Over ~~2,000~~2000 years in review: Revival of the Archimedes ~~screw~~Screw from ~~pump~~Pump to ~~turbine~~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 (1 m/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~~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~~ 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~~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~~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~~Screw device 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~~ 0.5° [9].

2.3.3 Land ~~Reclamation~~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~~Screw [10,11].

2.3.4 Injection ~~Moulding~~moulding

In modern design methods, the Archimedes ~~screw~~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~~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~~1980s 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 ~~20~~20th~~th~~ 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 to the infancy of the technology, there is currently a lack of research on the topic.

3.1 Inclined ~~Axis Turbine~~axis turbine

Currently only screw turbine type is 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~~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.

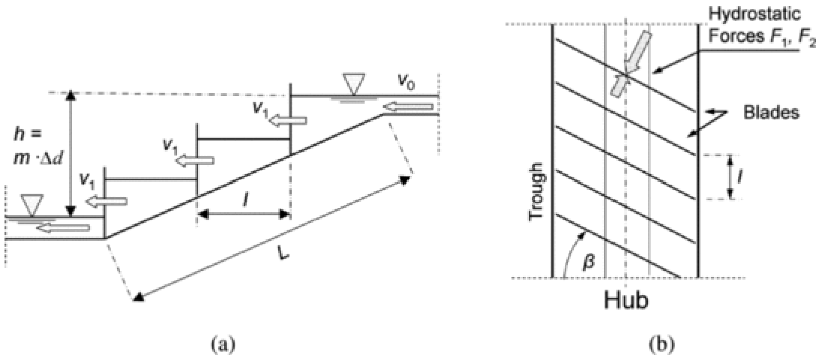

Fig. 1 Hydrostatic force acting on blades of Archimedes Screw ~~Turbine~~turbine [21].

3.2 Horizontal ~~Axis Turbine~~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, 58]. 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~~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 1 m/s [29].

4 Operational ~~Advantages~~advantages

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.

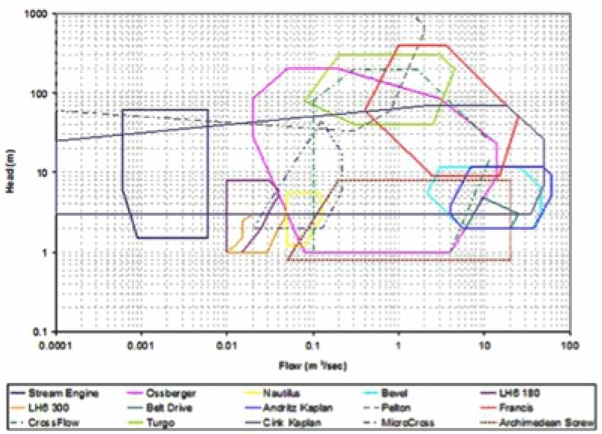

Fig. 2 Performance characteristics for various turbines [30–32].

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~~63 cm 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~~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.

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~~Screw is able to operate over a wider range of flows.

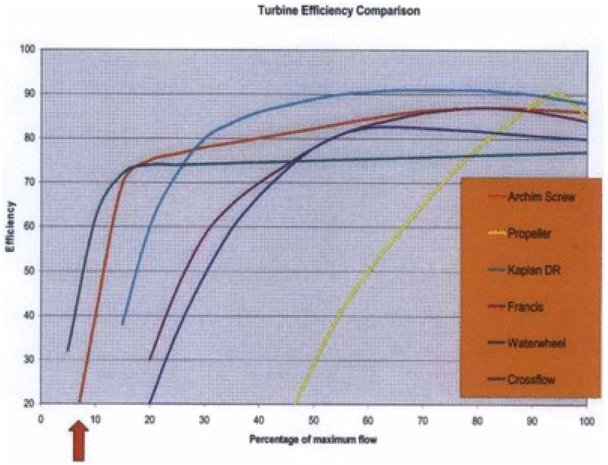

Fig. 3 Comparison of efficiency curves with varying flow [38].

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~~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~~criteria and ~~Optimisation~~optimisation

The design of any turbine involves a complex trade-off between the best and most cost ~~effective.~~effective~~ Muller~~. Müller and Senior [21] originally stated that the efficiency of an Archimedes ~~screw~~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.

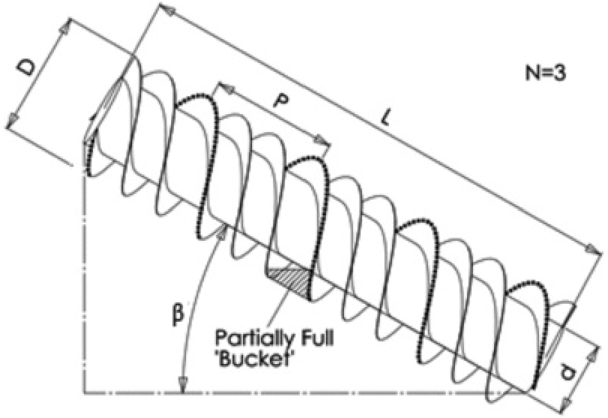

Fig. 4 Geometry of Archimedes Screw [41].

Table 1 Geometric Identities for Archimedes ~~Screw.~~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	

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.

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 3~~

Table 2 Performance ~~Ratios~~ratios for optimisation.

Name	~~Ratio/Relationship~~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~~parameters

5.1.1 Pitch ~~Ratio~~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.

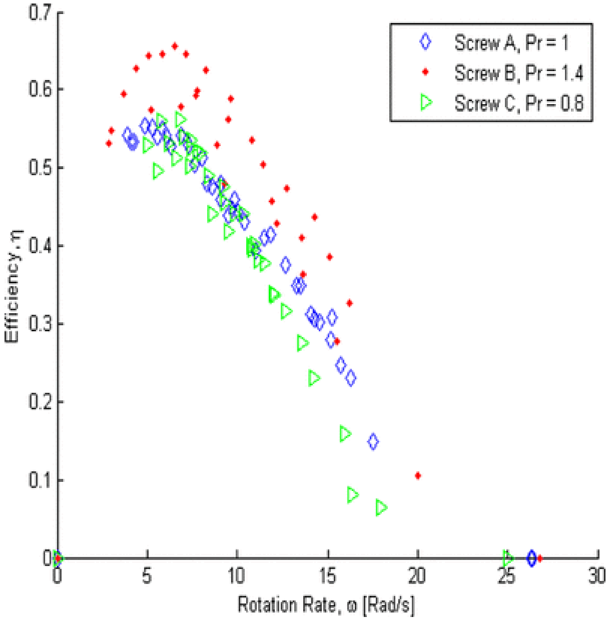

Fig. 5 Analysing how pitch ratio effects efficiency [44].

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~~speed

The fewer rotations per minute mean a more complex gearbox is required to convert the mechanical energy of the turbine into electricity. However, Lyons [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 Lyons [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%~~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 Müller and Senio [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 (Eq. (1)~~),~~) [20]. When more than one blade is used the power produced multiplied.

$$P = m \times P_{Blade} \quad (1)$$

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 4 m [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 [21,35,45–47].

Until the introduction of composites such as vinyl ester, screw diameters were limited to 4 m [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~~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~~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~~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~~50 m^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).

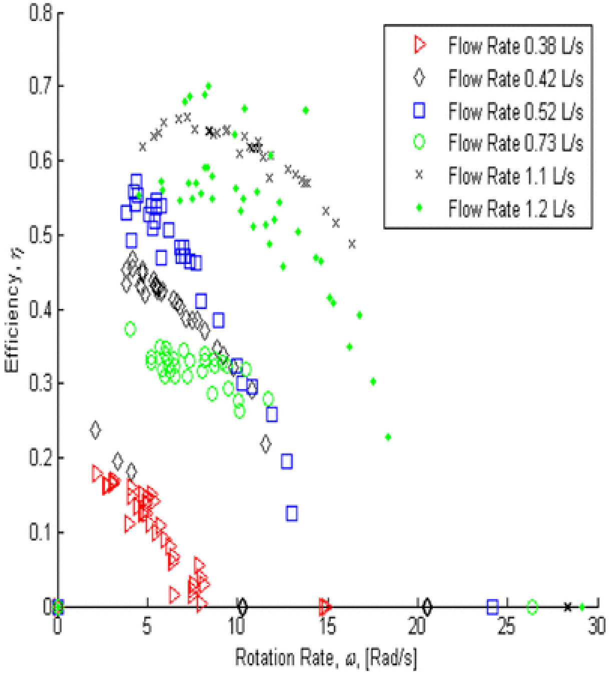

Fig. 6 Effects of varying flow rates to efficiency [44].

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 1.1 and 1.2 L/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).

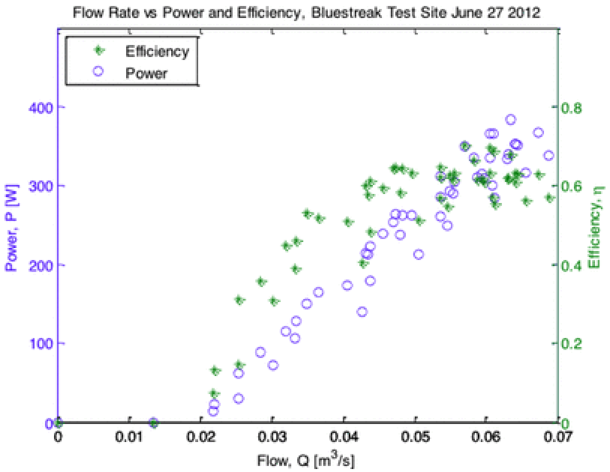

Fig. 7 Effects of flow rate to power and efficiency [44].

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.

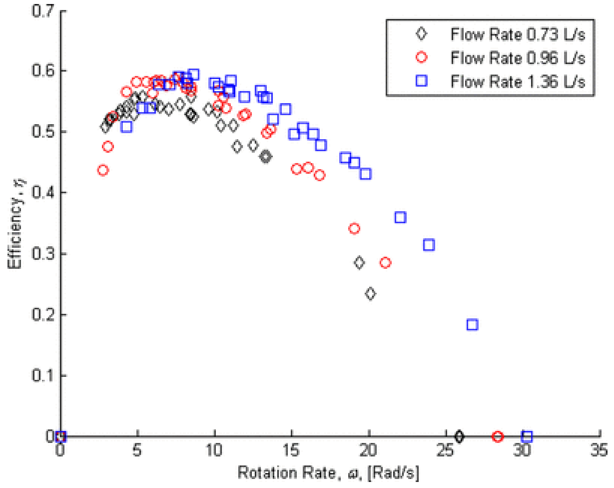

Fig. 8 effects of flow rate and efficiency [49].

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~~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.~~al. [48] state that the angle of efficiency increases as the angle of inclination is decreased as shown in Fig. 9.

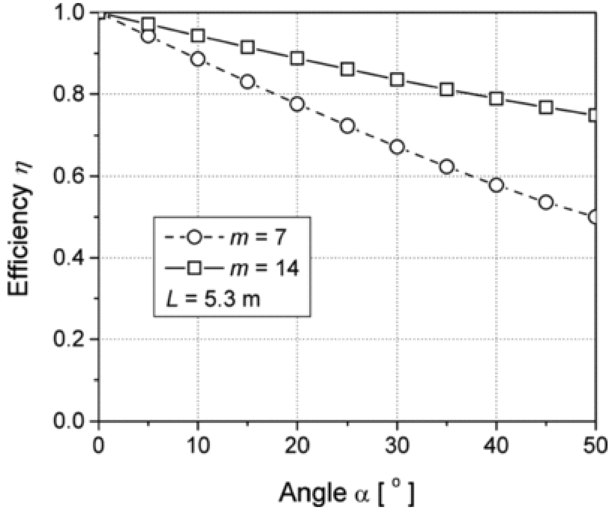

Fig. 9 Effects of inclination angle, number of turns and efficiency [21].

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).

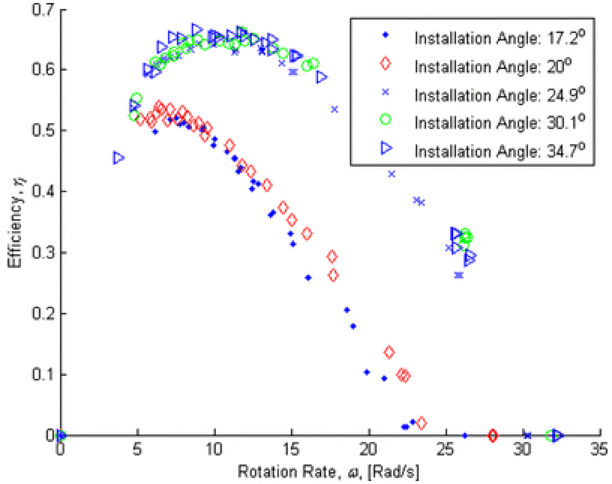

Fig. 10 Effects of inclination angle and efficiency [44].

From the graphs there is a clear limitation to how much improvement in efficiency there can be by altering the ~~angle,~~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~~ 0.1–50 ~~to 50m~~m^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 as 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~~development

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

6.1 Tidal ~~Barrage/Lagoons~~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~~was 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.~~invasive (Table 3).

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~~mode		Applications		Most recent publication	References	Comments

				Turbine	Pump	Current	Future			
Horizontal	Horizontal axis turbine	Theory and model testing	Hydrokinetic using kinetic energy in:	Yes	No	Yes	No	2013	[22–25,35,45–47, 58]	Model testing in progress
			River currents							
			Tidal currents							
			Tidal Fence	Yes	No	No	Yes	2015	[55,56]	Theoretical. Research currently in progress at Lancaster University (UK)
Inclined	Submerged Stream Turbine	Full scale testing	Deep sea currents above 1 m/s	Yes	No	Yes	No	2014	[26,27,29,57]	Full scale testing in progress in Norway
	Inclined axis turbine	Full scale deployment	River flows with head difference.	Yes	No	Yes	No	2014	[18,20,21,23,25,30,33–35,41,42,45–48]	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 2000 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	[13–15]	Passed successful human trails to replace heart
			Groundwork	No	Yes	Yes	No	2001	[9]	Performed delicate task of stabilising the leaning tower of Pisa

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.~~energy.

6.2 Tidal ~~Fence~~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~~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~~nature 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.

Uncited reference

[58].

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Queries and Answers

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