid flow. The inflation layers can be seen in (Fig. 38) and (Fig. 39). 10 layers of inflation were used at the enclosure wall, and 7 on the turbine blades. This amount was large enough to adequately capture the velocity gradient for the initial testing phase and any increase caused a reduction in mesh quality.

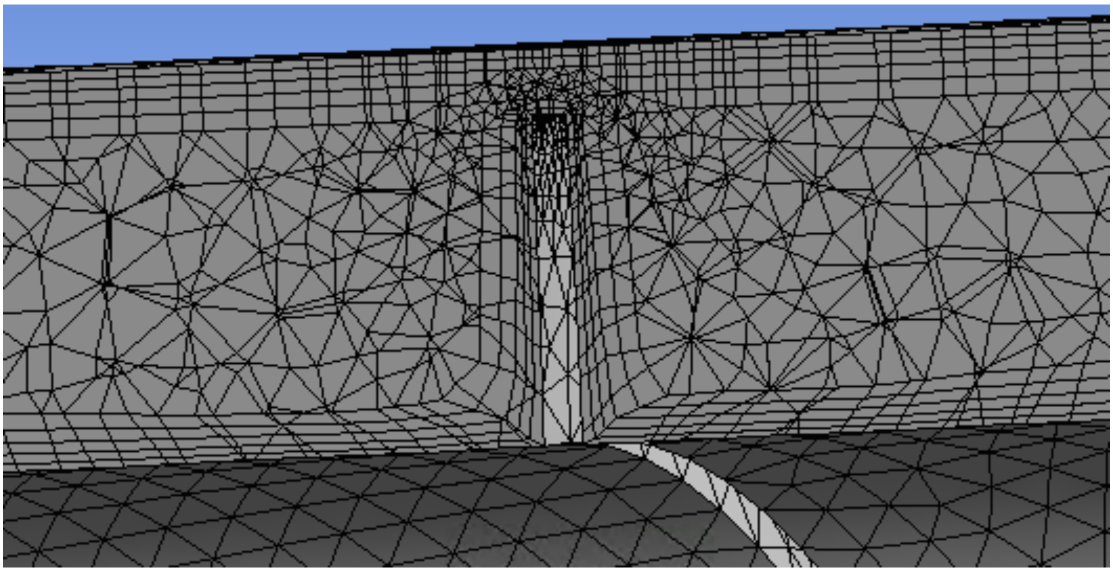

Figure 38 - Inflation layers around the turbine blades and enclosure wall

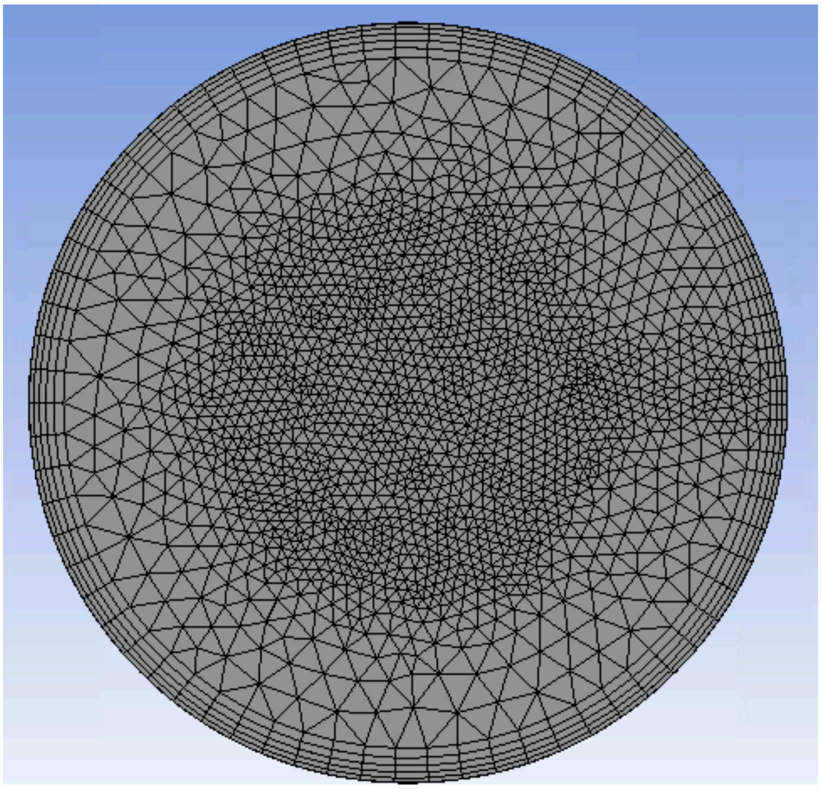

Figure 39 - Inflation layers around the walls of the enclosure

This domain contains 836070 elements and 264651 nodes, with a maximum skewness of 0.89925 and minimum orthogonal quality value of 0.16309, both of which are in the acceptable range.

8.4.3 Stationary Domain Mesh

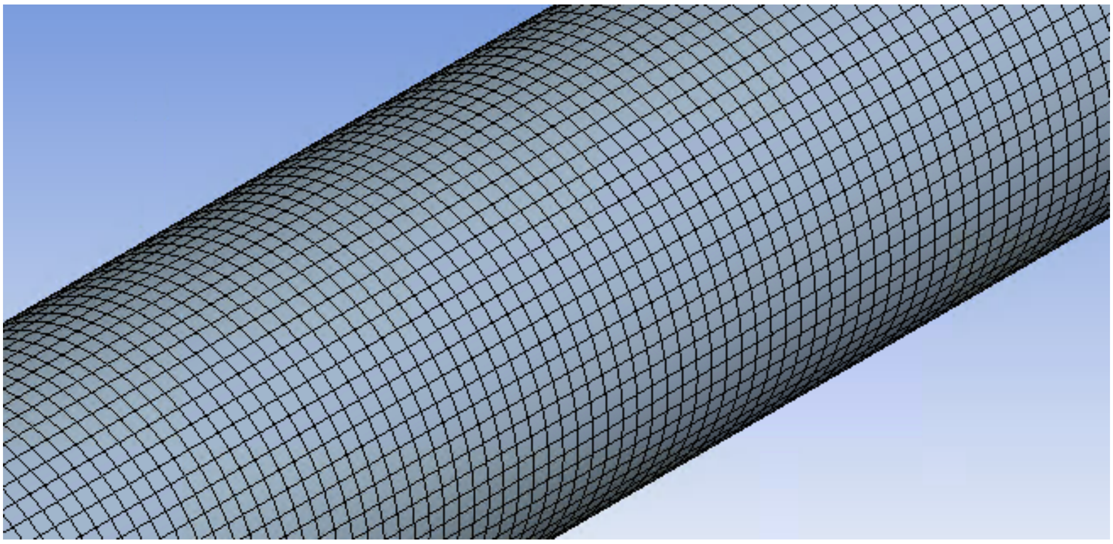

Figure 40 - Example of the Hex mesh used for the stationary domain

As the information from the inlet and outlet sections was not of as much interest as the rotating section, the node and element sizes within are larger (Fig. 40). This is partly to lower the overall amount, as to keep computational requirements down and help reduce the time needed for the solver to reach convergence. Although the size used was small enough not to cause any inaccuracy due to large jumps in size between the stationary and rotating domains (Fig. 41).

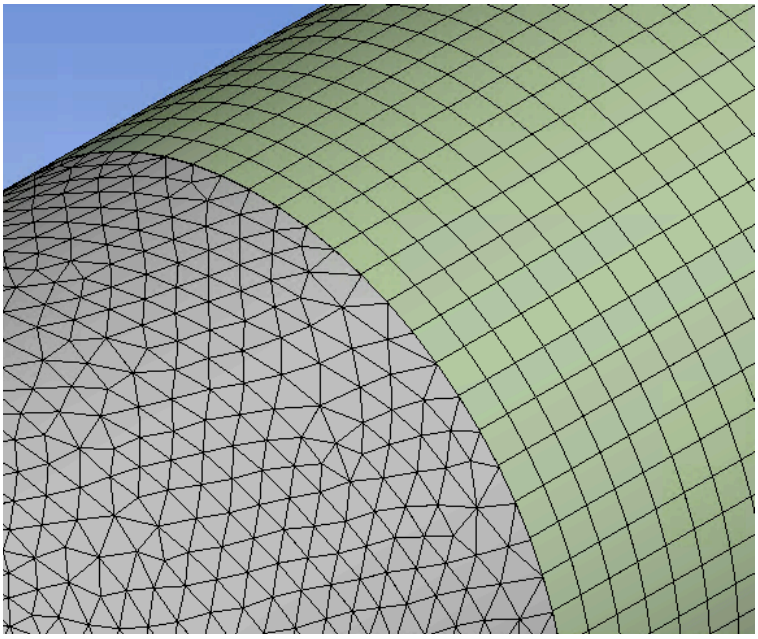

Figure 41 - Junction where rotating mesh connects with the stationary mesh

The sweep feature was used for both inlet and outlet sections, which creates a hexahedral dominant mesh, with quad and tri elements created where the hex elements could not be because of the introduction of inflation layers. These were used at the walls of both the inlet and outlet pipe sections to capture the changing velocity gradients near the pipe wall (Fig. 42).

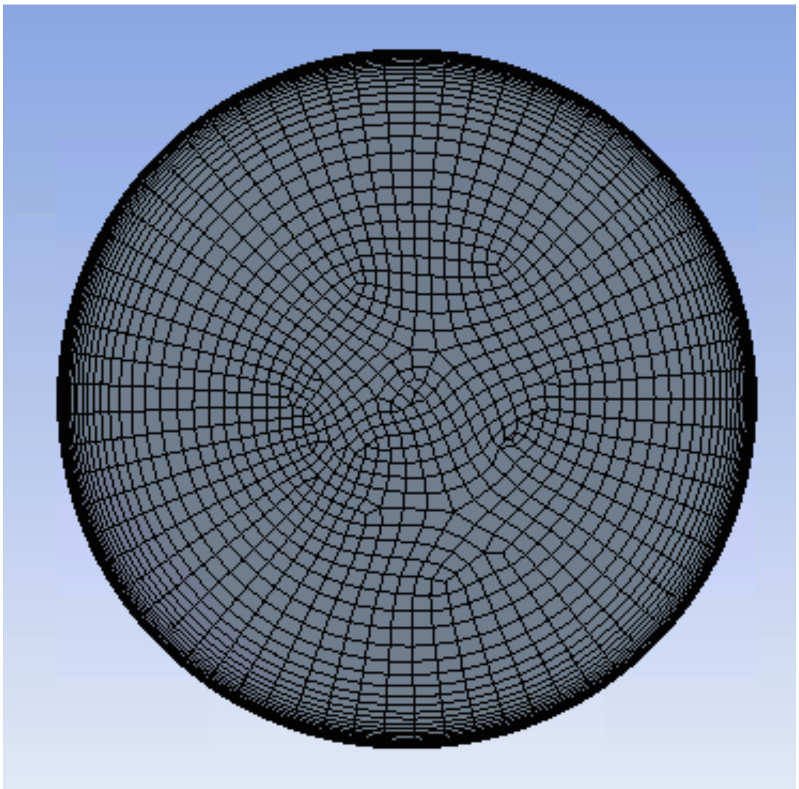

Figure 42 - Inflation layers at the wall

Although the sizes of the inlet and outlet sections are each over 5 times larger than the rotating domain, it contains 2069353 elements and 2104500 nodes. The inlet section has a minimum orthogonal quality of 0.75844 and a maximum skewness of 0.54573. The outlet has a minimum orthogonal quality of 0.54138 and maximum skewness of 0.60027. All of which are well within the acceptable range and should provide a good quality mesh.

8.5 Physical Setup (CFX Pre)

CFX Pre is where the mesh is imported into and the physics of the experiment are added. The way the physics is applied to the experience through the use various domains, boundary conditions and interfaces is vital to achieving a good accurate analysis. Any wrong values or inputs will result in incorrect data or error outputs.

As the aim of this initial CFD simulation was to begin to understand how the screw turbine works, prior to the first stage of experimental testing in NTUA due to commence next year (2016), it was decided to choose a steady state simulation to save time. This was instead of using transient simulation, which creates results for each time step over a specified length. Therefore there will be numerous simulations required using different inputs to collect snapshots of how the device operates over a range of head values.

There are two different types of set ups possible to solve the simulation required. The first is by moving the mesh in the rotating domain around the stationary wall of the turbine at the required rate of rotation to simulate the experiment. By moving the mesh at the correct speed this method accurately depicts the rotation of the turbine.

The second method, which has been chosen for use throughout this project, is referred to as the rotating frame of reference method. This method is able to model the entire domain as rotating with a specified rate of rotation, with reference to the stationary walls that surround it (ANSYS, 2009a). In this case, the walls of the turbine cavity and fluid surrounding it are rotating, with the circular pipe shaped enclosure around it acts as the stationary reference frame. When using this method, two extra terms are included with the governing equations for momentum to solve for centripetal and coriolis acceleration (Eqn. 7 and 8) (Schleicher, 2012).

$$\frac{\partial}{\partial t}(\rho\vec{v}_r) + \nabla\cdot(\rho\vec{v}_r\vec{v}_r) + \rho(2\vec{\omega}\times\vec{v}_r + \vec{\omega}\times\vec{\omega}\times\vec{r}) = -\nabla p + \nabla\cdot\bar{\bar{\tau}}_r + \vec{F} \tag{7}$$

$$\frac{\partial\rho}{\partial t} + \nabla\cdot\rho\vec{v}_r = 0 \tag{8}$$

This simulation was set up to provide good starting values to begin understanding the performance and flow interaction with the turbine in these submerged, pressure based situations. Following this computational analysis, scale model testing will be carried out in partnership with NTUA to prove the validity of the current simulations, and then, the next stage will be to advance the CFD setup (using the current results as a starting point) through the use of more computationally demanding transient moving mesh method.

As there are no existing computational or model testing results (on the public domain) where the Archimedes screw turbine has been used in this method (fully submerged, with a pressure head) the model and set up validity could not be honed to exactly mirror existing data. If it had been available, each of the different CFD set up methods would have been created and compared with the data to determine which set up method provides the most accurate results.

8.5.1 Domain Setup

Both domains were set up using 'Water' as the single fluid material, as the device will be constantly submerged, there is no need for multiphase mixtures with air.

8.5.2 Boundary Conditions

Every domain must have boundary conditions applied to it. These can be in various forms of inlets, outlets, walls or openings. If no boundary condition is applied, they will be automatically applied, however these are frequently not correct for the specific experimental setup required (ANSYS, 2009b).

8.5.3 Stationary Domain – Boundary Conditions

The stationary domain contains both the inlet and outlet. The inlet is a pressure based boundary condition, with the value calculated based on the pressure head at the inlet. To mimic the possible experimental setup that will be available for model testing in NTUA, the inlet head is kept constant at 1.5m. Using Eqn. 9 and the set head value the pressure could be calculated:

$$Pressure = \rho g h \tag{9}$$

where:

ρ = the density of water

g = acceleration of gravity

h = height of water head

The outlet boundary condition was treated as an entrainment style opening. This was chosen as it operates much like the pressure outlet and is appropriate as the flow is being pulled through the outlet and as it is in the wake of the flow, the exact direction is unknown

(ANSYS, 2009c). Again, the value of pressure at the outlet was calculated using the same pressure equation. The value of this outlet pressure will be modified throughout the testing to simulate the changing head level at the outlet. The pipe walls were treated as no slip, smooth walls throughout all of the initial tests.

8.5.4 Rotating Domain – Boundary Conditions

In order to set up the rotating frame of reference, the turbine was set up as a rotating, no slip wall, with no wall velocity so it would be rotating at the same rate as the whole domain. The surrounding wall of the enclosure was set up the same, except it was given a wall velocity as a counter rotating wall, which means it is treated as stationary in respect to the rotating domain, because it effectively rotates in the opposite direction at the same rate to nullify the set domain rotation rate.

8.5.5 Turbulence

Modelling turbulence is a difficult task and still has not been fully understood or perfected, with no ideal model available, however it is required in almost all engineering fluid flow simulations to predict how turbulent fluctuations will affect the flow. Turbulence is a dominant phenomenon, meaning that when it is present, it greatly affects other phenomena; therefore it is critical to model it as accurately as possible (Sodja, 2007).

As each model has good and bad points it is important to choose the turbulence model that is most suitable for the project. The turbulence model used was the Shear Stress Transport (SST) k-ω model developed by Menter. This is a two equation model, of which the non conservative form of the model can be written algebraically in Eqn. 10 and 11 (NASA, 2013).

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho u_j k)}{\partial x_j} = P - \beta^* \rho \omega k + \frac{\partial}{\partial x_j}\left[(\mu + \sigma_k \mu_t)\frac{\partial k}{\partial x_j}\right] \tag{10}$$

$$\frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho u_j \omega)}{\partial x_j} = \frac{\gamma}{\nu_t}P - \beta \rho \omega^2 + \frac{\partial}{\partial x_j}\left[(\mu + \sigma_\omega \mu_t)\frac{\partial \omega}{\partial x_j}\right] + 2(1-F_1)\frac{\rho \sigma_{\omega 2}}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j} \tag{11}$$

This model combines both an equation that operates well at boundaries near walls and a second equation, which operates well in areas away from wall boundaries (Innovative CFD, 2012). This is a common choice with turbo machinery applications as it is able to predict how rotating flows among other types will react.

8.5.6 Interfaces

Two interfaces were required for this setup. One connecting the stationary inlet domain to the rotating turbine domain and the second required between the rotating turbine domain and the stationary outlet domain. These were necessary to connect the hexahedral mesh from the swept inlet and outlet sections, to the tetrahedral mesh used to create the rotating domain and also to cope with the transition from stationary to rotating.

To successfully connect to the two different mesh sections, the GGI connection method was used. This is necessary when the nodes either side of the interface are not exactly aligned which occurs when two meshing methods are used side by side.

The interfaces were given the frame change model of Frozen Rotor as the rotating and stationary domains share the fixed pipe wall, however the frame of reference is changing due to the movement of the rotating domain. There is also no need to include pitch change as the components are directly connected and the shapes of the two domains matching perfectly with no overlap (SHARCNET, 2015). Therefore the option was set to None.

8.5.7 Monitor Points

In addition to the variables calculated by the CFX solver, extra monitor points were added to quantify two important values that will be used to compare the performance of the initial turbine to how the geometrical variations compare to one another in terms of output. As the role of the turbine is to produce energy, the most important value to know is the devices ability to produce an output power.

To be able to calculate the power produced by the turbine, the torque value must be known as seen in the CEL expression used:

Power (W): trq * ω (rad/s) (11)

[rad]

Where:

Trq = Torque [N.m]

ω = Rotational rate (rad/s)

To monitor torque accurately a coordinate frame was needed about the axis of rotation for the turbine, in this case it was through the origin of both the circular spirals used to create the blade helices and the origin on the cylinder used to create the inner diameter of the device. Using this new coordinate frame, the expression to monitor torque was:

Torque [N.m] = torque_z_Coord 1()@Turbine

Where the z axis of Coord 1 is in line with the axis of rotation.

8.6 Solver Set up

Two different methods were used to actually run the solver, the first and most common was using the workbench graphical user interface (GUI) to access the CFX solver and run the program through a single computer. During this, the Platform MPI Local Parallel run mode was used to create 4 partitions so each partition could be assigned to a processor core.

The second method took advantage of the processing power of Lancaster Universities' supercomputer otherwise known as the High End Computing Cluster (HEC). Although most of the tests were run on an individual machine and not on the cluster, it was useful to know how to set up and use the extra processing power for the future stage of the project.

By conducting two identical tests, it was determined that double precision was not needed, as it made a negligible difference to the results. As this setting uses much more processing power, it was decided to only use single precision for the duration of the project.

8.7 Mesh Sensitivity Analysis

The creation of the mesh requires a delicate approach with a smaller mesh providing greater accuracy, however it also requires greater computer power and takes longer to compute each run. Therefore it is important to use a mesh size which is small enough to capture the required fluid flow phenomena accurately, without being too small that it takes uses more computational power and time than is necessary. It is important to conduct a mesh sensitivity analysis to determine the point where increasing the number of elements within the mesh does not affect the results. Studies like this are common with all CFD projects and are an important part of the process to produce an accurate set up (Schleicher, 2012).

To do this, four different mesh setups were created and analysed with sizes ranging from relatively large to very small. Each individual mesh was created and set up using the same method and boundary condition values, with the primary modification being the size. The main area of interest for the study was the interaction of the flow around the rotating domain, especially where the fluid comes in to contact with the turbine blade, therefore it was important to make sure this was the area of the mesh that was being reduced in size.

The number of elements within the various mesh set ups ranged from approximately 1 million to a maximum of 5 million elements. The necessary values for mesh quality (skewness and orthogonal quality) were kept within the acceptable range for all four different meshes. Details for each of the different meshes are outlined in table 7. With the assigned mesh number increasing numerically as the size was reduced.

Table 7 - Mesh statistics for the mesh sensitivity analysis

Mesh Number	Number of Nodes	Number of Elements	Orthogonal Quality (min)	Skewness (max)
1	368106	927218	0.18547	0.89987
2	1553898	2117163	0.17668	0.89997
3	2451415	3025207	0.17739	0.89991
4	4657748	5284134	0.19515	0.89993

Once created with the same physical setup and boundary conditions each mesh was computed through the ANSYS Solver and the values for torque and power monitored by the Solver. By comparing the values obtained by the solver, it is possible to find where the size of the mesh does not affect the output results. The variations in torque for the different mesh numbers can be seen in Fig. 49.

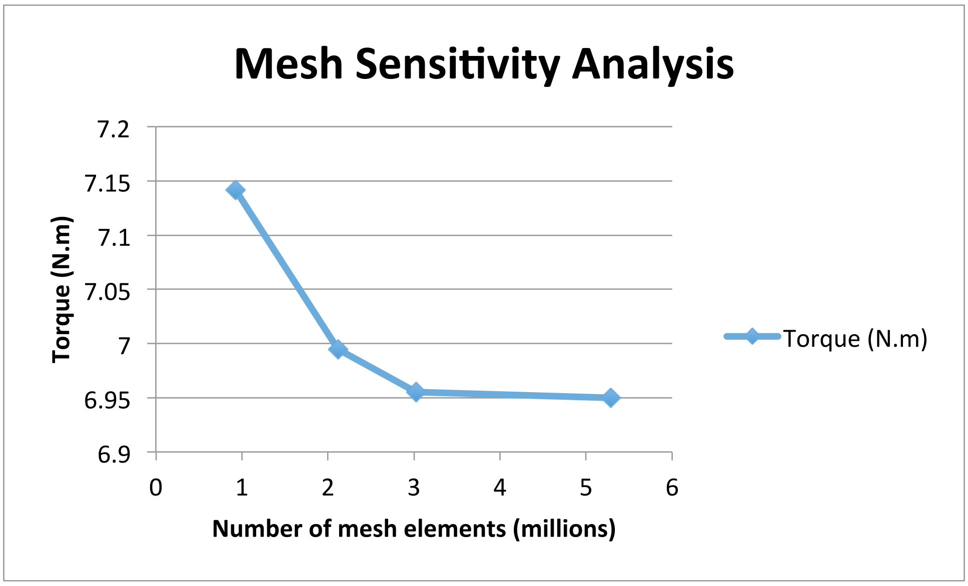

Figure 43 - Mesh sensitivity analysis

As seen in (Fig. 43) the mesh values first fall rapidly as the mesh size increases, up until approximately 3 million elements. From this point the line begins to even out to approximately a flat line. As the value of torque only changes by a negligible amount between the results for the 3 and 5 million mesh, it means that past the 3 million element mark, decreasing the mesh size does not alter the output values.

The mesh value chosen for use throughout the project was the 3 million element version (mesh number 3). It was decided that the difference in output torque value between the 3 and 5.3 million element mesh was too small to necessitate its use, due to the added computational time that would be required for the smaller mesh.

9 Results and Discussion

The following section contains the results from the CFD analysis carried out. Throughout the testing process, each of the geometric parameters, which were found to affect the performance of the turbine, have been modified (see section 7.4). For each test, the results have been compared with one another and existing data where possible, to understand both how the modifications affects the performance for use as a tidal range device and how this compares with devices operating with partial submergence without a pressure head.

The CAD geometries created and modified were created and designed to act as a 1:1 scale between computational analysis and physical model testing to be carried out at a later stage.

9.1 Initial Reference Turbine and Testing Method

Before the geometry optimisation stage could begin, a single reference geometry had to first be created for all of the modifications to be compared to (Fig. 44).

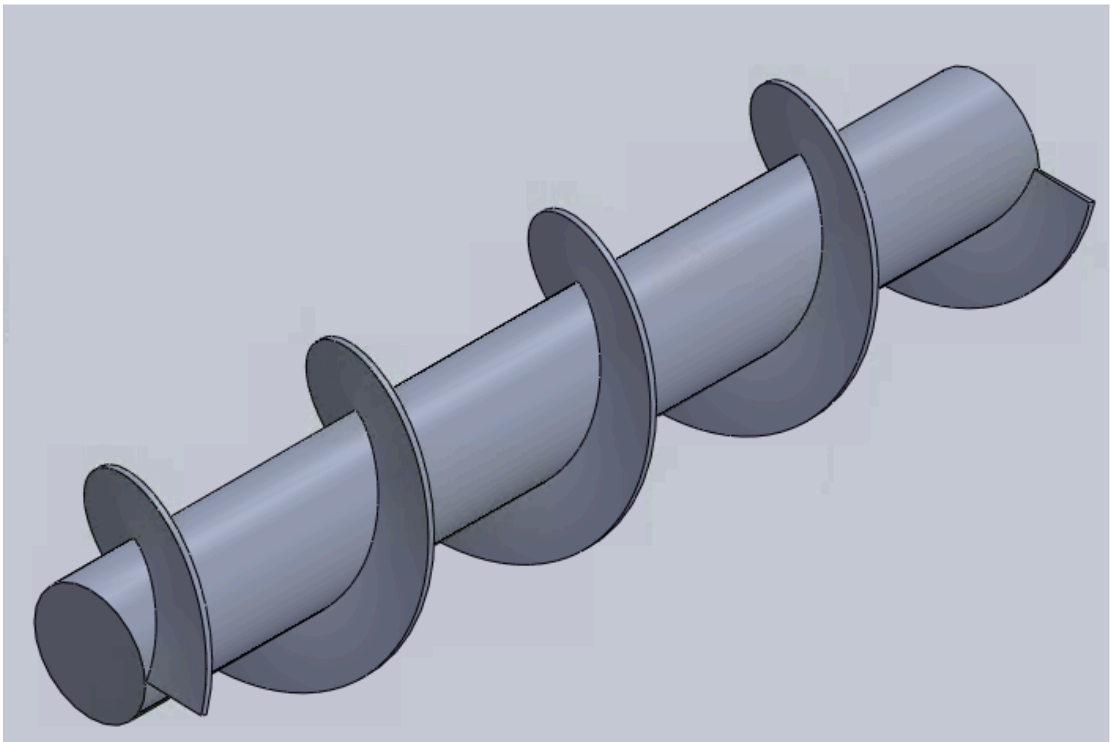

Figure 44 – Reference CAD geometry

The results obtained from the tests with this geometry form the baseline for all subsequent modifications to be compared to. The main constraint that was set was the 0.2m outer diameter. It was decided that this would be the maximum value as any measurement larger than this would reduce the effective head difference during the physical testing phase. All of the other geometric values were chosen based on arbitrary values. Details of the other geometry variables can be seen in Table 8. The values were chosen based on the future model testing facilities available, so the computational and physical testing model could be built the same.

Table 8 - Reference turbine geometry and set up values

Symbol	Description	Value
D	Outer Diameter	0.2m
d	Inner Diameter	0.1m
δ	Diameter Ratio (d/D)	0.5
L	Length	0.8m
Lr	Length Ratio (L/D)	4
P	Pitch	0.2
Pr	Pitch Ratio (P/D)	1
N	Number of Blades	1
G	Thickness of blades	0.005m
N	Rotation Speed	50 RPM

To achieve the required results, the tests needed to cover a wide range of head values to simulate the ever changing tide head and flows. To do this, the boundary conditions were modified and 6 computational runs were completed for the reference geometry and all of the modified versions. Each of these runs has had the outlet pressure boundary condition modified to reflect a change in head difference, while the inlet boundary condition was kept constant. The variations for pressure for each test can be found in Table 9.

Table 9 - Head and pressure values of water at inlet and outlet sections

Test Number	Inlet water Height (m)	Inlet Pressure (Pa)	Outlet water height (m)	Outlet pressure (Pa)
1	1.5	14715	1.3	12753
2	1.5	14715	1.1	10791
3	1.5	14715	0.9	8829
4	1.5	14715	0.7	6867
5	1.5	14715	0.5	4905
6	1.5	14715	0.3	2943

The results for the tests carried out on the reference geometry setup will be used as a starting point to compare the new modifications to analyse their effectiveness. Images detailing the post processing of test 1 results are shown below. Figures 45 and 46 show the velocity streamlines of the flow as it passed through the turbine, with Fig 46 focused on the downstream wake of fluid created by the turbine.

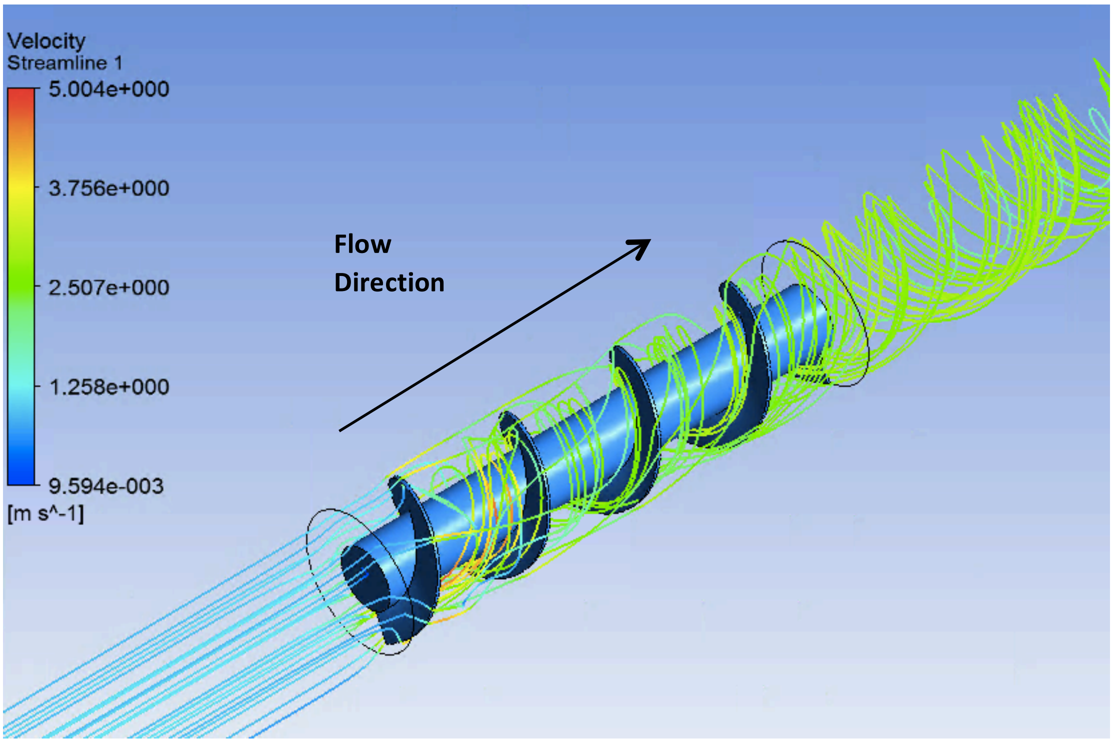

Figure 45 - Velocity streamlines around the turbine

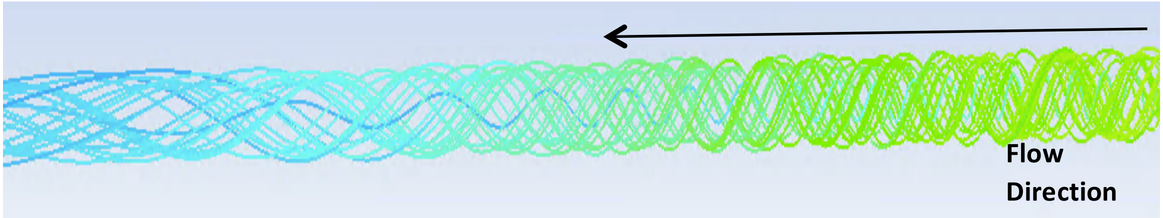

Figure 46 - Wake created downstream of the turbine

As expected there is an area of high velocity flow as the water enters the turbine. As the fluid exists the turbine it is highly turbulent, forming a spiral wake as soon as it exits and travels towards the outlet boundary condition. However, it does begin to even out the closer the flow gets to the outlet.

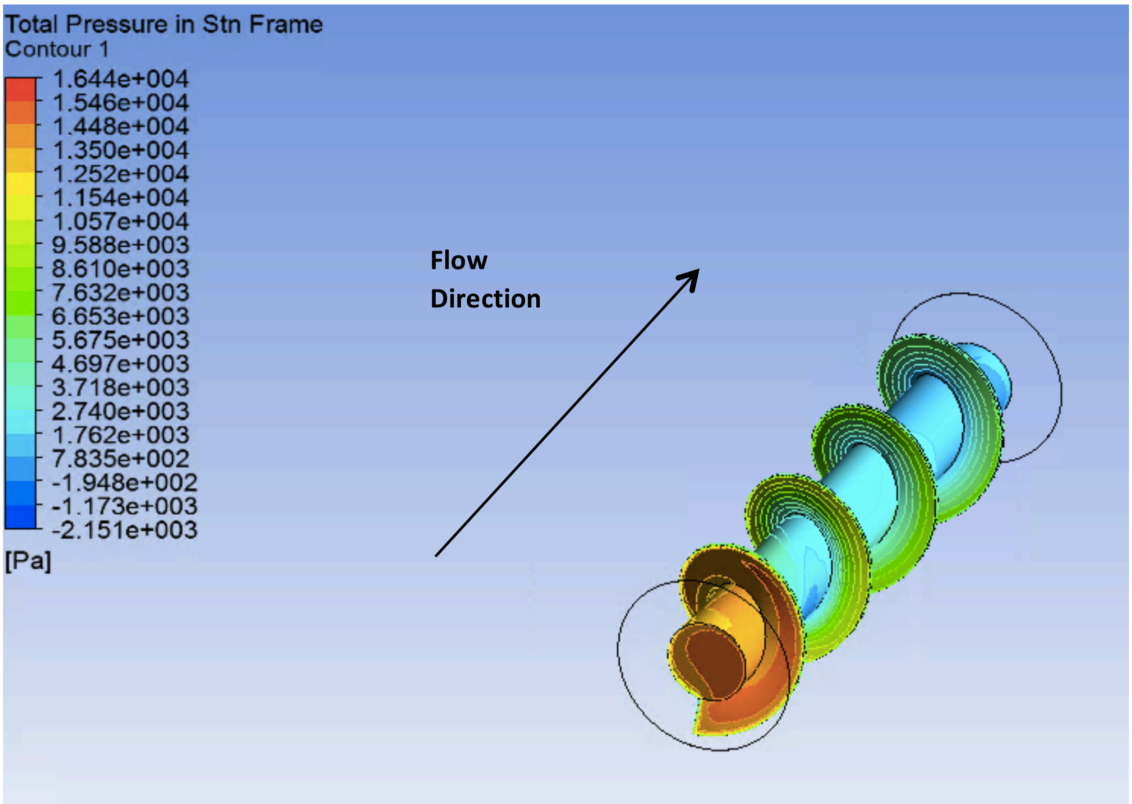

Figure 47 - Pressure contours over the turbine

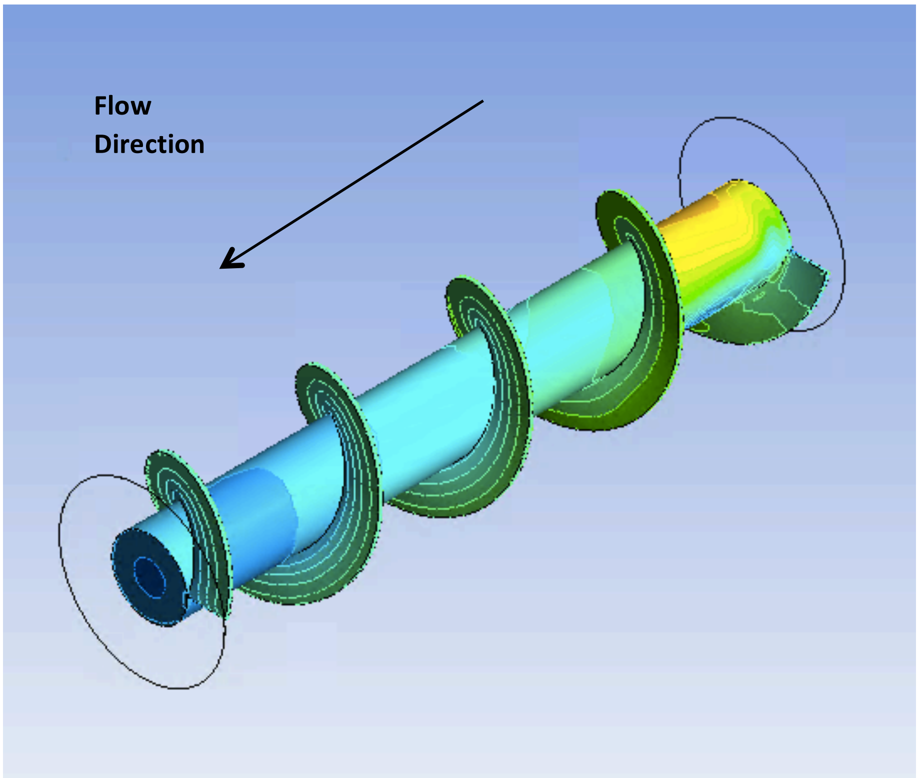

Figure 48 - Pressure contours over the turbine

Figures 47 and 48 outline the pressure distribution created over the turbine blade. Once more, as expected, mirroring the areas of high velocity, the areas with the highest pressure values are close to the leading edge of the turbine blade where the flow first comes into contact with the device. This too would was expected.

For the experiments the main components monitored were the torque created by the turbine and the power. For a turbine designed for power generation, these are by far the most important parameters to know and therefore will be the values compared between each computational run and geometry modification. The results from the reference geometry tests are outlined in Table 10 and (Fig. 49).

Table 10 - Torque and power values created by the reference geometry for various head differences

Test Number	Head difference	Torque Value (Nm)	Power (W)
1	0.2	1.4359	7.5184
2	0.4	2.8599	14.964
3	0.6	4.2697	22.356
4	0.8	5.6704	29.69
5	1	7.0788	37.065
6	1.2	8.4974	44.492

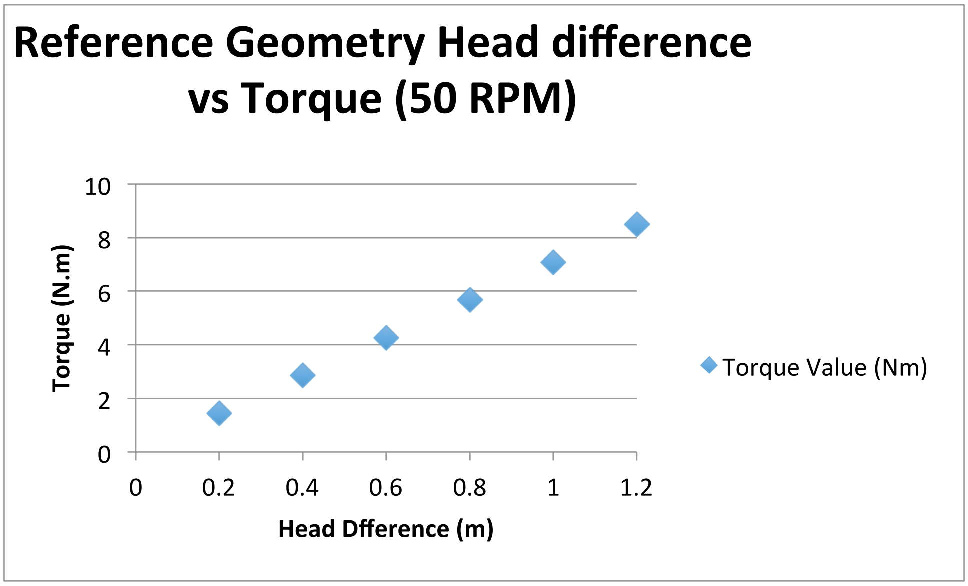

Figure 49 - Graph detailing how increasing the head difference affects torque production

The head difference axis label from (Fig. 49) is based on the difference between the water height levels at the inlet and outlet section (head difference = inlet water height – outlet water height).

From the results obtained, it is clear to see that an increase in the head difference directly relates to an increase in torque (and therefore power output). This was predicted before the tests, as the ability to produce power for all tidal range projects is very closely linked to the operating head difference. From the graph (Fig. 49), it can be estimated that this relationship is almost linear.

9.2 Revolutions per minute (RPM) and Mass Flow Rate

Modifying the RPM of the device does not only affect the rate of rotation, but for an Archimedes screw turbine, it also drastically changes the mass flow rate through the device. The mass flow rate through the turbine can be theoretically calculated, based on both the rotation rate and the geometry of the device. This is also valid for the geometry and operating method of the screw turbine for a partially submerged device operating in the usual method.

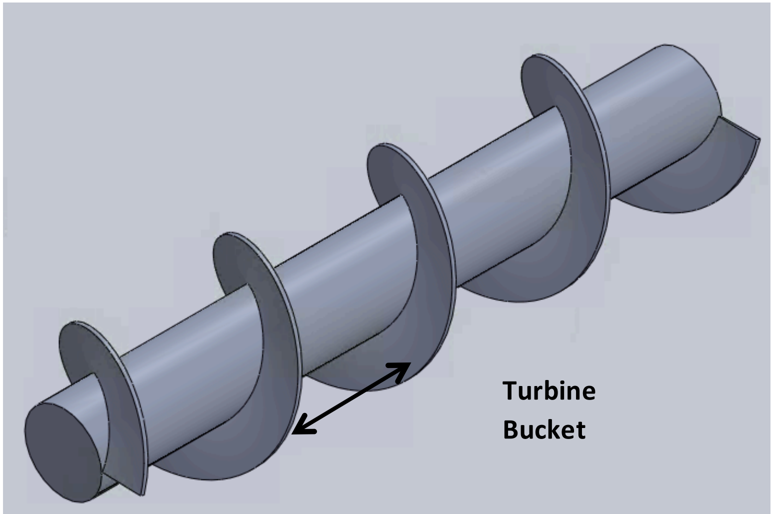

Figure 50 - Archimedes screw bucket

When examining the geometry, it is clear to see the relationship between the bucket size (Fig. 50) of the device and the volume of flow passing through it. If the volume of each screw bucket is known, combined with the RPM, the flow rate for the device can be calculated (Eqn. 12) (Lyons, 2014). This also works to find out the RPM, if the volumetric flow rate is known.

$$Q = n_b . V_b . \omega \tag{12}$$

Where:

Q = Volumetric Flow rate (m^3/s)

n_b = Number of buckets

V_b = Volume for each bucket (m^3)

ω = Rotational rate (rad/s)

This formula was originally developed for use with the partially submerged version, where the volume of each bucket was based on the volume of water in each bucket. With the fully submerged version, the volume available within each bucket will always be 100% full.

Previously, Archimedes screw turbines had been limited to low RPM values in the region of 25 RPM to avoid unwanted leakage losses and creating excessive turbulence in the partially filled buckets (Renewables First, 2014). However, as the device is being used with full submergence, these drawbacks do not have the same effect. Therefore higher rotational rates than normal were investigated with the tests conducted for 25, 75 and 100 RPM, as well as the reference value of 50RPM. For these tests, the same geometry was used for each test, with only the rotation rate modified. The results from these tests are displayed graphically in (Fig. 51) and Table 11.

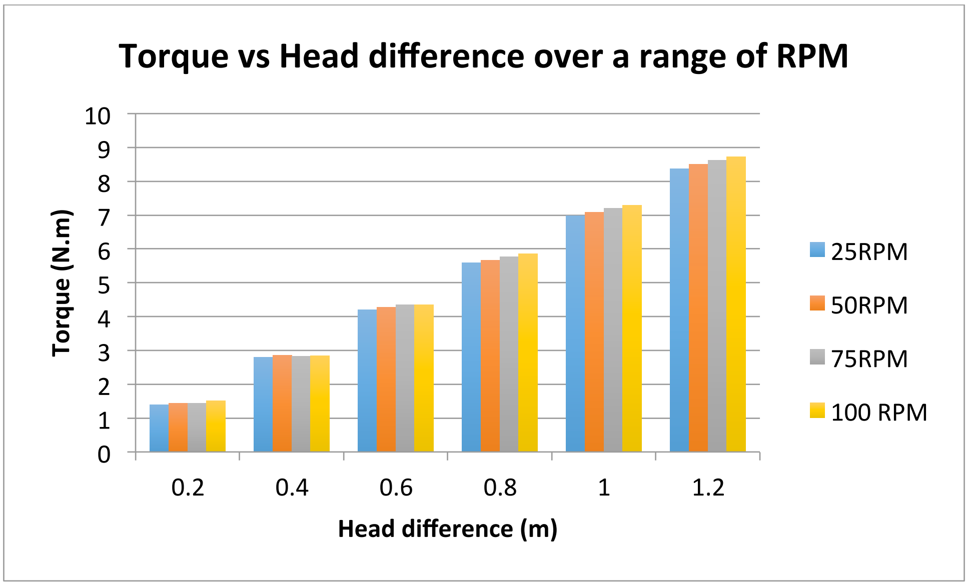

Figure 51 - Torque v head difference graph for various RPM

Table 11 - CFD results for a range of RPM

Test Number	Head difference	Torque (N.m)			
		25RPM	50RPM	75RPM	100 RPM
1	0.2	1.4009	1.4359	1.4397	1.512
2	0.4	2.7981	2.8599	2.9503	2.8449
3	0.6	4.1969	4.2697	4.3472	4.3572
4	0.8	5.5924	5.6704	5.7694	5.8512
5	1	6.9744	7.0788	7.1955	7.2917
6	1.2	8.3681	8.4974	8.6162	8.7249

As can be seen in (Fig 51), as the rotation rate is increased the value of torque produced during each head difference is also increased. However it is easier to view this increase when looking at the power produced (Fig. 52).

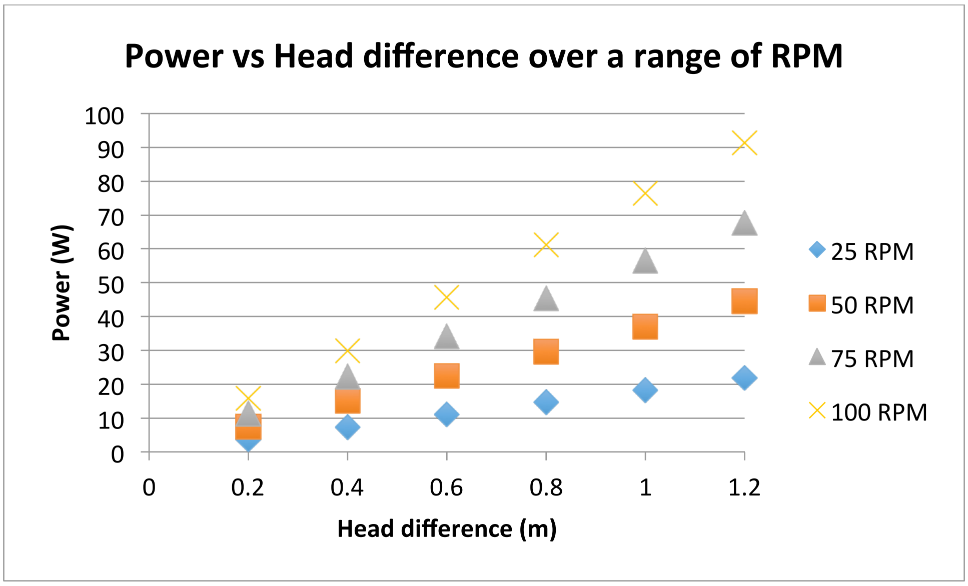

Figure 52 - Power v head difference for various RPM values

This trend was to be expected, as the increased mass flow rate through the system means that there is a greater value of potential energy within the flow accessible for the turbine per rotation. Also the lack of common leakage losses and excessive turbulence sustained by existing screw turbines at high RPM values will not be valid for this set up.

The trend of increasing the rotation and mass flow rate resulting in an increased power and torque values is well documented in literature, with existing data also showing the same trend. However, one test, which investigated a very wide range of RPM values on a theoretical design, found there was a limitation to how far this trend works (Fig. 53).

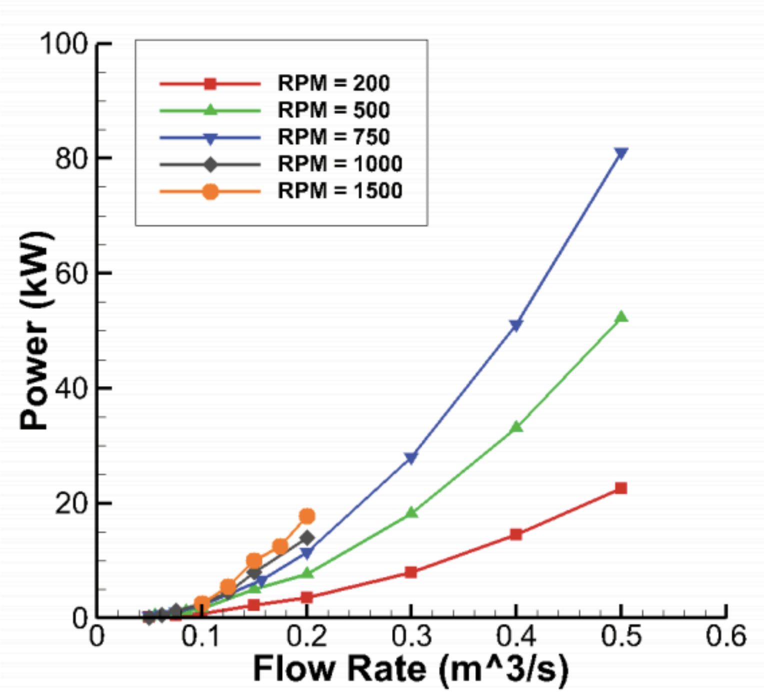

Figure 53 - effect on power generation for various volume flow rates and RPM values (Schleicher, 2012)

In this experiment, although the trend occurs, the most extreme values for RPM result in a vastly reduced power output. This was also seen during physical testing carried out by (Lyons, 2014), where the highest values of volume flow rate did not equal the peak power production value, although for much of the testing, it did follow the expected trend. Therefore, to find the optimum RPM and mass flow rate, further tests would need to be conducted to find where the maximum power generation point would occur.

Due to the computational set up, increasing the rotational rate also increases the mass flow rate through the device. During scale model testing the rate of rotation will only be able to be measured, rather than controlled. However, the mass flow rate entering the device can be controlled to increase or decrease the value as needed.

9.3 Diameter Ratio

As previously stated, the outer diameter measurement was kept constant (0.2m) throughout the testing. Therefore, in order to change the diameter ratio, the inner diameter was the value changed. By changing this ratio, the size of the inner cylinder is either increased or decreased in respect to the outer maximum. Other than this modification, the other geometrical parameters remained the same as the reference, including the 50 RPM. The two different geometries created with diameter ratios of 0.75 and 0.25 can be seen in (Fig. 54) and (Fig. 55)

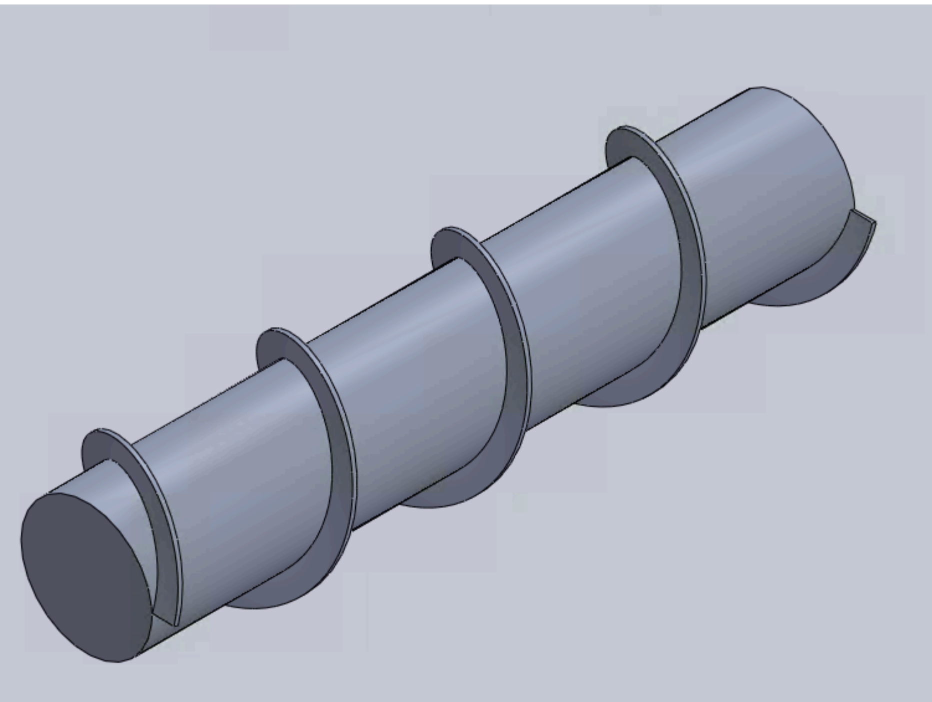

Figure 54 - Diameter ratio 0.75

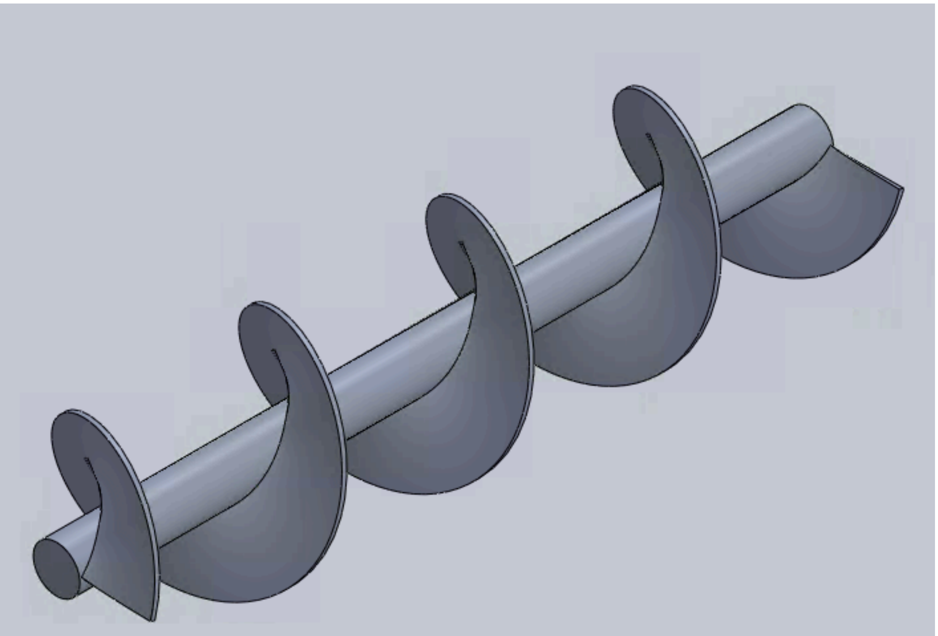

Figure 55 - Diameter ratio 0.25

In the same manner as the other tests, the effect of modifying the head difference was changed and the torque measured. The results can be found below (Fig. 56) (Table 12).

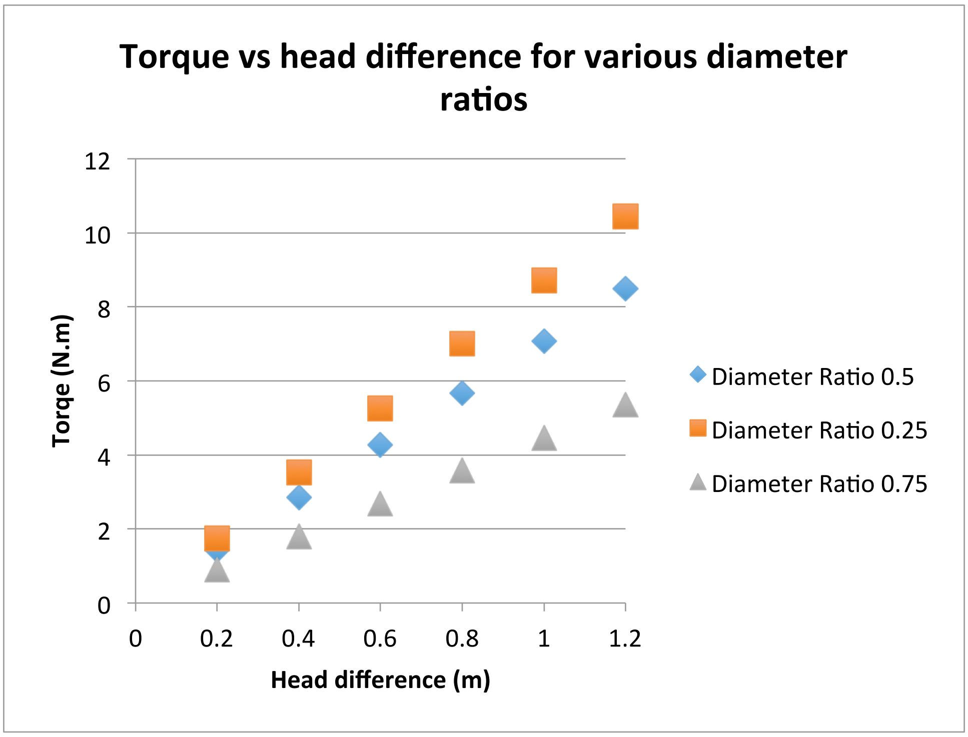

Figure 56 - Torque v Head difference for a range of diameter ratios

Table 12 - CFD results for a range of diameter ratios

Test Number	Head difference	Torque (N.m)		
		Diameter Ratio 0.25	Diameter Ratio 0.5 (Reference)	Diameter Ratio 0.75
1	0.2	1.7476	1.4359	0.90594
2	0.4	3.5191	2.8599	1.795
3	0.6	5.2547	4.2697	2.683
4	0.8	7.0094	5.6704	3.5737
5	1	8.7103	7.0788	4.468
6	1.2	10.45	8.4974	5.3621

It is clear to see from the output data that the diameter ratio is a very important parameter in terms of performance. The results show that the smaller ratio values provide far greater performance characteristics than the larger version. Therefore it can be assumed that an increasing diameter ratio decreases performance over the whole of the operating characteristics.

This trend is emulated in experiments carried out for a normal, partially filled screw turbine. Where the decrease in diameter ratio consistently resulted in an increase in peak torque production (Fig. 57)

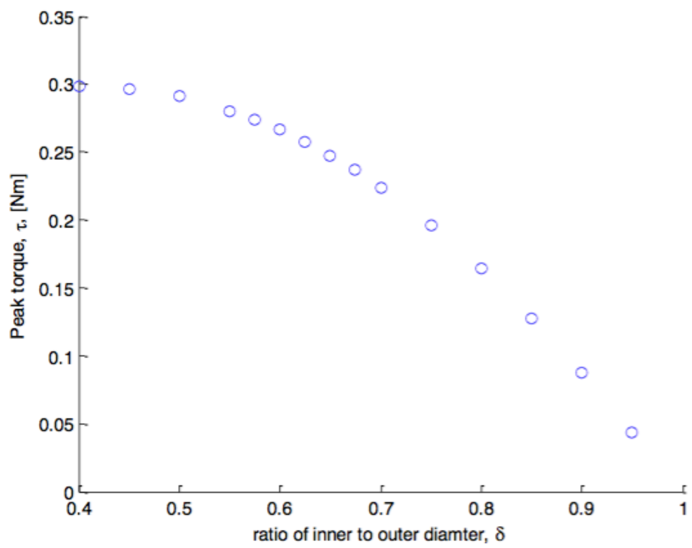

Figure 57 - Ratio diameter modification compared to peak torque produced (Lyons, 2014)

As the diameter ratio increases, the maximum volume of water within the turbine decreases, therefore there is less force acting on the blades to aid the production of torque. This is especially important when operating horizontally as without the hydrostatic force created by the incline, the primary factor creating the torque is the force within the velocity of the fluid flow.

However, the optimisation process will not be as simple as decreasing the diameter ratio as small as possible. The inner diameter section is a vital part in providing structural stability, and any significant lowering in this value would require extensive structural analysis to analyse how the reduction would affect the structure to confirm if there would be any chance of failure due to the forces and pressures applied.

It would seem as though the optimum value for the inner diameter would be the smallest; however, the minimum value possible will always be constricted by construction requirements, as it is vitally important to have a reliable and long lasting device.

It is not clear if this trend is valid when both the inner and outer diameter is modifying when changing the diameter ratio. During this testing phase, only the inner diameter is modified to mirror tests that will be conducted in NTUA.

9.4 Length

The length of the device was changed significantly to understand the effects this would have. The pitch of the blade helix was kept the same so although the number of buckets for the turbine, the maximum volume of flow inside the bucket would not change. The length chosen to compare to the 0.8m long reference geometry were 0.4m and 1.6m. These were chosen to represent extreme values away from the reference. The geometries created can be seen in (Fig. 58) and (Fig. 59).

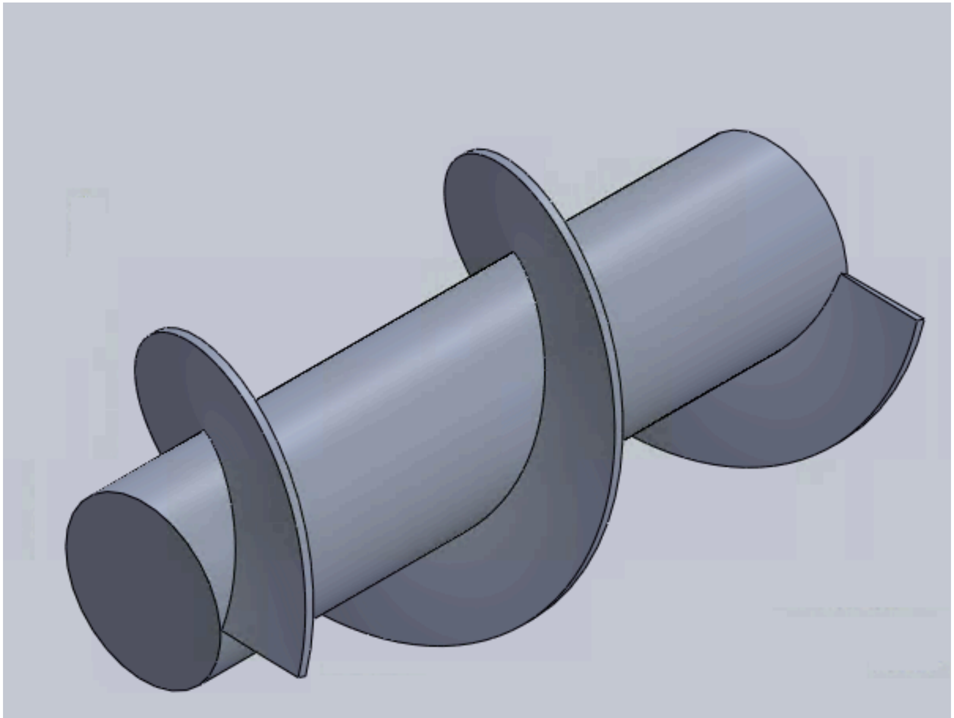

Figure 58 - Turbine length 0.4m

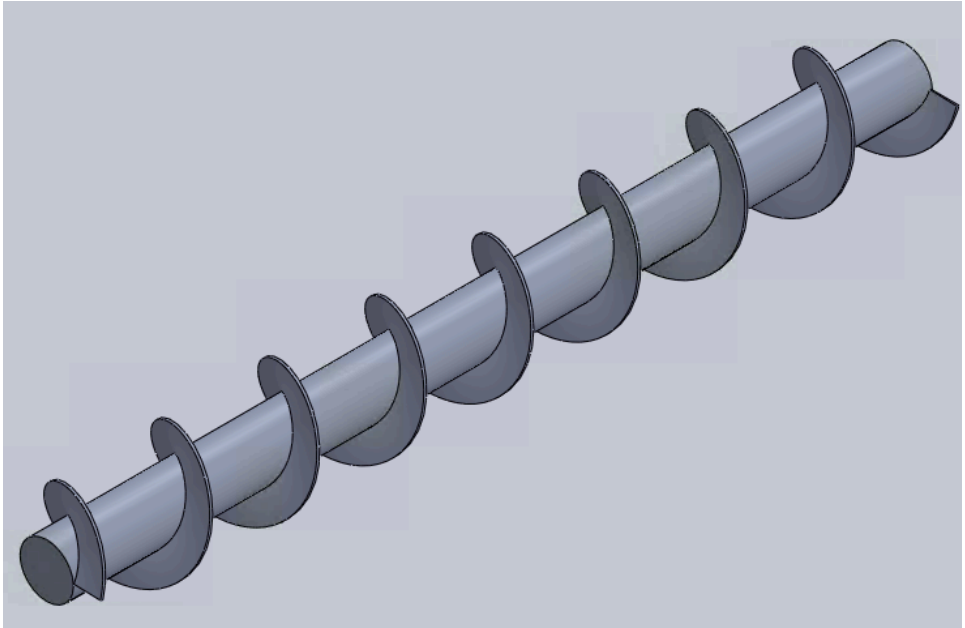

Figure 59 - Turbine length 1.6m

The resulting torque value results from the 6 head differences can be seen in (Fig. 60) and Table 13.

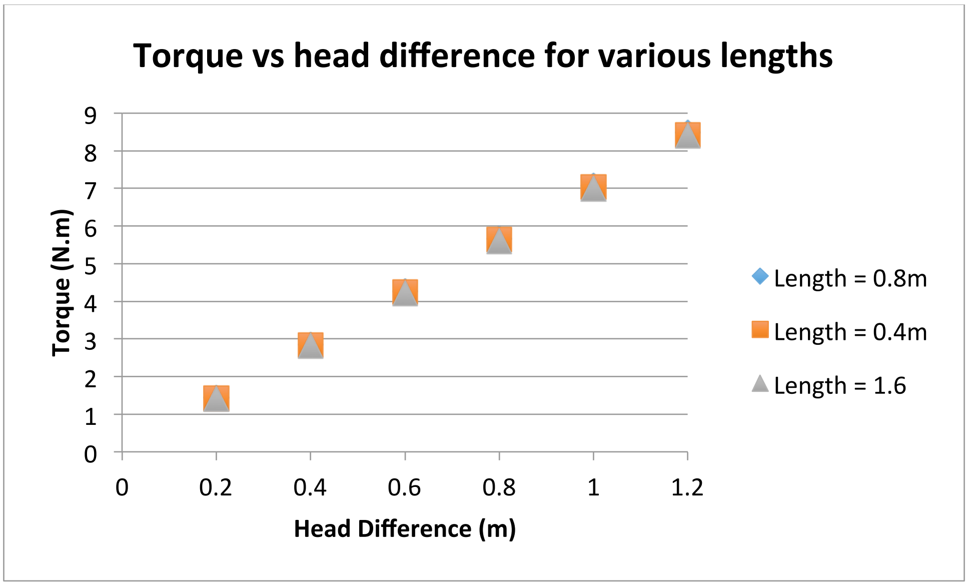

Figure 60 – Torque v Head difference for a range of lengths

Table 13 - CFD Results for various turbine lengths

Test Number	Head difference	Torque (N.m)		
		Length = 0.4m	Length = 0.8m	Length = 1.6
1	0.2	1.4303	1.4359	1.3995
2	0.4	2.8409	2.8599	2.8225
3	0.6	4.2477	4.2697	4.2115
4	0.8	5.6449	5.6704	5.6016
5	1	7.0428	7.0788	6.9974
6	1.2	8.4219	8.4974	8.3969

The results of the test show that although the smaller length provides the greatest values of torque, there is only a very small difference between each turbine length. It is believed that although a greater length means the turbine is able to be in contact with the fluid for longer, potentially being able to extract more of the energy from the flow. However, by being in contact with the turbine blades for longer, there is a substantial increase in friction losses incurred.

The reference length performs the best, producing the greatest amount of torque over the length of the results, with the smaller and larger versions producing slightly less. Due to this, it is thought that there is an optimum length where the increased torque produced by the greater length is greater than the reduction in performance due to the friction losses. It is important to find this peak length value, which if increased would result in friction being the domain force, and begin to decrease the performance.

However, having a turbine of reduced size is a positive point, as it would reduce construction costs of the turbine itself and the costs associated to housing the turbine within a lagoon wall. The results show only a very small variation between the wide range of values chosen, meaning it may be best to have the smaller version if no significant increase in performance is found when looking at a number of other lengths.

It has been suggested in literature that increasing the length of the device improves performance (Webber, 2013). This trend was not seen as the longest device performed worst, however, it was claimed valid for a partially submerged device.

9.5 Pitch Ratio

By altering only the pitch ratio, the bucket size increases and the number of buckets the turbine has decreases (for a fixed length). With the reference pitch ratio of 1, the two geometries to be analysed had a pitch of 0.4m and 0.1m giving pitch ratios of 2 and 0.5 respectively. The two CAD geometries created can be seen in (Fig. 61) and (Fig. 62).

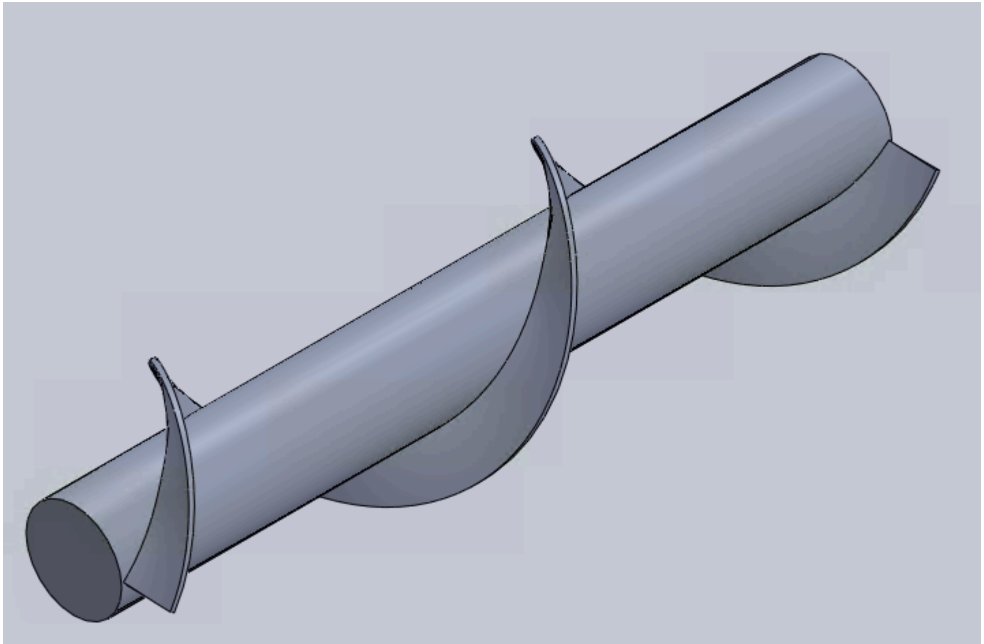

Figure 61 - Pitch ratio 2

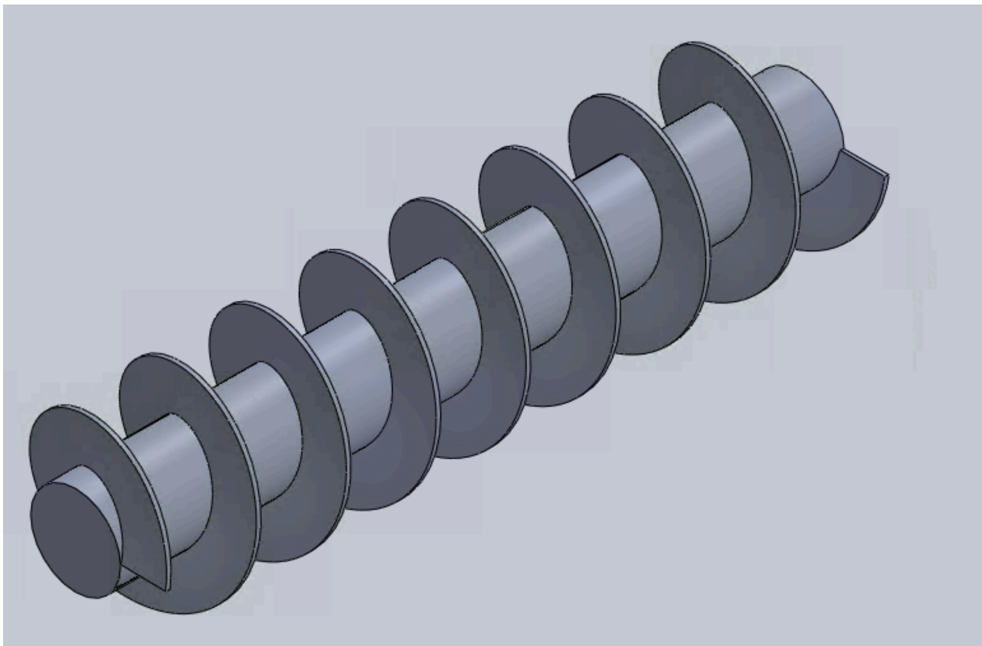

Figure 62 - Pitch ratio 0.5

The results from the CFD tests 1 to 6 are displayed below (Fig. 63) and Table 14.

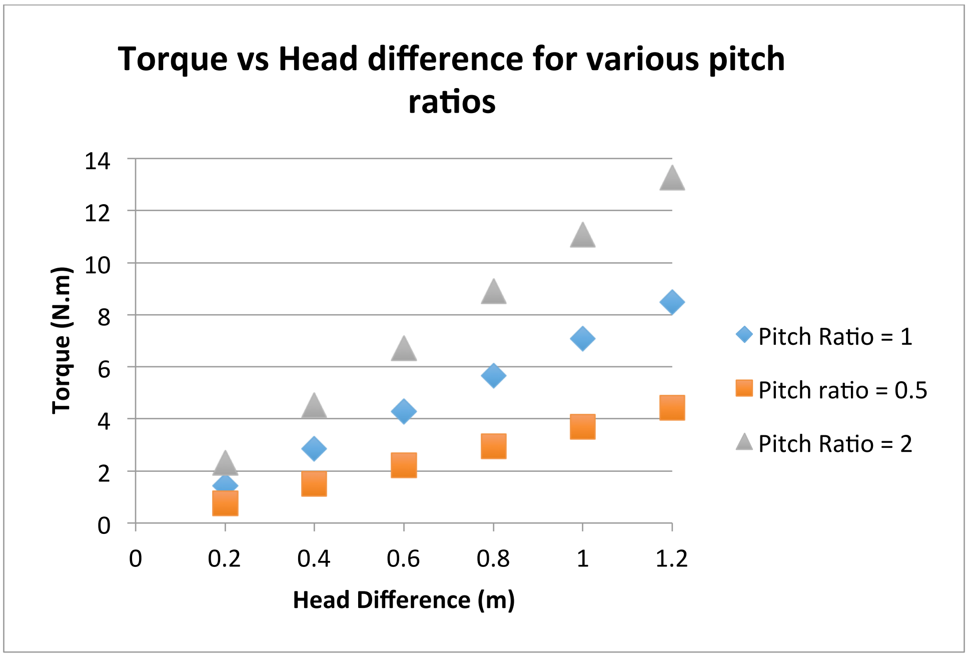

Figure 63 - Torque v Head difference for a range of pitch ratios

Table 14 - CFD results for a range of pitch ratios

Test Number	Head difference	Torque (N.m)		
		Pitch Ratio = 1	Pitch ratio = 0.5	Pitch Ratio = 2
1	0.2	1.4359	0.75955	2.3085
2	0.4	2.8599	1.4883	4.5192
3	0.6	4.2697	2.2159	6.7133
4	0.8	5.6704	2.9586	8.8995
5	1	7.0788	3.694	11.075
6	1.2	8.4974	4.4293	13.255

These results show a clear trend between the pitch ratio and the production of torque. As the pitch ratio increases and the number of buckets per length decreases, the torque produced is greater. This trend is backed up with existing data both experimentally and with theoretical CFD results for a partially submerged version, with the experimental data shown in (Fig. 64) below.

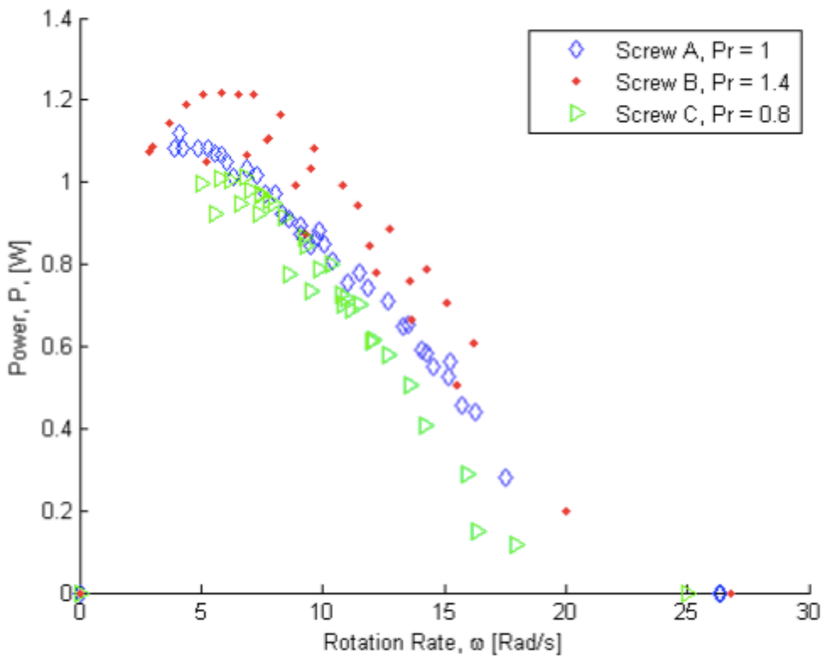

Figure 64 - Experimental testing of Archimedes screw turbine with various pitch ratios (Pr) (Lyons, 2014)

It is however, expected that this trend is not valid indefinitely, and there will be a peak value for pitch ratio, where increasing it any future would result in a lower production of torque.

Once more, this trend found for screw turbines is contrary to the findings of (Rorres, 2000) and his work with the screw pump. During this research, Rorres found that for a pump, the optimum pitch ratio for a single bladed device is below 0.15.

As the pitch ratio increases, the volume per bucket increases, meaning there is more flow acting on the blade per bucket and less surface area of the turbine for the flow to come in direct contact with and therefore incur friction losses. It is assumed however, that a minimum value of pitch ratio must include one full bucket.

9.6 Number of Blades

The amount of blades or helices the turbine contains was modified to compare against the single bladed reference geometry. Both 3 and 5 blade designs were investigated and the geometries can seen in (Fig. 65) and (Fig. 66).

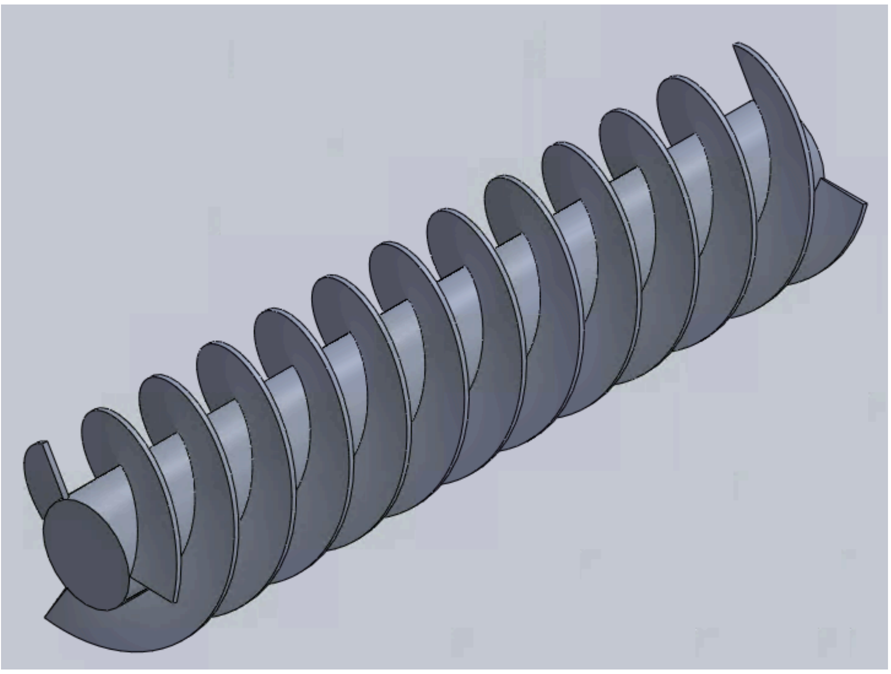

Figure 65 - 3 blade geometry modification

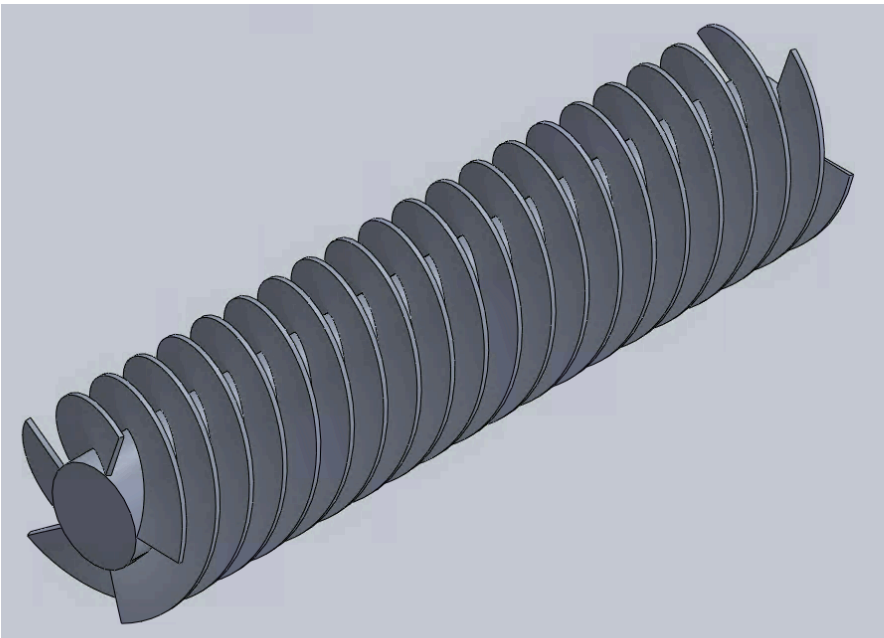

Figure 66 - 5 blade geometry modification

The effect of altering the blade number can be seen in (Fig. 67) and Table 15.

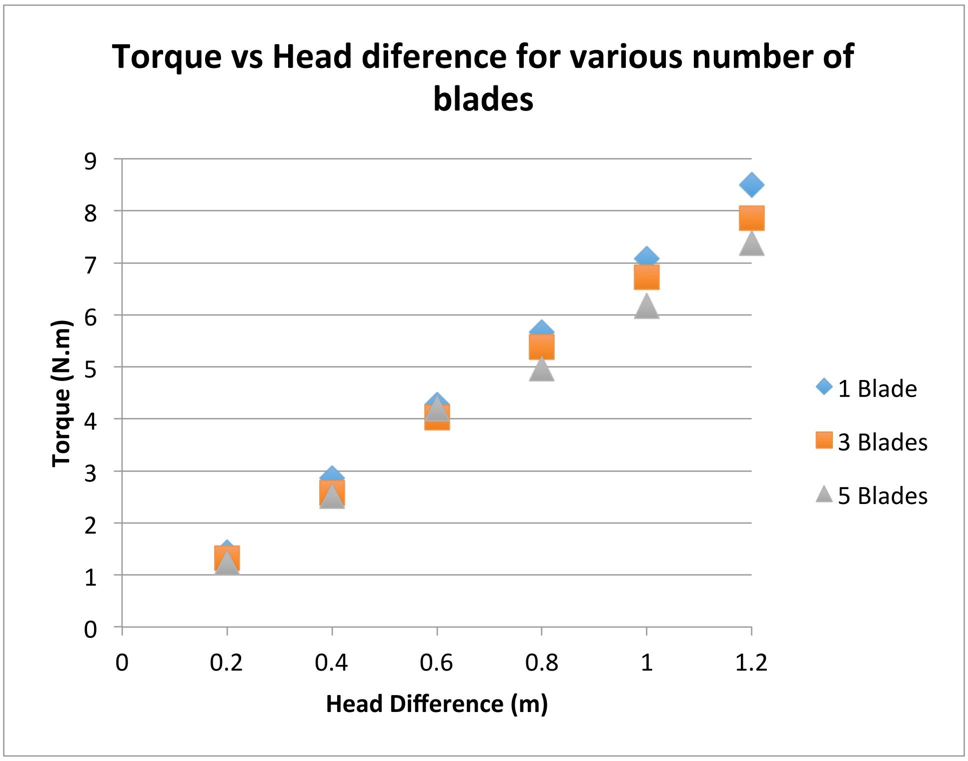

Figure 67 - Torque v Head difference for a range of blade numbers

Table 15 - CFD results for various blade numbers

Test Number	Head difference	Torque (N.m)		
		1 Blade	3 Blades	5 Blades
1	0.2	1.4359	1.3203	1.2397
2	0.4	2.8599	2.5834	2.5181
3	0.6	4.2697	4.0281	4.2056
4	0.8	5.6704	5.378	4.9636
5	1	7.0788	6.7234	6.1707
6	1.2	8.4974	7.854	7.3744

From the results, it can be seen that the introduction of extra turbine blades reduces the torque and power values created. This can be seen as the results unanimously decrease with the added blades. For example in test 6, with a 1.3m head difference the three blade version has a -7.58% change in torque production and the 5 blade version incurred a 13.22% drop, which is almost double.

This is contrary to the findings and predictions of (Rorres, 2000) who predicted the performance of the Archimedes screw pump increased with increase blades. However, this research did not factor in the thickness of each blade, or the loss of volume this would bring. This adds to the fact that although many methods in design work both ways, not all trends that are used for optimising a screw pump can be assumed to be true when designing a turbine.

It is believed that the decrease in torque produced with the extra blades is due to the extra turbine surface area that comes in contact with the flow, and the reduction in fluid volume able to be contained within the turbine at any time. Reducing the turbine area to improve performance has already been seen with the comparisons with pitch ratio, and maximising the volume present within the turbine buckets proved effective with the reduction in diameter ratio.

9.7 Losses

It is expected that the CFD results will over predict the values that will be obtained during the model testing phase. No CFD set up can be as accurate as real model testing due to inaccuracies both as a result of the program used as well inaccuracy brought in by the user for example in the mesh. A smaller and more accurate mesh would have been more precise, however computational and time limitations meant it was not chosen beyond that of the mesh sensitivity analysis as the output value difference was deemed small enough to ignored.

The physical set up will suffer from friction losses caused by the bearing necessary to let the model rotate.

There will also be losses due to the gap necessary between the turbine and the enclosure wall. This gap allows fluid to flow around the turbine rather than through the device and therefore reduces the actual fluid flow through the turbine and this amount does not aid in the production of torque or power. The actual flow of through the turbine can be quantified in Eqn 13.

$$Q_T = Q_i - Q_c \tag{13}$$

Where:

Q_i = Flow rate at the inlet to the turbine enclosure

Q_c = Flow rate passing through the clearance gap instead of the turbine

In each of the model set ups this clearance gap was set to 0.01m from the outer diameter of the turbine and it this value is intended for the physical model. Therefore it is hoped that the difference in these losses for model testing will be minimal, however, as the model has not been created yet, this gap may have to be changed.

9.8 Operational Head

It has been seen throughout the results that although the turbine performs best at high head differences, it is still able to consistently produce torque even at the smallest head difference measured. With the optimised version still being able to produce 18.78% of the peak torque value. The device is able to function well over a wide range of flow values away from the optimum and is also able to perform with a superior efficiency (compared to the kaplan bulb turbine) when the flow values are very low (Fig. 68).

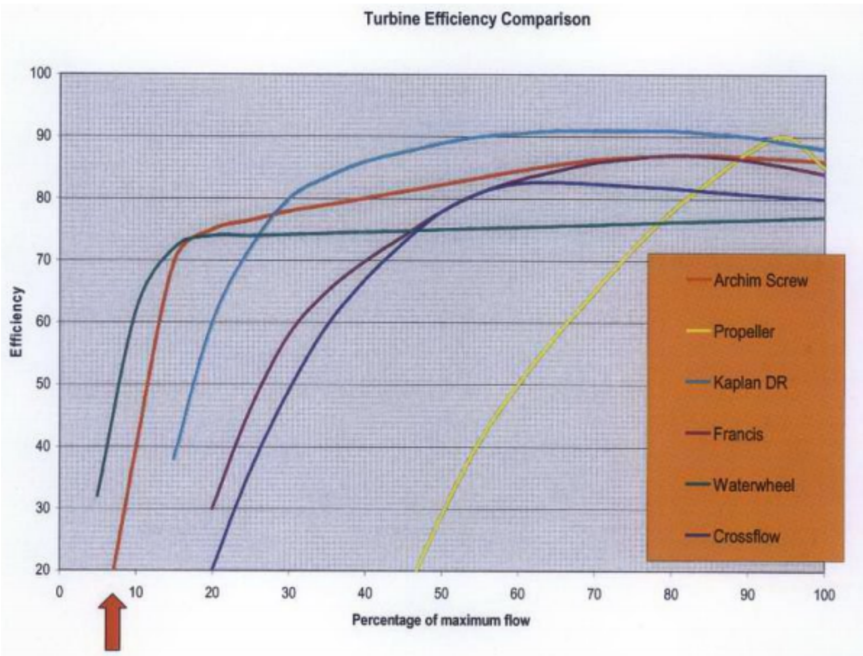

Figure 68 - Performance of various turbines over a wide range of flow values (Mann, 2010)

The ability to do this is vital for any tidal range turbine, where the head and flow characteristics change drastically during each day and especially during spring and neap tides.

The current favourite device for these kinds of projects (the bulb turbine) requires a relatively large head difference to operate effectively. The turbine set for use in the Swansea Bay project requires a head difference between the sea and lagoon basin of approximately 4 – 4.5m before power generation is able to begin (Tidal Lagoon Swansea Bay, 2013) (Shorrock, 2014). This means that there is a long time where the turbines are not operational while the tide builds up or recedes to create the necessary head value.

Based on the results from the CFD for all of the geometries, the Archimedes screw turbine would not require such a large value. There are several advantages to being able to begin power generation at a lower operational head difference. To begin with it means that the turbines can operate and produce electricity over a longer amount of time per tide cycle. As it is likely that the Archimedes screw will not be able to produce the peak output power values the bulb turbine can, by being able to take advantage of this extra time to produce power, the yearly output difference can be reduced. By generating with a lower peak output for longer, there would be the added benefit of a smoother and easier connection to the national grid.

With the numerous planned expansions of tidal lagoon projects around the UK, this longer power generation time would add to the idea and hope that tidal range generation could provide a base layer of electricity. This base layer means that at all times there would be a guaranteed amount of energy supplied to the national grid. Currently due to the types of renewable energy used in the UK such as wind and solar, which cannot be relied upon, this is not possible and the ability to do so would be a first and a very important step for renewable energy.

9.9 Results Summary – Design Trends

As all of the results displayed in this section are based on a fully horizontal screw turbine, in practice the values attained are valid for both flood and ebb generation methods. This is because although every geometry model is different, they are all fully symmetrical and without the inclusion of inlet guide vanes, the flow entering from either end is treated in the exact same way.

Throughout the testing, there have been several design trends found. Increasing the rate of rotation and mass flow rate were found to produce larger values of both torque and power, due to the increased amount of energy available in the flow and number of turns contributing to the power equation.

The length was not found to be as important as previously thought. There was little difference found between the torque production of any of the three length values. Out of the three, the benefits of having a smaller and the reduction in the construction costs would be the most useful. However, it would be worth investigating where the optimum length lies where the increase in torque due to the length outweighs the friction losses incurred.

Increasing the diameter ratio was found to have a significant impact. Increasing the diameter ratio resulted in an increase in the volume of water contained in each turbine bucket. By doing this, the results over the whole range of head values investigated were improved, with a percentage increase in peak torque of 22.98% when compared to the peak values reached by the reference geometry.

There was also a clear trend with the pitch ratio. Where increasing the pitch ratio and therefore increasing the size of the turbine buckets while reducing the number of buckets on the turbine per length clearly increased the torque and power production. The optimum pitch ratio value found was 2 and had an increase in peak torque of 55.99% compared with the reference geometry.

It was also found that when the number of blades was increased, the performance of the device was reduced. With the 3 blade producing a 7.57% decrease compared to the single blade version and the 5 blade geometry had a 13.22% reduction also.

It is believed that that the trends for diameter, pitch ratio and blade number follow the same pattern. The geometry modifications which reduced the surface area of the turbine and maximised the volume of water within each turbine bucket produces the greatest values of torque. This was backed up due to the rapid decrease in performance seen with the extra blades where each added turbine blade both increased the surface area of the turbine in contact with the fluid and reduced the flow volume per bucket.

9.10 Optimum Design

Based on the results and the design trends found, one final geometry was created. Each geometrical value chosen, was done so based on the results that provided the greatest increase in torque production. The values chosen are displayed in Table 16 and the CAD geometry in (Fig. 69).

Table 16 - Design parameters and values for the optimised geometry

Symbol	Description	Value
D	Outer Diameter	0.2m
d	Inner Diameter	0.05m
δ	Diameter Ratio (d/D)	0.25
L	Length	0.4m
Lr	Length Ratio (L/D)	2
P	Pitch	0.4
Pr	Pitch Ratio (P/D)	2
N	Number of Blades	1
G	Thickness of blades	0.005m
N	Rotation Speed	100 RPM

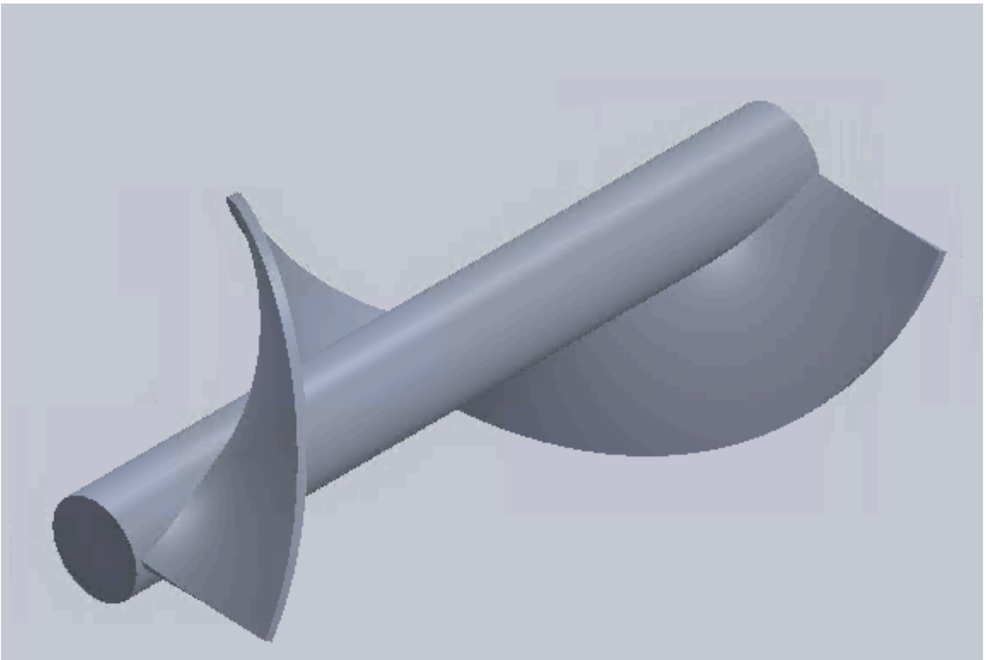

Figure 69 - Optimised turbine geometry based on results

Following the same testing method as the previous, the optimised geometry was run 6 times with the different head differences. The results were directly compared with the reference geometry values as seen in (Fig. 70), (Fig. 71) and Table 17.

Table 17 - CFD results from reference and optimised geometries

Test Number	Head difference	Power (W)		Torque Value (Nm)	
		Reference	Optimised	Reference	Optimised
1	0.2	7.5184	28.979	1.4359	2.7673
2	0.4	14.964	54.298	2.8599	5.1851
3	0.6	22.356	79.604	4.2697	7.6016
4	0.8	29.69	104.74	5.6704	10.002
5	1	37.065	129.64	7.0788	12.38
6	1.2	44.492	154.27	8.4974	14.732

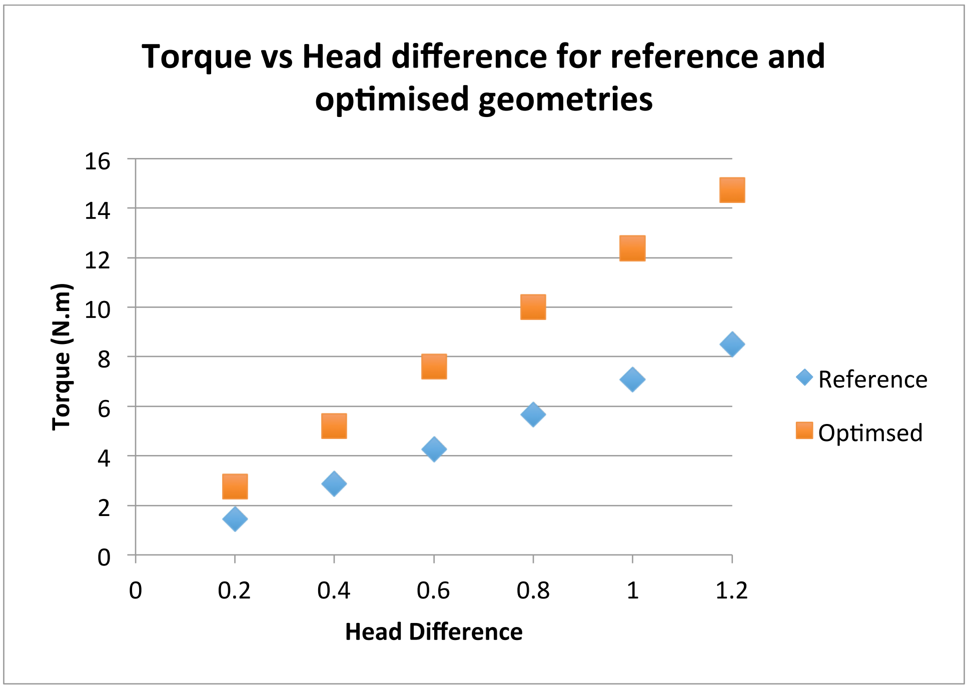

Figure 70 - Torque v Head difference graph comparing the reference and optimised turbine

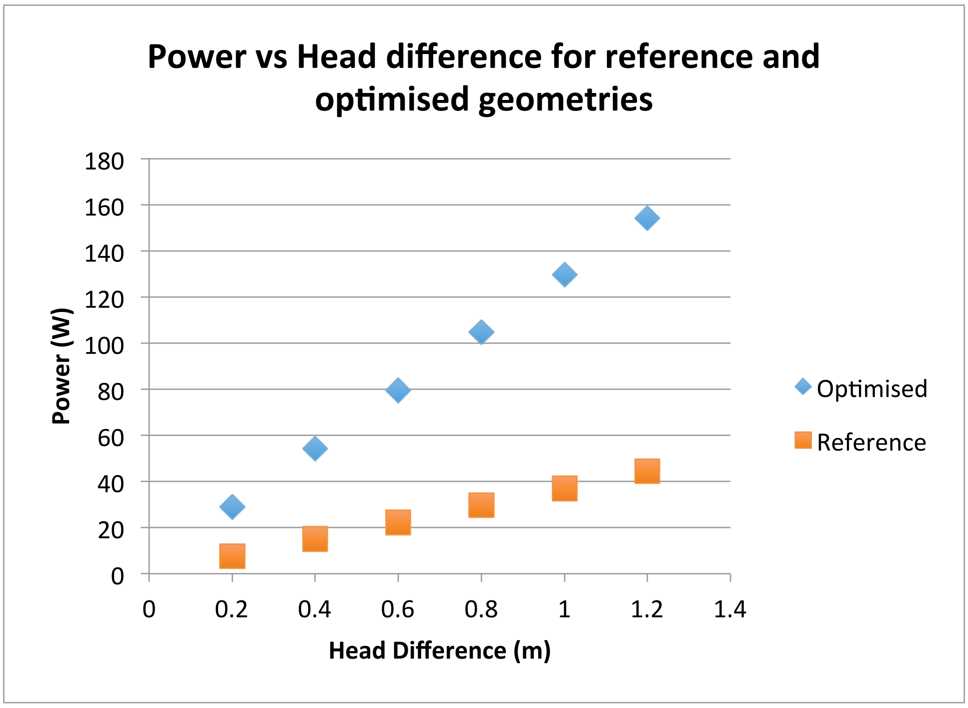

Figure 71 - Power v Head difference graph comparing the reference and optimised turbine

It is clear to see from the graph that the optimised version performs significantly better than the reference geometry, both in terms of torque and power production. The peak torque created by the optimised version is a 73.37% increase, which is a staggering figure. The peak power increase is also a rise of 246.74%, although this drops to a 68.85% increase when comparing to the 100RPM reference geometry. As only a few geometry values for each design identity were investigated, this increase is huge and there is still great potential for further improvement. However, as the geometry values for the reference turbine were picked arbitrarily, the device originally created was heavily un-optimised. Therefore, it was expected that the values would have a large increase once the first stage of CFD analysis was complete. It is not expected that these large increases continue during the future optimisation stages.

The next step will be to conduct model testing with this design set up, to see how closely the values from CFD and real testing match. Following this, CFD should look at much smaller increments for each design parameter, paying close attention to diameter and pitch ratio, as well as finding the exact optimum length. It would be expected in the results that for each of these there will be a value where the trends found peak and then begin to fall if further increased/decreased. It is these peaks, which must be found.

9.11 CFD Results Accuracy

When looking at the almost linear trends found for each of the tests, and the 5m/s of flow passing through the device (Fig. 45), the accuracy of these results can be called into question. Looking back at Eqn.1 there is a square relationship between the energy produced by a tidal range project, and the head difference, therefore this square trend would also be expected during these results.

One reason for achieving a linear trend is due to setting the rotational rate of the turbine, instead of allowing the solver to automatically do this based on the input conditions. To set up the CFD in this method would have taken much longer than the MSc project allows, and would mean the initial scale model testing phase would also have to be delayed therefore, it was decided to use the quicker rotating method as the aim of the initial CFD phase was only to identify design trends.

The accuracy of the simulation is great enough to decide these trends and to create a basic geometry for testing. When real test data is available, in depth computational analysis will continue during the 3 year PhD period, using this data to make the solver more accurate using transient methods and fully optimise the device.

10 Next Steps – Model Testing

It is the author's intention to continue the current research in the form of a PhD project. In preparation for this a link has been made with the National Technological University of Athens (NTUA) who were keen to collaborate and help to do so through offering the use of the facilities available in Athens, as well as funding the production and manufacture of the geometries to be tested. In preparation for the next stage of this research, the author visited NTUA and met with other researchers interested in developing the project further. During this visit a thorough examination of the available facilities was undertaken and based upon this, a method to analyse the performance of the Archimedes screw experimentally was created.

For the testing procedure, the large flow tank has been made available for the duration of the project (Fig. 72).

Figure 72 - Channel to be used for Testing

This very large flow channel of dimensions: width = 1.6m; depth = 1.7m and length = 18m will be more than sufficient as the entire dimensions of channel will be accessible for the modifications that will be required.

The testing process outlined is intended as an initial testing phase. The purpose of these tests in part is to determine the accuracy and validity of the first stage of CFD runs and optimisation phase. The second reason is to understand and attain a wide range of accurate results for an Archimedes screw turbine, which is fully submerged and operating with a pressure head at both the inlet and outlet. To date, there is no data or information on the public domain regarding using this turbine in this method and it would be considered as a world first. As the purpose of the turbine is producing the greatest amount of power possible, this is the value that will be measured and compared.

Pre existing links between NTUA and outside manufacturing companies will be used to create the Archimedes screw geometries. The turbine will be created using an aluminium alloy material that will be able to provide the required rigidity for the tests.

11 Project Future and Outcomes

The overall aim of the project is to completely understand how well an Archimedes screw turbine could operate in a tidal range project. All positive and negative aspects will be thoroughly investigated and taken into account. The success of the project will be measured on if the fully optimised turbine is a viable alternative to existing tidal range devices.

Following these initial model tests, further computational analysis will be carried out to broaden the understanding and to continue to optimise the screw turbine. The transient CFD analysis method will be developed, and the rotating mesh method will be also be used and the results will be compared with the rotating frame of reference method used in the project so far. Each method will be compared with the physical testing results to determine which provides the most accurate results. Once the varieties of CFD methods have been compared, with the most realistic chosen, a second testing phase will begin. The new model geometries will be based on the second phase of computational modelling and optimising results. The same geometrical identities will once more be modified, however this time the device will include an incline. With the extra time available for the next research phase, each identity (diameter, pitch etc.) will be modified with much finer increments to analyse exactly where the peak values lie. This process of computational and real world testing phases will be repeated as much as necessary and for as long as time permits.

11.1 Pumping

It is also the intention to run the turbine in reverse, as a pumping device to accurately understand and quantify the pumping advantage the device will have over alternatives such as the current Bulb turbine. The aim for this is to know the volume of water the turbine can pump over a range of head and flow values.

As the head difference between the sea and lagoon basin is such an important value, the ability to pump water in or out of the lagoon when necessary to increase this difference will be critical. It is even estimated that a project using pumping methods can increase the power production by approximately 4 times (MacKay, 2007).

As the main use of the Archimedes screw for the past 2,000 years has been pumping, therefore the device has a significant advantage over the current bulb turbines. This increased pumping ability can be used as a significant advantage to increase the head difference. Based on the experience in La Rance Bulb turbines are only able to reach pumping efficiencies around 66% (MacKay, 2007). On the other hand, the Archimedes Screw is able to consistently achieve high pumping efficiencies of just under 80% over a wide range of operating capacities, with the efficiency only falling when operating with flow values of about 40% of the maximum (Fig. 73).

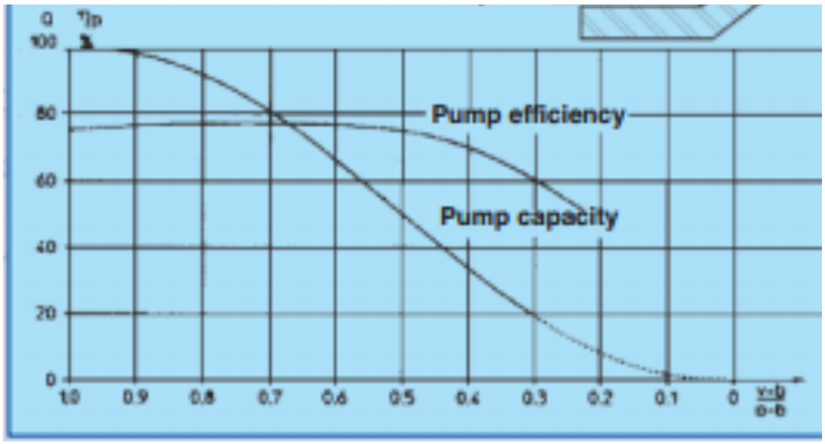

Figure 73 - Pumping efficiency for Archimedes screw turbine (Landustrie, 2012)

These efficiencies are not for pumping fully submerged with a pressure head. Therefore it will be necessary to evaluate how the device performs in this way. It would be expected that the pump will lose efficiency when pumping with greater pressure values due to increased gap losses, although the main restraint will be the maximum height available for pumping, due to the size of the wall. Even with this lagoon wall height restriction, pumping could be used to reduce the power production values between spring and neap tides, when the tidal range is naturally reduced.

Being able to quantify how this increase in pumping equates to an increase in fill height of the lagoon basin means the head difference between the sea and basin can be known. As the screw turbine is not able to reach efficiencies on par with the bulb turbine, the increase in power available due to the added head difference may be able to reduce the drop in power output created when using the screw device. As the overall project intends to take all aspects into account, this could be a critical value to take into consideration, as a plain comparison of power and torque outputs over the normal operating tidal ranges do not paint the full picture of what the screw turbine is able to provide.

11.2 Inclined Non Uniform Designs

Depending on the success of the inclined axis version during the model testing phase, the second stage of computational analysis and optimisation will include designs with changing pitch values (Fig. 74)

Figure 74 - Archimedes screw with a non uniform pitch design (Schleicher, 2012)

If (as expected) the inclined model version is able to produce greater torque, power and efficiencies, it would mean the inclined version would be the primary set up for any future project. Therefore, having a screw device with a uniform design, which would work with equal efficiency in either direction, serves no purpose.

11.2.1 Potential Inclined Deployment Method

If the inclined method is superior, the original theory of using an Archimedes screw turbine in place of the Bulb turbine within the same horizontal, cylindrical enclosure, will not work. However, the idea of incorporating an incline into the design is not too difficult or a disadvantage. Previous projects have considered using an inclined tubular turbine (Fig. 75).

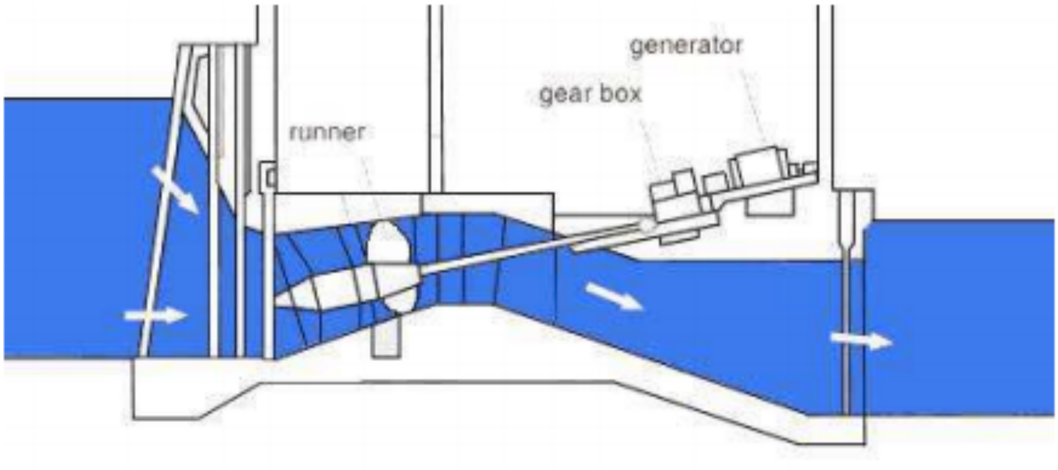

Figure 75 - Tubular turbine for Tidal Range with incline (Coulthard, 2011)

A similar set up could be used with the inclined screw turbine, which would also have the added advantage of keeping the generator out of the flow.

The new inclined arrangement could operate solely with ebb generation, with the incline pointing upwards towards the lagoon basin. This would allow for both power production and increased pumping into the lagoon. An alternative method would involve twice the number of screw turbines, with half inclined for ebb generation and half for flood generation, therefore allowing the project to continue operating bi directionally. The reduced cost of the screw turbines would allow for the production of more devices without requiring further investment and funding.

Although it is acknowledged that any incline of the device would result in a loss of head difference, as the Archimedes screw turbine’s normal operating conditions are partially filled, if the head reduction was too great, the device could function in this proven method alongside the fully submerged application when the tide level drops significantly. This partial submergence is a proven technology with high efficiencies of up to a reported 90% attainable (Andritz, 2015).

11.3 Erosion/Lifetime

As there is a potential for very high silt content in the flow, it is intended to include this in future computational analysis. Using information regarding the sand/silt particle composition and sizes likely to be present in the Severn estuary, the analysis will investigate how the turbine will be affected over the approximate operational lifetime of the device and if there would be any reduction in this amount or if there would be a risk of unpredictable failure. How the damage or erosion affects the performance and efficiency of the device will also be looked into.

12 Conclusion

Since the 1960's, turbine technologies have changed radically and a plethora of new designs with the potential for use in tidal range situations have been created. These theoretical devices were evaluated, looking at a variety of key aspects. Out of all of the devices investigated the Archimedes screw turbine was deemed the device with the greatest potential. This robust, long lasting turbine is able to operate well at a wide range of efficiencies while being cheap and extremely environmentally friendly, as well as having superior pumping abilities. As many barrage projects are dismissed because of cost and environmental effects, this turbine addresses both of these important points.

With the first aspect of the project complete, the next stage was to perform a literature search on the existing design information. It was found that there is a distinct lack of research available regarding operating the screw as a turbine, with the majority based on the pump application.

To begin to evaluate the performance of the turbine in a tidal range situation a CFD model was set up with the objective to evaluate the main design trends found within the literature. The set up involved a variety of Archimedes screw turbine designs being fully submerged with a head difference applied at both sides to simulate the changing head values seen in a tidal lagoon.

Based on a reference device, the geometry was modified repeatedly, looking at the how a variety of geometrical identities and ratios affect the overall performance of the device. It was found that the modifications which increased the surface area of the turbine and also increased the number of turbine buckets resulted in a reduction in performance. This was seen when increasing the number of turbine blades. There was also a reduction in torque over the entire testing range when the pitch ratio was reduced, increasing the number of buckets for a given length. Both of these trends were opposite to the optimum values for the pump version, proving that there is a very difference approach needed to optimise the turbine.

A further decrease was found when increasing the diameter ratio, therefore making the inner diameter occupy more of the enclosure the turbine is located within and reducing the volume of water contained in each bucket.

As expected, increasing the mass flow rate resulted in an increased performance, however, increasing or decreasing the length did not show a clear trend where there was very little change in results between all of the geometries investigated. It is thought that when increasing the length with a fixed pitch and diameter ratio, the added buckets are able to aid to the production of torque as the turbine is able to extract more energy from the fluid by being in contact with it for longer. However, the increase in friction forces due to this negates any increase. An optimum length will exist where the extra torque produced by the added length will improve the results and where any increase above this value will cause the friction forces to become dominant and reduce the results.

When incorporating all of the positive aspects of the trends found into a single geometry, there was significant increase in both power and torque produced. A 73.37% increase in the peak torque produced by the optimised geometry was found when compared to the reference.

Importantly, each of the geometries were able to perform even at the lowest head difference measured, with the optimum design producing 18.78% of the peak torque value found at the highest head difference. For tidal range situations this ability could allow longer generation time per tidal cycle and if used in multiple locations around the country could offer a guaranteed base level of electricity to the national grid. However, these values have not been confirmed with scale model testing and due to the methods used during the CFD analysis, may not offer a complete picture.

There have also been no adverse effects found to the screw turbine when operating in flows with a high silt content, unlike the bulb turbine which can suffer sever damage resulting in lower lifetime and efficiencies. Leading experts in the field have expressed doubts about the silt modelling software used to evaluate Swansea bay and believe there could be a significant amount present, potentially causing expensive complications.

The Archimedes screw has many positive points making it a good potential candidate for lagoon projects. However, much more research is needed to fully meet the aims and objectives of the project. Model testing facilities have been arranged in NTUA and are currently under development with the hope to be operational during 2016. With the data from these tests, more in depth computational analysis can be accurately performed to put the trends found into use and begin optimising a device fully. It is also intended to research and quantify the pumping ability, as well as investigating both inclined and non-uniform pitch designs. Over the next few years Lancaster University in collaboration with NTUA will continue research on this topic, using an extensive combination of model testing and in depth CFD analysis taking into account each of the factors outlined in this research before ultimately comparing the performance to existing devices planned for use in Swansea Bay.

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Appendix A – Summary of Current and Potential Archimedes Screw uses

Summary of the Archimedes screw/pump applications and technologies available or under research (Table 18).

Table 18 - Summary table outlining how the Archimedes screw is or could be used (Waters & Aggidis, 2015)

Type	**Status**	**Potential Deployment Characteristics**	**Comments**
Submerged Stream Turbine	Full scale testing	Deep sea currents above 1m/s	Full scale testing in progress in Norway
Horizontal axis turbine	Theory and model testing	Hydrokinetic using kinetic energy in: River currents Tidal currents	Model testing in progress
		Tidal Fence	Theoretical. Research currently in progress at Lancaster University (UK)
Inclined axis turbine	Full scale deployment	River flows with head difference.	Low cost, established turbine, preferred in locations with delicate environments. Requires very little maintenance
		Submerged, using tidal range methods (Theoretical)	Theoretical. Research currently in progress at Lancaster University (UK)
Inclined Axis Pump	Full scale deployment	Pumping	Used for over 2,000 years, oldest engineering device still in use
		Fish Ladders	Used to safely divert or move fish
		Land Reclamation	Widely used in Netherlands to create ponders
		Injection Moulding	Able to transport fibres for manufacture undamaged
		Heart Valves	Passed successful human trails to replace heart
		Groundwork	Performed delicate task of stabilising the leaning tower of Pisa

Appendix B – Over 2,000 years in Review: Revival of the Archimedes Screw from Pump to Turbine

Over 2,000 years in review: Revival of the Archimedes Screw from Pump to Turbine

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Abstract

The Archimedes pump is one of the oldest feats of engineering still being used today. In recent times, it has seen a major revival in modern engineering, by reversing it for use as a turbine. This is now an established turbine, being used in Europe since 1994. It has been found this new turbine device has a plethora of advantages over current existing devices, with the simplicity and robustness that has kept the pump in use for centuries acting in its favour. Most existing design theory is for use as pump; however there are many key differences between operation as a pump or turbine, such as the direction the water flows through the device. With further research for turbine operation alone required.

The Archimedes Screw turbine currently has a variety of operational modes: inclined, horizontal or submerged. These new devices have the possibility to unlock a wide range of applications. The submerged tidal stream device can operate in low flow velocities (1m/s) that current devices are unable to. The inclined and horizontal turbines offer greatly reduced environmental effects and can be used in areas previously passed over because of delicate habitats. However, there are still more potential uses, for example in tidal range or tidal fence situations, although research for use in these methods are currently only in the initial stages with Computational Fluid Dynamics (CFD) simulations and scale modelling required to prove the validity.

Keywords
Archimedes screw; Optimisation; Pump; Renewable energy; Tidal power; Turbine.

1 Introduction

The link between climate change and the increasing use of fossil fuels is well established. However, the threat of global warming is not the only reason to promote the use of renewable energy. Dwindling reserves of oil and gas in the North Sea has seen the UK become dependent on foreign nations for energy security. Since 2012, air pollution has become the leading cause of preventable death, attributing to one in eight deaths worldwide [1] which puts a heavy burden on the National Health Service (NHS) costing approximately £15 billion [2]. The UK has pledged to reduce its carbon emissions and provide 20% of the country's energy demands through renewable sources [3].

As it is unfeasible to drastically reverse the trend and lower energy consumption, a large part of the solution is to promote the usage and expand the range of renewable energy. To curb this trend, there has been a significant increase in research and development of renewable energy devices. Over two thirds of our planet is covered in water which offers a multitude of renewable energy options. The main three are wave, tidal stream and tidal range. Twice-daily tides and strong ocean/river currents allow these forms of renewable energy to be predictable – a valuable advantage over other forms of clean energy such as wind and solar.

2 Background

2.1 History

Invented by the Greek mathematician Archimedes in antiquity, the Archimedes Screw is one of the oldest feats of engineering still in use today. One theory regarding its creation is the King of Egypt asked Archimedes to devise a way to remove water from his ships, another suggests the device was created hundreds of years prior to Archimedes birth and he just adapted it to make it popular around the known world [4]. After Archimedes, Vitruvius wrote about the screw pump extensively during the first century BC [5].

Regardless of its origins it was first used for the purposes of aiding irrigation and pumping water out of ships. Since then the device has found a variety of new and different uses to fit in with the modern world since the industrial revolution.

2.2 Pump Application

The primary method of use for the turbine has always been as a pump [6]. Whether this be, pumping water, fish or food grains from one location to another. The hassle free, versatile nature of the device is part of the reason it is lasted through the ages [7]. Combined with a long lifetime, and low cost the pump has proved an ageless technology with an ever expanding plethora of adaptions.

2.3 Modern Adaptations

2.3.1 Fish ladders

Used to provide fish a method to move from one area or height to another safely. This can be to aid migration patterns along rivers or divert these migrating fish from a potential danger or obstruction [8].

2.3.2 Leaning tower of Pisa

In 2001, John Burland used an Archimedes screw device was used to perform the very delicate task of stabilising the leaning tower of Pisa. With the foundations created on weak and compressible soils were dangerously unstable, causing the "lean" angle to increase over time. The high instability and historical importance of the building meant conventional methods to stabilise the foundations were too invasive. To reduce the angle enough to stabilise the tower a method called soil extraction was used. Using an Archimedes Screw, soil could be removed from the foundations without causing damage and reducing the angle by approximately 0.5 degrees [9].

2.3.3 Land Reclamation

Used extensively in the Netherlands to create polders (reclaimed land that is under sea level). Used to carefully manage the water level, these polders form much of the flat farmland that is ubiquitous with the Netherlands [10]. Polders are created through a complex process of locks and pumping stations where excess water is pumped from one area of interest back towards the sea, often through the use of an Archimedes screw [10] [11].

2.3.4 Injection Moulding

In modern design methods, the Archimedes screw is used during injection moulding to deliver the compound material to the mould. The low rotation rate and lack of pressure required to move the material mean there is little to no damage to the fibres [12].

2.3.5 Heart valve replacement

Heart failure is the cause of death for over 600,000 people per year in America alone. The technology behind the Archimedes screw has been used in over 20,000 people to help keep patients alive until a donor heart can be found [13]. During the 1980's a device was created to mimic and replace the left ventricle, generating a constant flow using a screw pump [14]. In an attempt to create a more permanent replacement, Cohn and Frazier combined two of these devices and the result not only passed animal testing but also was successful in replacing a terminal patient's heart [14].

With an estimated lifetime of 10 years, these devices can offer a long time replacement for people ineligible or unable to have a transplant [15]

3 Rebirth

The latter part of the 20th century found a re-emergence of the Archimedes Screw, operating in a new and reversed form as a turbine. The first of these devices were installed in Europe during 1994 and later introduced to the UK in 2004/2005 [16] [17]. One of the main drawbacks, which prevented this development from occurring sooner was the complexity of the gearbox required [18].

Ever since this leap in engineering, there have been three distinct designs that have developed. However, due the infancy of the technology, there is currently a lack of research on the topic.

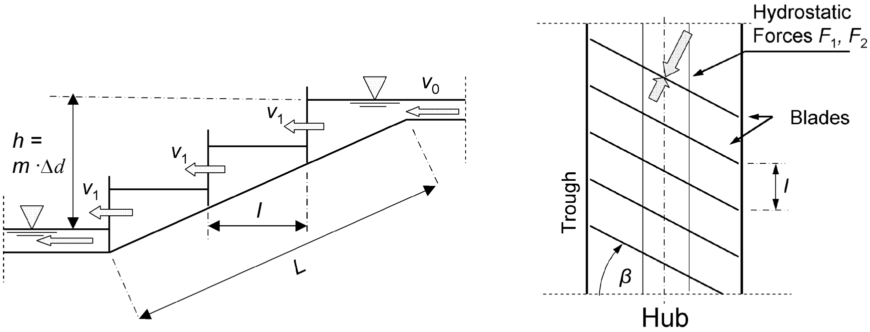
3.1 Inclined Axis Turbine

Currently the only screw turbine type in full-scale deployment. Visually similar to the inclined pump turbine and often treated the same during the design [19]. However, there are some key differences. When it comes to creating and optimising a pump device, the key is to increase the amount of water moved during each turn of the device. For the turbine, the maximum amount of energy in the flow needs to be extracted.

It is assumed the weight of the water is fully acting on the device and if there were no losses, 100% of the energy in the flow could be extracted [20]. Obviously this is not possible as losses are present and the majority of the water weight rests on the unmoving trough, meaning only a small component of water weight actually contributes to energy production and can be neglected.

Energy is generated during the transmission of torque an attached gearbox and generator system. The torque is created through two components, the velocity of the flow and the hydrostatic force. The complicated gearbox is necessary for connection with a generator because of the relatively low rotational values that Archimedes screw turbines usually operate.

Hydrostatic force is created through the difference in upstream and downstream pressure. The change in head between each blade of the screw means the pressure acting on the blade is greater upstream (fig. 1). Only the component of hydrostatic force acting in the direction of rotation contributes.



(a) (b)

Figure 1 - Hydrostatic force acting on blades of Archimedes Screw Turbine [21]

3.2 Horizontal Axis Turbine

The turbine itself is akin to the inclined axis version, however it's method of operation is what sets it apart. By placing it horizontally on top of flowing water gives easy access and greatly limits negative environmental effects.

Designed for zero head locations to operate on either tidal flows or river currents [22] [23]. With the lack of incline, no hydrostatic force is created, so the only source of energy that can be used to convert to power is the kinetic energy in the flow [24] [25]. Created with a uniform design, they can operate with equal efficiency in both directions.

As this is a very new and experimental technology, with only preliminary research, the design of the screw used runs on the same principals as the inclined device. More research is required in order to optimise the design for kinetic energy alone.

3.3 Submerged Tidal Stream Turbine

The face of tidal stream technology has been continuously changing with new and innovative devices being constantly designed. The major designer leading the pack with the Archimedes Screw is the Norwegian company Flumill [26]. Using a symmetrical screw attached to the seabed on a pivot which allows the device to incline [27]. The top fin controls the level of incline. During each tidal flow water flows up and through the device causing it to rotate and create electricity with the connected generator.

Currently, the device has passed model testing and CFD simulations, with the next stage being full scale testing in Tromsoe, Norway [26]. It has proven popular with both the public and with the government, being awarded with grants through the Environmental Technology Scheme [28].

The versatile nature of the design means it can operate in flows as little as 1m/s [29].

4 Operational Advantages

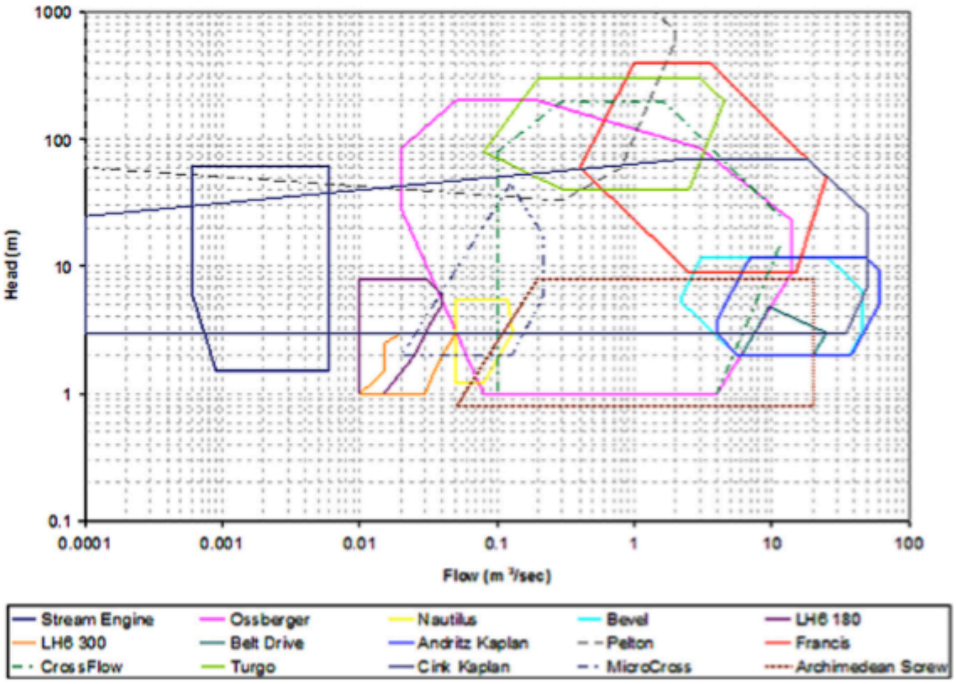


Figure 2 - Performance characteristics for various turbines [30] [31] [32]

As seen in (fig. 2), the screw device is well suited for low head and a wide range of flow conditions, making it suitable for a large number of applications. There are also a plethora of reasons for the resurgence of the Archimedes Screw which points to this being integral to the future of green energy.

4.1 Environment

Already known for being the most environmentally friendly turbine available and have been used extensively as fish pumps/ladders. In 2008 live fish trails were undertaken in partnership with the environmental agency. A wide variety of fish species (including eels which are easily injured when passing through turbines) and sizes up to 63cm were investigated [33]. The results found that "none sustained any damage" [33], however 1.4% of smolts (very small fish) had repairable scale damage, which may have occurred when the fish were being caught for the test.

Any fish mortalities sustained during the use of the turbine were due to the leading edge. This was remedied through the use of a rubber bumper so no damage was sustained [34].

The low rotational speeds the device operates at means there are very low values of shear stress, combined with the turbulence levels that fish are exposed to in normal circumstances [33].

A further test comparing the mortality rates for adult eels when passing through different pumping stations showed a significant reduction when using the Archimedes screw instead of a propeller pump [10].

The drastic reduction in environmental effects compared to conventional turbines such as Kaplan or bulb mean locations previously not viable due to environmental concerns can be revaluated.

4.2 Efficiency

Although not as efficient as modern bulb turbines, the values of efficiency achievable currently range from a modest 83% [35] to a competitive 92% achievable from Andritz [36]. Investigations from 1999 discovered existing devices in Germany were operating with efficiencies of approximately 80% [37]. Bearing in mind, at this point there was little to no research for using this as a turbine instead of a pump, with more in depth research for power generation the efficiency values achievable should increase.

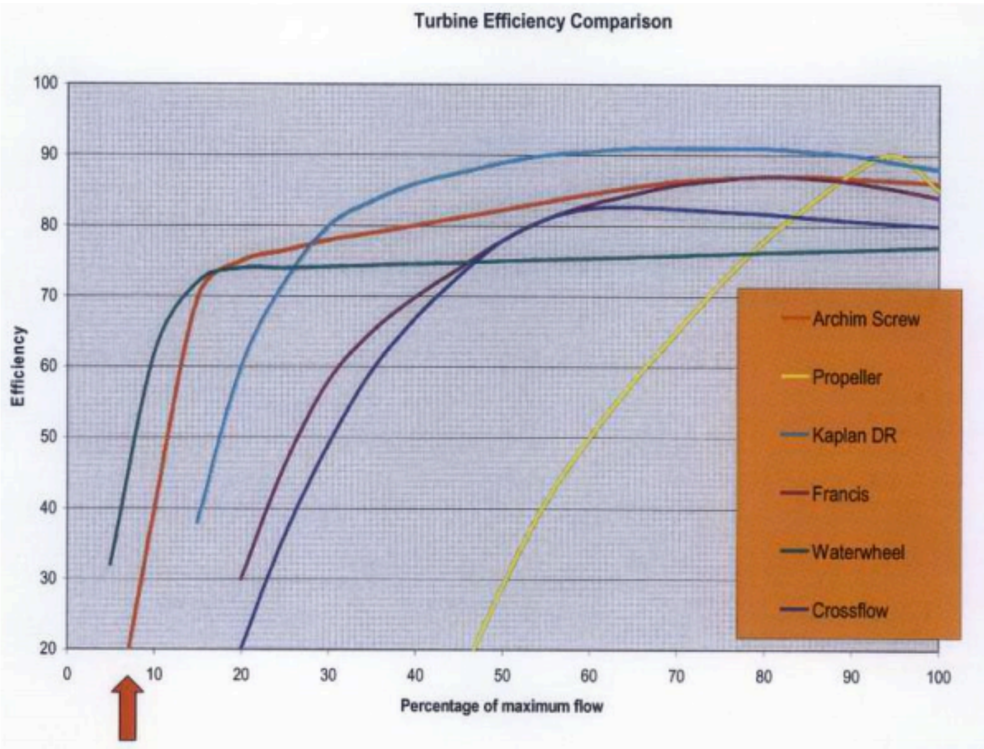


Figure 3 - Comparison of efficiency curves with varying flow [38]

(Fig. 3) shows how the screw turbine can perform at high efficiencies over a wide range, with only the Kaplan device performing better in terms of efficiency. However, the Archimedes screw is able to operate over a wider range of flows.

4.3 Cost

The very simplistic design, without the need for complex and very expensive parts such as adjustable guide vanes or runner blades.

Improved manufacturing methods means the screw can be created in a single structure and with a composite material. This not only reduces costs, but also increases stability [39]. This also removes the need for a costly assembly facility near to the deployment site.

Unlike conventional turbines, the Archimedes screw device is excellent at handling debris. Therefore, debris screening is not required. This process can be expensive to implement, requiring regular cleaning and if blocked reduces efficiency.

4.4 Maintenance

Maintenance costs associated with these turbines are extremely low. The lack of adjustable parts combined with the rigidity of a single structure result in a very robust device with a long lifetime. Re-tipping is required approximately every 20 years with a minimum lifetime of 30 years [40].

5 Design Criteria and Optimisation

The design of any turbine involves a complex trade-off between the best and most cost effective. Muller and Senior [21] originally stated that the efficiency of an Archimedes screw turbine is based on a mixture of the geometry of the device and the mechanical losses the turbine is subjected to.

The geometrical identities (fig.4) in table 1 include both the internal and external properties that affect the outputs of the turbine.
Internal: Parameters that can be set changed and edited by the designer
External: Site-specific parameters that are dependent on the location the device is to be deployed at.

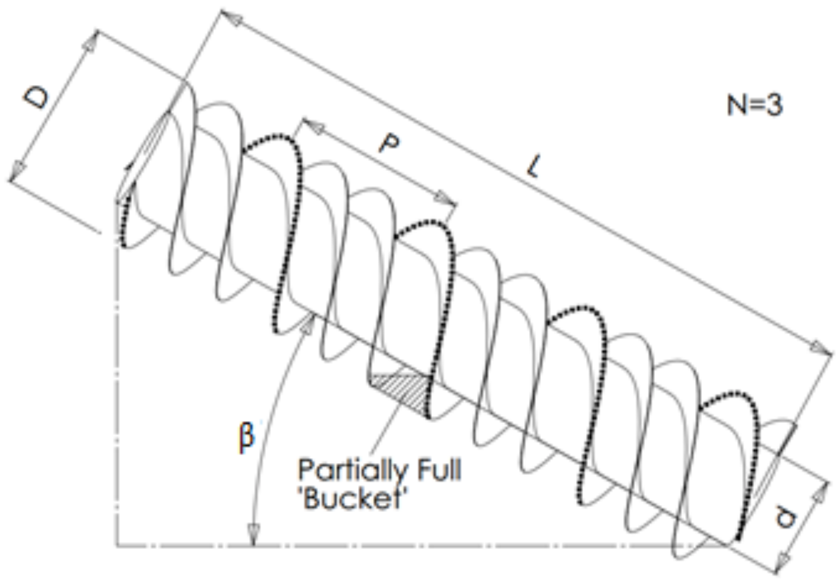


Figure 4 - Geometry of Archimedes Screw [41]

Table 1 - Geometric Identities for Archimedes Screw

Symbol	Name	Internal (I)/External (E)
D	Outer Diameter	E
d	Inner Diameter	I
P	Pitch	I
L	Length of screw	E
θ	Angle of Inclination	E
N	Number of flights	I
G	Thickness of Spiral Profile	I
n	Rotational Speed	
Q	Flow rate	E
H	Head	E
ω	Rotation rate	

Incorporating the effects of internal and external parameters, the designers' problem can be classified as finding the optimum mixture of internal parameters that provide the greatest efficiency/power output with the set values of external values.

The process of optimising a turbine is delicate and often design ratios (Table 2) are an important part of the process. When one design parameter is changed it can often have a knock on effect. Identifying these links between different parameters means that they can be changed in relation to one another in the hope that the overall performance of the turbine can be improved.

Table 2 - Performance Ratios for optimisation

Name	Ratio/Relationship
Diameter ratio	$\delta = d/D$
Pitch ratio	$Pr = P/D$
Length ratio	$Lr = L/D$
Profile ratio	$\varphi = G/d$

5.1 Internal Parameters

5.1.1 Pitch Ratio (Pr)

Rorres [42] and Nagel [43] correctly suggested that the pitch ratio would have a significant effect on the efficiency of an Archimedes Screw.

Data from [44] (Fig. 5) confirms this link between Pr, output power and efficiency. Three screws, with only different pitch values were tested in an identical situation. The results showed that both power output and efficiency increased with larger Pr values.

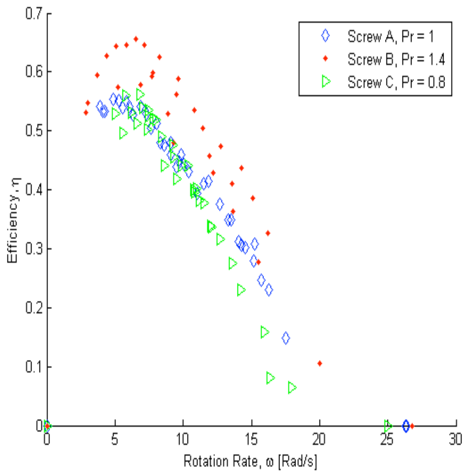


Figure 5 - Analysing how pitch ratio effects efficiency [44]

By increasing the pitch there is a decrease in volume per bucket and a proportional decrease in force acting on each bucket. Conversely, this does cause an increase in the number of buckets per length.

Despite this increase in the number of buckets, as the graphs prove, it is more important to increase the volume and force per bucket.

Lyons [44] suggests that with a decrease in pitch, there are less leakage losses. However a larger pitch creates more static pressure (and therefore torque) on each flight of the screw.

5.1.2 Rotational Speed

The fewer rotations per minute mean a more complex gearbox is required to convert the mechanical energy of the turbine into electricity. However, [44] theorises that at low rotational speeds, the turbulence losses inside the turbine are lower. Further to this, as the rotational speed decreases so do the friction losses [18].

From the data gathered by [44] it suggests that the optimum efficiency is reached when the turbine is close to the stall rate of the system. When operating at this speed, the turbine buckets are filled so the most torque can be applied on each turbine flight.

Variable speed ASTs provide the greatest efficiencies, with values consistently reaching 80-85% [39].

When designing the turbine as a pump, increasing the rotational velocity can increase the volume of water lifted per minute [42]. This corresponds to an increase in efficiency for a pump, but is contrary to information for screw turbines. This furthers the notion that the design procedure for a screw pump should not be considered correct for use as a turbine.

5.1.3 Number of helices (N)

A variety of helices can be used on one screw device. It has been suggested by [21] that a greater number of turns around the turbine means higher efficiencies can be reached. This is due to the reduction of head difference between each turn.

As the number of blades increases, so does the power (Eqn. 1), [20]. When more than one blade is used the power produced multiplied.

$$P = m \times P_{Blade} \tag{1}$$

5.1.4 Diameter

To a point, the increase in diameter of the device should increase the output power. To date, the maximum diameter has been limited to approximately 4m [18]. This limitation is based on manufacturing methods alone and with the introduction of new materials such as vinyl ester based composite the useable diameter (and stability) could be increased [39].

Many references give notion to the relationship between diameter and water level, as this limits the amount of water able to pass through the device. However none give an optimum ratio [35], [45], [46], [21], [47].

Until the introduction of composites such as vinyl ester, screw diameters were limited to 4m [39]. This restriction was because of fatigue limits in the fabrication welds between the blades and inner diameter [48].

5.1.5 Clearance

Clearance is the gap between the trough casing and the screw. For maximum efficiency this value should be as low as possible [48]. The smaller the gap is, the less flow passes around the turbine blades, not contributing to energy production and lowering efficiency.

5.1.6 Fixed or Moving Trough

Either the screw can be rotated around a stationary trough, or a more radical design incorporated a moving trough with a stationary screw. Hawle [49] found the most efficient method was by having a fixed trough. This also allowed the device to operate with high efficiencies over a wider range of flow values when compared with the rotating trough.

5.1.7 Variable Speed

ASTs show promise for operation in tidal range situations due to their ability to operate with high values of efficiency over a wide range of both flow rates and head values. When operating with variable speed instead of fixed, this ability will be enhanced [41] [49].

5.2 External Parameters

5.2.1 Volume Flow Rate (Q)

As the turbine is being designed for use in a tidal range situation, it needs to be able to operate efficiently under a wide range of flow rates. It is already known that they are very versatile, being able to operate with flows ranging from 0.1 to $50m^3/s$ [35]. Even when the flow rates exceed these values, multiple devices can be placed in series.

When testing a single screw with various flow rates it was found that with increasing flow rates, both the power and efficiency increase (Fig. 6).

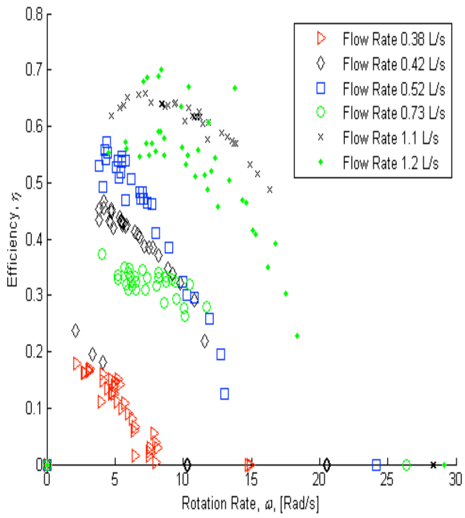


Figure 6 - Effects of varying flow rates to efficiency [44]

However, although both outputs increase with increasing flows, the graphs also suggest there is a maximum flow rate for each individually designed turbine. The values for 1.1 and 1.2L/s overlap one another, which suggest that the maximum flow value for the turbine used is between these values.

Data gathered from a prototype turbine installed in Ontario also showed this correlation (Fig. 7).

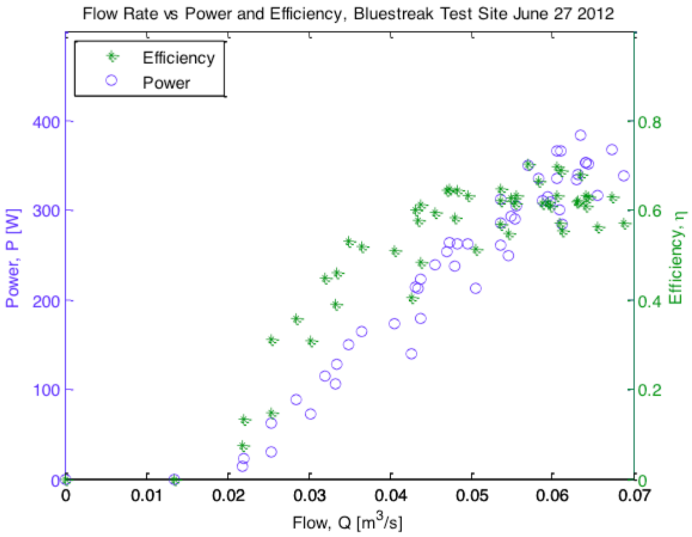


Figure 7 - Effects of flow rate to power and efficiency [44]

The trend of increasing efficiency and power are backed up by data collected by Hawle [49] (Fig.8) where efficiency was increased for higher flow rates.

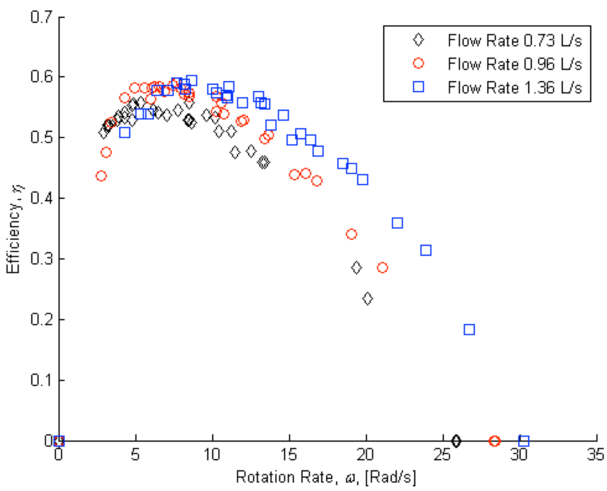


Figure 1 - effects of flow rate and efficiency [49]

The efficiency decreases greatly at lower flow rates because the system losses will not reduce as the flow rate does [44]. However, tests carried out in [38] proved the screw device was able to perform even with large variations in flow.

5.2.2 Inclination Angle

In part, by altering the complete length of the device means the angle can be chosen. Muller et al [21] and Raza et al, [48] state that the angle of efficiency increases as the angle of inclination is decreased as shown in Fig. 9.

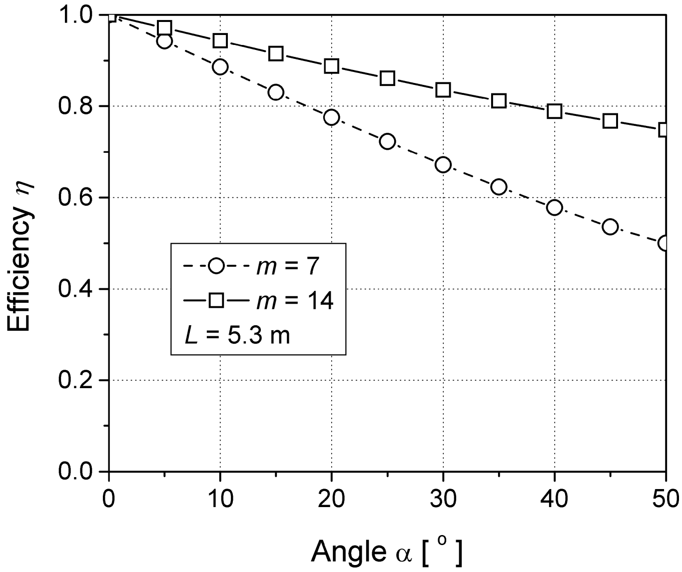


Figure 9 - Effects of inclination angle, number of turns and efficiency [21]

Data from Lyons [44] shows the opposite effect. A single screw was tested while altering only the angle of inclination. Both the efficiency and power output increased with the angle (Fig.10).

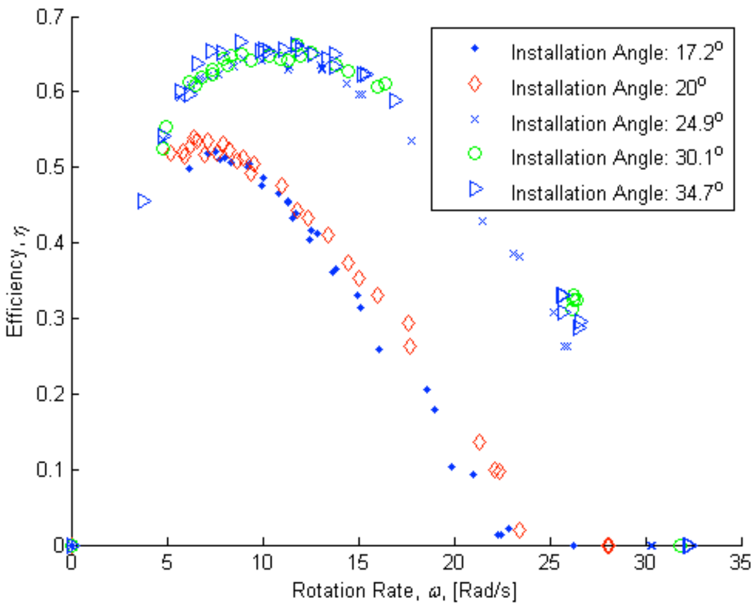


Figure 10 - Effects of inclination angle and efficiency [44]

From the graphs there is a clear limitation to how much improvement in efficiency there can be by altering the angle, however, trend continues for longer when examining the output power.

However, this test does not take into account any increase in length provided by reducing the angle. The same correlation was seen for [50].

The inclined devices operate well in flow rates in the range of 0.1 to 50m^3/s. Successful operation in larger flow rates is achievable through the use of multiple devices in series, such as [51].

5.2.3 Length

The length can be chosen (to a point) by the designer in the same manner the inclination angle can be. The ability to have long lengths is unique to Archimedes Screw turbines and means the water is able to pass across a great number of buckets so more energy can be extracted from the flow [52].

However, the efficiency increase due to length will reach a point where losses will overcome the benefits.

6 Potential Development

Although there has been significant increase in the applications for the Archimedes screw there is the potential for more. The ideas and methods presented at in theoretical stage with CFD and model simulations required to confirm the possibilities.

6.1 Tidal Barrage/Lagoons

The tidal barrage in the Severn Estuary is the most discussed tidal range project in the UK with it first being suggested almost 100 years ago [53]. Since then, it has been reviewed countless times. However, each time it has dismissed because of the very high initial costs and adverse environmental effects.

The bulb turbines used for situations such as this, can be estimated to cost in the region of 25% of the overall project.

By adapting an Archimedes Screw turbine to operate in this way the very simple design drastically reduces the initial costs, turbine lead-time and maintenance. As well as reducing the complexity of any barrage/lagoon created, as there is no need for well-designed inlet and draft tubes. There will also be less environmental effects associated with the turbine, with only the structure of the barrage/lagoon itself being invasive.

The La Rance tidal barrage and the planned Swansea bay tidal lagoon both use pumping to increase the tidal range for generation [54]. This process involves using the turbines in reverse, increasing the operational head. The Archimedes Screw has been used in this fashion for centuries and is far more effective for this purpose than traditional turbines. This means more water can be pumped, using less energy to do so.

6.2 Tidal Fence

A less structurally invasive adaptation of the tidal barrage, a tidal fence uses only the kinetic energy in the flow for energy creation [55]. Like Tidal barrages, they are able to combine energy creation with infrastructure. Tidal stream turbines are deployed in series across a waterway, with a bridge structure created above [56]. Using a construction design that does not require an environmentally damaging dam or barrage, combined with the fish friendliness of the Archimedes screw creates a power generation method that has minimal impact to its surroundings.

7 Conclusion

As the world begins to understand the dangers of global warming, green energy is generating much interest. It is only fitting to look back at the great engineers of the past who first exploited the natural energy of the earth. With little change in the design from pump to turbine the simplistic Archimedes Screw offers a plethora of advantages over the fine-tuned machines of the present. The lack of environmental concerns combined with the wide range of deployment possibilities and robust, hassle free natural of the design has the possibility to unlock a great deal more locations.

Further research is required to optimise the design for the different types of deployment (submerged, inclined and horizontal), as each method generates electricity in a different manner. Most current design theory is based on the pump design instead of turbine. Many of the design criteria can be used for either; however there are key differences in operation such as the direction the water passes through the turbine.

There are many more possible ways the Archimedes Screw could be used, such as tidal range, using a series of submerged inclined screw turbines, or tidal fence methods using multiple horizontal screws. However, these are currently in a theoretical stage, but preliminary research shows promise.

8 Acknowledgements

The authors would like to thank Lancaster University Renewable Energy Group and Fluid Machinery Group.

9 Summary Table

Table 3- Summary table of the Archimedes Screw technology, operating in a turbine or a pump mode, under different configurations as applied to current and potential future applications.

Configuration	Type	Status	Potential Deployment Characteristics	Operation Mode		Applications		Most recent publication	References	Comments
				Turbine	Pump	Current	Future			
Horizontal	Horizontal axis turbine	Theory and model testing	Hydrokinetic using kinetic energy in: River currents Tidal currents	Yes	No	Yes	No	2013	[22] [23] [24] [46] [45] [47] [35] [25]	Model testing in progress
			Tidal Fence	Yes	No	No	Yes	2015	[56] [55]	Theoretical. Research currently in progress at Lancaster University (UK)
Inclined	Submerged Stream Turbine	Full scale testing	Deep sea currents above 1m/s	Yes	No	Yes	No	2014	[27] [26] [57] [29]	Full scale testing in progress in Norway
	Inclined axis turbine	Full scale deployment	River flows with head difference.	Yes	No	Yes	No	2014	[23] [21] [46] [20] [45] [47] [35] [33] [34] [30] [18] [25] [41] [48] [42]	Low cost, established turbine, preferred in locations with delicate environments. Requires very little maintenance
			Submerged, using tidal range methods (Theoretical)	Yes	Yes	No	Yes	N/A	N/A	Theoretical. Research currently in progress at Lancaster University (UK)
	Inclined Axis Pump	Full scale deployment	Pumping	No	Yes	Yes	No	2014	[36] [7] [42] [5] [10] [6] [4]	Used for over 2,000 years, oldest engineering device still in use
			Fish Ladders	No	Yes	Yes	No	2015	[8]	Used to safely divert or move fish
			Land Reclamation	No	Yes	Yes	No	2014	[11], [10]	Widely used in Netherlands to create ponders
			Injection Moulding	No	Yes	Yes	No	2005	[12]	Able to transport fibres for manufacture undamaged
			Heart Valves	No	Yes	Yes	No	2013	[13] [14] [15]	Passed successful human trails to replace heart
			Groundwork	No	Yes	Yes	No	2001	[9]	Performed delicate task of stabilising the leaning tower of Pisa

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