11 Archimedes Screw—An Alternative for Safe Migration Through Turbines?

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11.1 Introduction

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 turbine (Waters and Aggidis 2015).

Archimedes turbines are frequently considered more "fishfriendly" than conventional turbines due to their very low rotational rates (30 rpm) and blade tip speeds (3.8 m/s), low rates of pressure change, low fluid shear, and a low overall number of blades reducing contact probability. But this considered fish-friendliness has only been examined in a handful of studies. Hence, many unanswered questions on the fish friendliness of Archimedes turbines remain. For instance, it is unknown if and how the harmfulness of the screws depends on the operation of the screw (e.g. do the rates of injury and mortality decrease if we operate the screw at a low rotational speed over a longer period of time)? Besides, it

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is not clear how the characteristics of the screw influence the rates of injury and mortality, and if the potential relations differ per species. It may be the case that smaller screws pose an increased risk of injury and mortality than larger screws, and in general, screws may be less injurious when installed with a lower angle of inclination.

There are multiple ways to investigate the fish-friendliness of Archimedes screws at site. Until present scientists have been examining this by observations of injury and mortality of life fish (Schmalz 2010), or by sensors that sense the hydraulic forces fish are exposed to during passage (Boys et al. 2018). A few studies have combined life fish and sensor experiments (Deng et al. 2005), but not on an Archimedes turbine yet (Pauwels et al. 2020). So, the relation between the results of life fish studies and sensor studies also remains to be conclusively investigated.

Whether at new hydropower projects, or at sites where old turbines reach the end of their life and require refurbishing or replacement, there is considerable opportunity to further develop and optimize technologies and drive better outcomes for fish passage (Boys et al. 2018). Therefore, governments, policy makers, river managers and turbine designers need a list of the causes to design, build and remediate screws, to ensure that they provide a truly fishfriendly installation at each site. This requires much more multi-species analyses, including sensor analyses of multiple Archimedes screws of different dimensions and operational modes.

Within the FIThydro project, we investigated the rates of injury and mortality by multi-species fish experiments and the physical forces by barotrauma sensors during downstream passage through a large Archimedes hydrodynamic screw (10 m head, 22 m length and 3 m width, 1 MW). It was the first study to investigate multiple species, to combine life fish and passive sensor data and to investigate this in such a large Archimedes hydrodynamic screw.

11.2 Fish Passage at Archimedes Screws

Archimedes screws are among the world's oldest hydraulic machines that are still used today. Their primary use is as a type of low elevation water pump. In the latter part of the twentieth century, the screw re-emerged as a turbine (Waters and Aggidis 2015). In 1994, the first Archimedes screw turbine was installed in Europe, and by 2012 Lashofer et al. counted some 400 worldwide (Lashofer et al. 2012). Archimedes screw turbines are classified as small (1–10 MW) or mini (<1 MW) hydropower plants and are typically used at sites with a total elevation difference of 8–10 m and for discharges of 1–10 m^3/s (Quaranta and Revelli 2018). The screws rotate around an inclined axis ranging from 22° to 35° from the horizontal. They are further classified as "hydrodynamic screws" when the external cover does not turn with the screw, but is fixed and acts only as a support (Waters and Aggidis 2015; Quaranta and Revelli 2018; Lubitz et al. 2014) see Figs. 11.1 and 11.2.

Fig. 11.1 The hydropower station of Ham (Belgium), equipped with three Archimedes hydrodynamic screws (on the left; the cover does not turn with the screw and is fixed; the screws can pump water and generate power as turbine), and one true Archimedean screw (on the right, the cover is fixed to the screw and turns with it; this screw can only pump water)

There are a limited number of detailed studies on fish passage and Archimedes screws, most notably the study of (Schmalz 2010), who investigated wild local fish species including roach (*Rutilus rutilus*), bream (*Abramis brama*), eel (*Anguilla anguilla*), bullhead (*Cottus gobio*), three-spined stickleback (*Gasterosteus aculeatus*), spined loach (*Cobitis taenia*), and grayling (*Thymallus thymallus*), among others. In contrast to many claims that screws are inherently fishfriendly a substantial number of fish were found with scale loss, grinding injury, bleeding, and partial or complete cuts. In a study on the River Dart, UK, it was observed that almost all fish, including eels (*Anguilla anguilla*), trout (*Salmo trutta*) and salmonids (*Salmo salar*), passed through the Archimedes screw either unharmed (eels) or with negligible scale loss (salmon) (Kibel 2007, 2008; Brackely et al. 2018). Similarly, scale loss did not differ between treatment and control groups of salmon in a study on the River Don, Scotland (Brackely et al. 2016). However, the investigations of scale loss on euthanized individuals at the same site showed severe scale loss and distinctive patterns of scale loss due to grinding between the turbine blades and housing trough (Brackely et al. 2018). In addition, further studies found that fish with a body mass

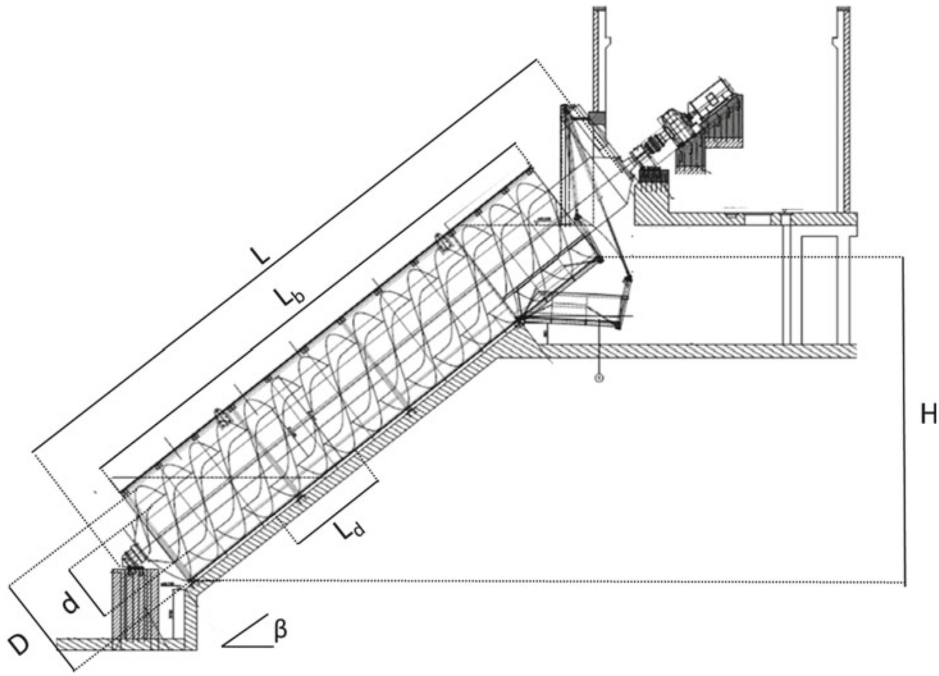

Fig. 11.2 Profile of the large Archimedes hydrodynamic screw at Ham (Belgium) that was studied within the FIThydro project, showing the injection location of fish and sensors on the top valve of the turbine (inset picture showing the valve in closed position; adapted from Pauwels et al. 2020)

less than 1 kg were not injured by contact with the screw leading edge if the tip speed was less than 4.5 m/s. The addition of a rubber leading edge further reduced injuries to larger fish at higher tip speeds (Kibel et al. 2009; Lyons and Lubitz 2013). In the study of river lamprey (*Lampetra fluviatilis*) on the River Derwent, UK, the damage rate was 1.5% for 66 juveniles released immediately upstream and who subsequently passed the Archimedes screw (Bracken and Lucas 2013). The impact of the screws in the River Sour, UK, and Diemel, Germany, were investigated by acoustically tagged eels (*Anguilla anguilla*) and salmon (*Salmo salar*). The behaviour of the eels in the River Sour was not found to be directly impacted by the screw passage. However, migration delay was introduced at this site by the fish being frequently milled and rejected back upstream (Piper et al. 2018). A screw study in the River Diemel observed a probability of 0–8% that a smolt would die after passing the screw (Havn et al. 2017). The findings of these studies show first that the published knowledge on Archimedes screws and fish passage are very limited in scope and are based on a limited number of live fish studies during Archimedes hydrodynamic screw passage. In order to improve designs, operational guidelines and improve downstream fish passage at screws, more research is needed to identify, define and establish the risk of injury and mortality to fish passing downstream through screws.

Apart from assessing the biological responses of live fishes, the development of safer screws can also be assessed by using passive sensors (Fig. 11.3). These sensors measure the physical conditions experienced during passage. Several studies for Kaplan turbines exist (Fu et al. 2016; Deng et al. 2005, 2010), however there is only a single study to date that has used sensors to measure the physical conditions in an Archimedes turbine (Boys et al. 2018). A recent sensor passage study evaluated event-based statistics including the number and severity of strike events, the nadir (lowest) and maximum pressures, and rate of pressure change. No live fish studies at the site were compared with sensor data in that study (Pauwels et al. 2020). However, two studies have combined live fish and sensor experiments (Deng et al. 2005, 2010). The first study was performed in a laboratory setting investigating shear-related injury and mortality, and the second related the percentage of severe events (collision and/or shear) to 48 h delayed mortality from live fish studies

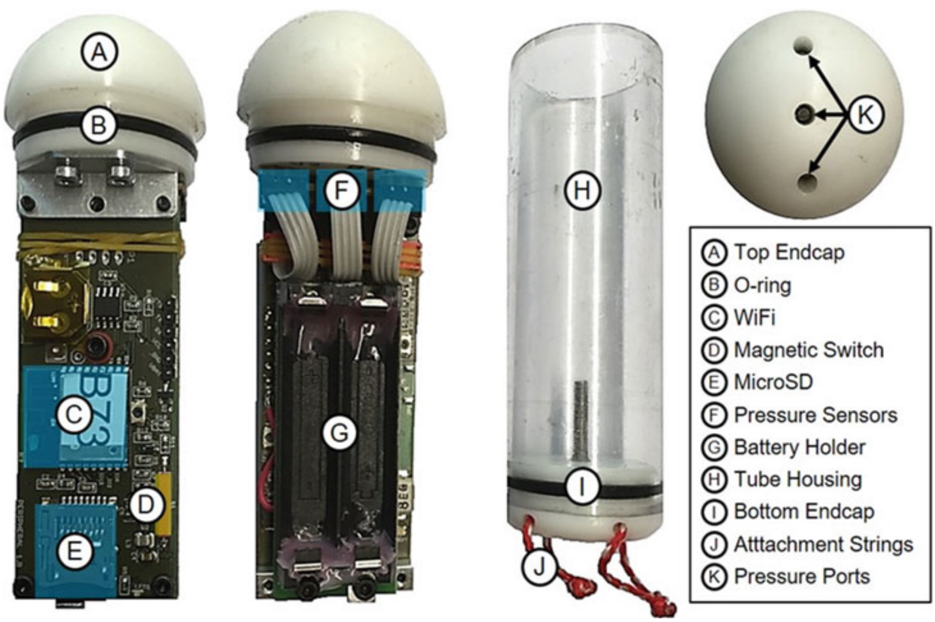

Fig. 11.3 Overview of the BDS sensors used in the study in the FIThydro project. The top endcap (**a**, **b**) contains three pressure transducers (**f**, **g**). Below there are two electronics boards containing the WiFi module (**c**), magnetic switch (**d**), microSD storage (**e**), and AAA battery holder (**g**). The sensor and electronics payload (**a**-**g**) is screwed by hand onto the bottom endcap (**i**), which also includes two rugged nylon attachment strings (**j**) for the balloon tags to bring the neutrally buoyant sensor back to the water surface (Pauwels et al. 2020)

in two Kaplan turbines. Therefore, the link between actively swimming fish and passive sensors remains to be conclusively investigated. Differences in the observed injury and mortality between fish species require multispecies, live fish experiments. Understanding the relationships among various strike variables and injury and mortality rates are necessary for improvements in turbine design), (Boys et al. 2018; Čada 2001). In our study within the FIThydro project, we evaluated injury and mortality of 2700 fish of three species that passed the Archimedes hydrodynamic screw of Ham shown in Fig. 11.2 at one of three rotational speeds: 30, 40 and 48 Hz. Additionally, we measured the total water pressure, linear acceleration, rotation rate, magnetic field intensity and absolute orientation (roll, pitch and yaw angles) during passage on each of the three rotational speeds with passive Barotrauma Detection System (BDS) sensors. The sensors illustrated in Fig. 11.3 were developed by the TalTech Centre for Biorobotics as part of the EU H2020 FIThydro project. We learned from this study that the chance to be injured or killed by the screws depends on the species. Substantial loss of fish due to screw passage was observed for bream, also for roach but not for eel, see Fig. 11.4. A screw passage was found to be a chaotic event and the relation between injuries and mortality and the rotational speed of the screw was not straightforward.

In summary, to date, the available studies strongly indicate that (A) Archimedes and hydrodynamic screws used as turbines are very unlikely to cause barotrauma-related fish injury and mortality, (B) mortality and injury rates are generally lower compared to conventional turbine types, but (C) they may cause injury and mortality, which is highly dependent on the fish species. Therefore, we stress the need for further studies on Archimedes screws to identify the causes of the observed species-specific injury

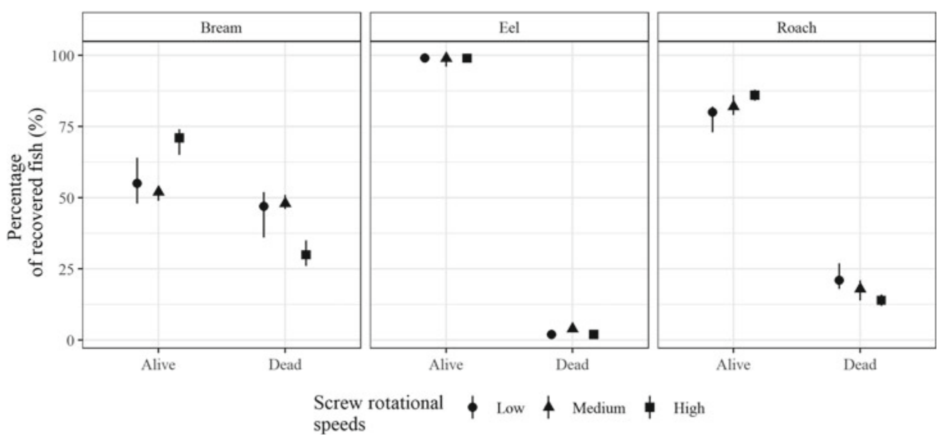

Fig. 11.4 Proportions of bream (Abramis brama), eel (Anguilla anguilla), and roach (Rutilus rutilus) indicating the state as either alive or dead after forced Archimedean screw turbine passage for each of the three rotational speeds tested: 33, 40 and 48 Hz (Pauwels et al. 2020)

and mortality rates. The largest challenge is to identify which screw characteristics significantly affect the rates of injury and mortality. Is it blade edge grinding, large-scale turbulence, shear stress, intermittent blade contact in the buckets or perhaps impingement between the blades and outer housing in hydrodynamic screws? Governments, policy makers, river managers and turbine designers need a list of the causes to design, build and remediate screws, to ensure that they provide a truly fishfriendly installation at each site. We believe these answers might specifically help to improve the design of larger screws (up to 10 MW) such as the one investigated in our study. Because screws can also pump water, improving their fish-friendliness, could make them better competitors for conventional pumps and turbines. To begin to address these key questions, it is imperative that future studies provide a list of standardized descriptions and physical metrics to cross-compare screws and identify the potential causes as they relate to the particular characteristics of the screw. We have provided an example of the basic characteristics needed for future studies in and have illustrated them on the profile of the investigated screw of Ham (Belgium; Fig. 11.2 and Table 11.1).

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Table 11.1 Basic characteristics needed in studies for the cross-comparison of Archimedes hydrodynamic screws, illustrated using values of the screw investigated in Ham, Belgium. Figure 11.2 indicates the screw parameters on the profile of the Ham screw (Pauwels et al. 2020)

Screw Parameters	Abbreviation	Value
Maximum power (MW)	–	1.2
Center tube length (m)	L	23
Helix length (m)	L_b	21.5
Slope (°)	β	38
Number of blades	–	3
Helix lead (m)	L_d	4.3
Centre tube diameter (m)	d	2.4
Helix diameter (m)	D	3.1
Helix operation (rpm/Hz/m^3/s)	–	13.71/33/3 16.62/40/4 19.95/48/5
Gap between helix and housing (cm)	–	±2 cm
Fish deterrence system	–	None
Fish injury reduction measures	–	None

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