FISH SURVIVAL IN THE TURBULENT® HYDRO TURBINE AT DENVER SLUICE

A THEORETICAL STUDY BASED ON NEN 8775
COMMISSIONED BY ENVIRONMENT AGENCY (UK)

Status report : final
Date report : 04-03-2022
Author : Dr. B.P.M. van Esch

BE Engineering
Registered in The Netherlands under KVK17118004

1. INTRODUCTION

The purpose of this study is to assess the survival rate of fish and eel passing through a Turbulent® hydro turbine designed for low head power generation. The turbine is of axial-flow, propeller type and has five blades with a backward-curved leading edge profile (figure 1). The runner is shrouded with a cylindrical metal plate that covers the full axial extent of the blades.

A turbine of a similar type will be installed at the Denver sluice (figure 2). Its runner has an outer diameter of 1500 mm and an inner diameter of 675 mm.

The expected duty point at Denver sluice:

- *system head* : $H_{sys} = 1.1$ m
- *capacity* : $Q = 1.1$ m^3/s
- *shaft speed* : $N = 52$ rpm

The assessment of fish damage is based on the Dutch NEN 8775 standard for fish safety in pumps, Archimedean screws, and hydro turbines (2020).

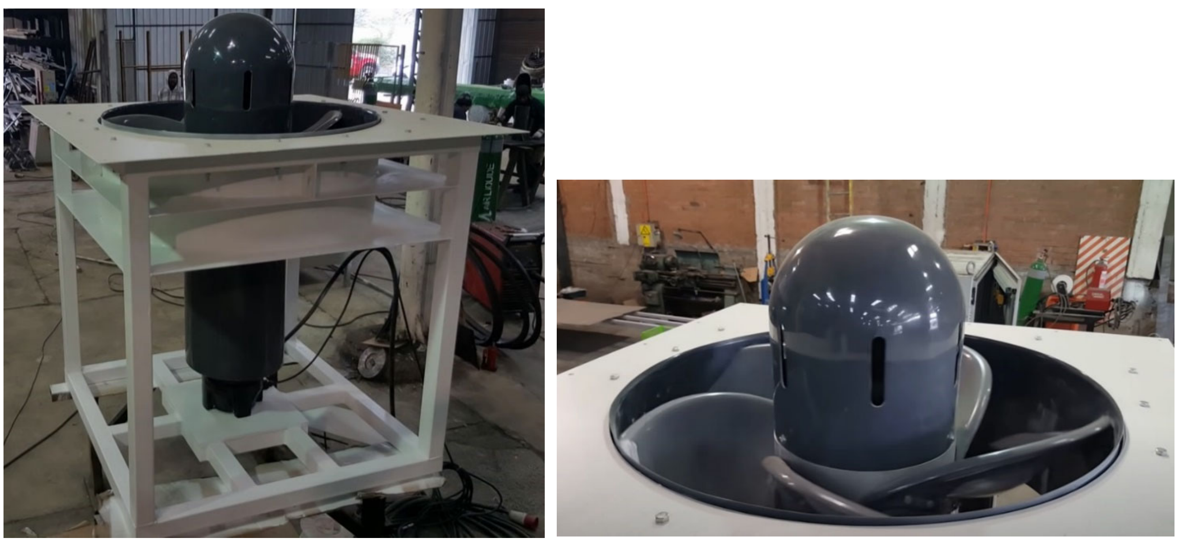

Figure 1: Five-bladed runner of the axial-flow Turbulent hydro turbine [YouTube: gY3p2e1-kN4]

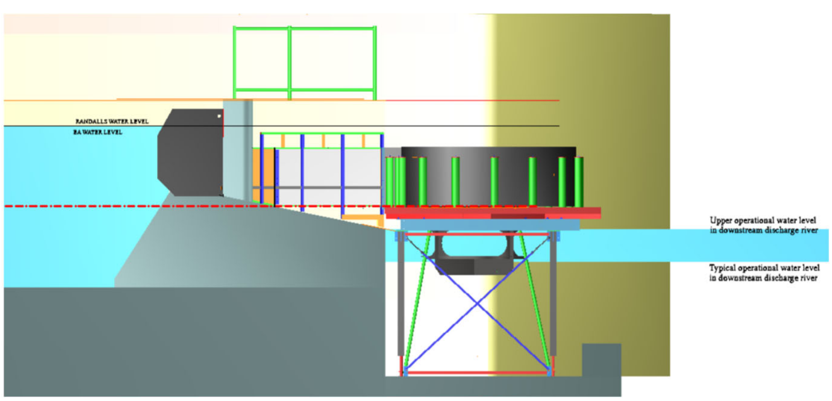

Figure 2: Cross-sectional view of the 1.5 m diameter hydro turbine at the Denver sluice site

2. HYDRAULIC PERFORMANCE

The head difference across the runner will be smaller than 1.1 m due to the head losses in the scroll and the tailwater channel, but still it appears that the design of this turbine deviates from what would be considered a conventional design at these operating conditions: a mixed-flow, Francis type turbine with a 1.75 m runner diameter. Instead, the Turbulent turbine is an axial flow, propeller type turbine with a smaller diameter of 1.5 m.

A second observation that distinguishes this turbine from conventional designs, is that it lacks inlet guide vanes. The shape of the intake promotes the occurrence of a vortex but its strength is difficult to control and hard to predict. The fact that the scroll intake channel is also uncovered complicates matters even more. Controllable Inlet guide vanes are missing, probably to simplify the construction and to reduce the costs. Figure 3 shows how the swirling flow is induced in the scroll before it passes the runner.

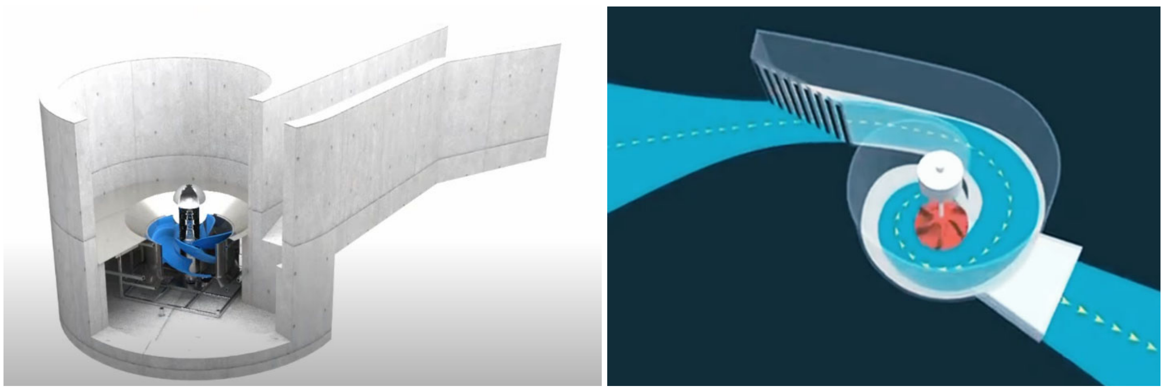

Figure 3: Runner installed in its scroll casing (left) and flow path through the turbine [YouTube: UA-llCWO_8w]

CFD calculation results (Turbulent Hydro, 2021) seem to suggest that the swirl velocity c_t near the entrance of the runner changes from an estimated 2.5 m/s near the hub to 3.8 m/s near the tip of the blades (figure 4). It means that the core of this vortical flow almost resembles a solid body rotation approximately equal to the runner angular speed. In other words, the flow entering the runner approximately rotates with the speed of the blades. The relative, circumferential velocity w_t is below 0.7 m/s anywhere along the leading edge of the runner blade.

	r [m]	U [m/s]	c_t [m/s]	w_t [m/s]	v_{ax} [m/s]	w_{strike} [m/s]	$H_E(r)$ [m]	$H_E(r)v_{ax}2\pi r$ [m3/s]	$H_E(r)v_{ax}dA$ [m4/s]
tip	0.750	4.084	3.800	-0.284	0.781	0.831	1.582	5.819	0.417
	0.668	3.635	3.540	-0.095	0.781	0.786	1.312	4.294	0.303
	0.585	3.186	3.280	0.094	0.781	0.786	1.065	3.056	0.212
	0.503	2.736	3.020	0.284	0.781	0.830	0.842	2.076	0.140
	0.420	2.287	2.760	0.473	0.781	0.913	0.643	1.325	0.087
hub	0.338	1.838	2.500	0.662	0.781	1.024	0.468	0.775	

Table 1: Velocities at the leading edge of several blade sections and ideal Euler head H_E, with r the radius, U the blade speed, c_t the absolute circumferential velocity, w_t the relative circumferential velocity, v_{ax} the axial velocity, and w_{strike} the strike velocity, at Q = 1.1 m^3/s, H_{sys} = 1.1 m, N = 52 rpm.

Assuming no losses in the runner and swirl-free exit flow, the average Euler head is computed as

$$\overline{H_E} = \frac{1}{Q}\int_A H_E\, v_{ax} dA = 1.054 \text{ m},$$

equivalent to an Euler power of $P_E = \rho g Q H_E$ = 11.4 kW, which corresponds to the available power in the water.

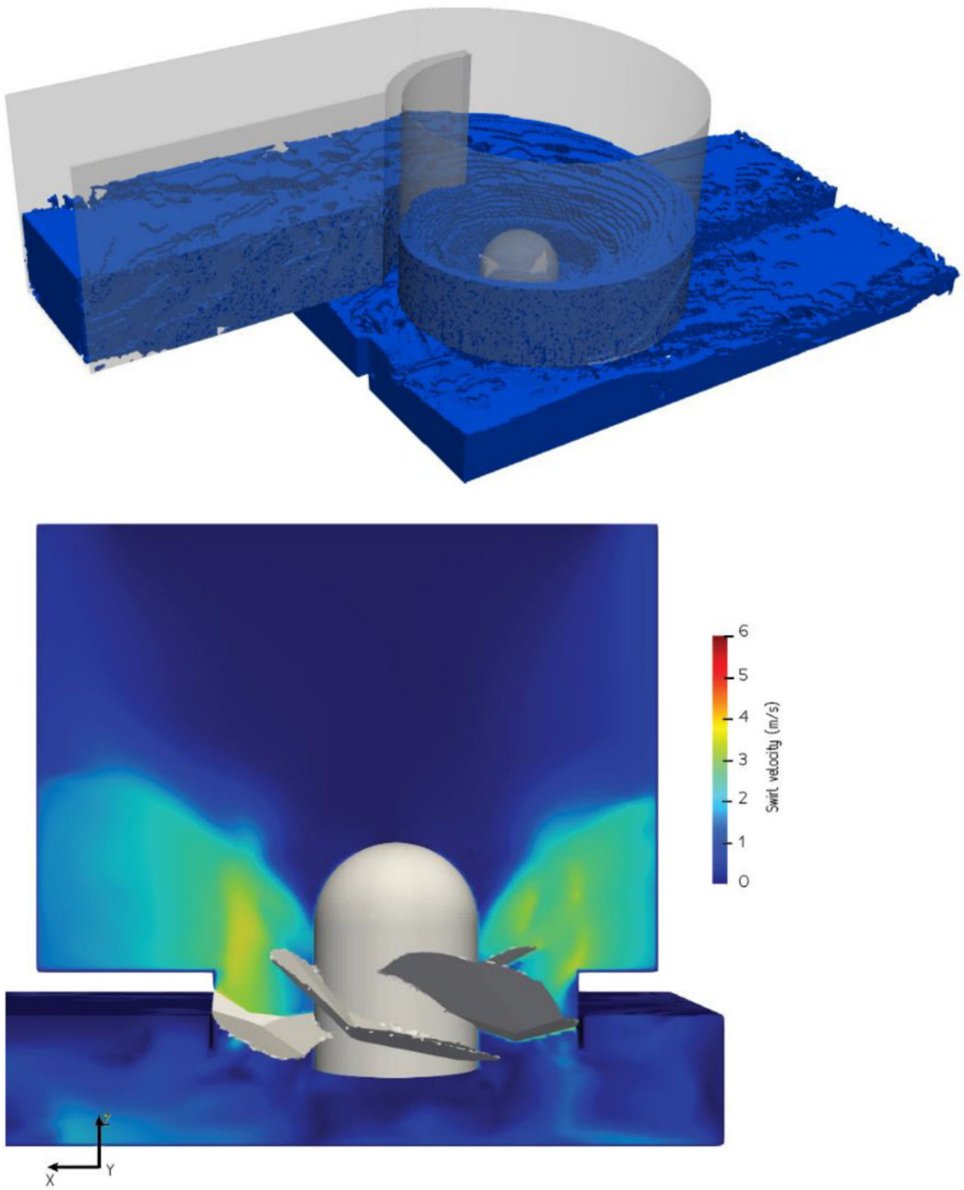

Figure 4: Two-phase flow CFD results showing the free surface of the vortical flow in the scroll and the distribution of swirl velocity c_t in a cross section of the turbine, at Q = 1.1 m^3/s, H_{sys} = 1.1 m, N = 52 rpm.

3. NEN 8775 STANDARD

Research on the mechanisms responsible for fish damage in pumps and turbines gained momentum after the start of the US Department of Energy's Advanced Hydropower Turbine Systems (AHTS) program in 1994. One of the goals of this program was to develop a new or improved runner for a hydropower turbine system that would reduce the risk of injury and mortality to fish passing through. An important step in the AHTS program was to study the biological criteria for fish injury and mortality. The laboratory experiments that were conducted were aimed at the three main mechanisms for damage to fish passing through turbine systems: mechanical damage, velocity shear, and pressure fluctuations (Cada et al., 1997).

Mechanical injury by blade strike is generally regarded as the primary cause of damage to fish passing through turbine systems with heads up to 30 m (Turnpenny et al., 2000; Cook et al, 2003; Amaral et al., 2011). It can lead to bruises, haemorrhage or even severing of the body. A study by Van Esch (2012) led to the same conclusion for fish passing through the pumps of a pumping station.

Secondary causes of mechanical injury are grinding of fish along rough surfaces, entrapment of fish in the clearance between a rotor blade and the stationary casing or wear ring, and fish being scissored by rotating blades and stationary guide vanes in the vaneless gap between both elements.

This study follows the Dutch standard NEN 8775 "Fish safety – Method for determining the fish safety of pumps, Archimedean screws and turbines used in pumping stations and hydroelectric plants". A blade strike model calculates the theoretical probability of a collision between the runner blades and a fish of a given length. This probability is then multiplied by the mutilation ratio, which is the probability that a blade hit (of a given velocity) will lead to instant death or severe injury. The result is the damage probability for a fish passing through the turbine.

A correlation by Van Esch (2012) of the most recent measurements of blade strike mortality rate to rainbow trout (EPRI, 2008/2011) is used in NEN 8775 to calculate the mutilation ratio of a blade strike to fish. For eel, a correlation by Van Esch and Spierts (2014) is used, based on measurements with European eel of 40-60 cm. These models correlate the blade strike mortality ratio with the velocity at impact and the ratio of fish length to leading edge blade thickness.

The following assumptions are made:

- *fish move passively and aligned in the direction of the flow*
- *fish enter the turbine runner uniformly distributed over the entrance area*
- *small eel (<40 cm) suffer mutilation rates in accordance with the NEN norm, even though their physiology may be quite different from larger eel*
- *the correlation for mutilation ratio of rainbow trout is also valid for coarse fish species such as bream, rudd, perch, and roach*

Later studies of blade strike damage for other fish species such as roach and perch (van Esch and Spierts, 2014; Krakers et al., 2015) and gizzard shad and striped bass (Bevelhimer et al., 2019) revealed that the mutilation ratio for these species is in accordance with the one for trout, but results show a variability of up to 15% between the 2011 and 2019 research data.

Experience over the past few years showed that model predictions of damage rates using NEN 8775 are in good agreement with trials for eel > 40 cm. For smaller eel there is not yet sufficient data to validate the method. For several types of scaly fish, the NEN 8775 method seems to over-estimate the mortality rates. Computed damage rates are often found to lie in between the observed mortality and the observed combined percentages dead and (slightly) injured. A possible reason for the difference might be that NEN 8775 prescribes a holding period of 48 hours after the trials to assess delayed mortality whereas fish in the EPRI (2011) tests were held for 96 hours after the experiments.

In the NEN standard, the secondary causes of fish damage (grinding, entrapment, and scissoring) are mentioned, but only in general terms – there is no evidence based method to quantify potential damage. It is acknowledged, however, that the resulting damage is usually much lower than that of blade strike. Still, it is advised to minimize any adverse effects.

4. BLADE STRIKE DAMAGE ESTIMATIONS

The probability of severe fish damage caused by blade strike is calculated following the Dutch standard NEN 8775 for fish safety in pumps, Archimedean screws, and hydro turbines (2020). The calculation is restricted to the duty point of the turbine, i.e. a capacity of 1.1 m^3/s and 1.1 m of head at a shaft speed of 52 rpm.

The probability of a blade strike at the duty point depends on the length of the fish, not on the species. Results for various fish lengths are listed in table 2, where it is assumed that fish move passively and aligned in the direction of the flow, and that fish enter the turbine runner uniformly distributed over the entrance area.

L_{fish} [cm]	P_{th} [%]
20	2.7
40	5.4
60	25.1
80	61.8
100	100

Table 2: Strike probability at the duty operating point for various lengths of scaly fish and eel.

The blades of the runner are equipped with strips of protective rubber that cover the full length of the leading edges (figure 5). This prevents the risk of cuts when fish come into contact with a leading edge as it would otherwise have sharp edges.

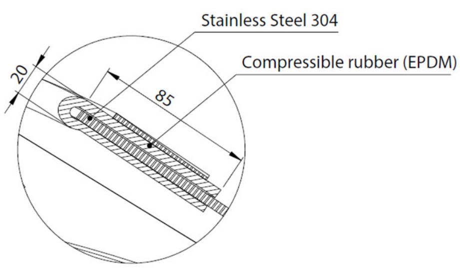

Figure 5: Cross section of the leading edge of a blade showing the rubber protective cover

The strike velocity w_{strike} between a fish and a point along the leading edge of the blade is calculated based on the shaft speed, the circumferential velocity induced by the scroll (based on CFD), the flow rate, and the dimension of the runner. Calculated values are listed in table 1. Strike velocities are below approximately 1 m/s anywhere along the leading edge. It means that severe damage to fish caused by a hit by the runner blades is unlikely since the expected strike velocities anywhere along the blade (from hub to tip) are well below 4.8 m/s. This threshold is the maximum velocity not to cause severe damage to scaly fish according to the NEN standard. For eel this threshold of safe strike velocities is even higher: 8 m/s.

5. SECONDARY CAUSES OF FISH INJURY

In the NEN standard a number of secondary causes of fish damage are mentioned. These causes are merely covered in general terms – there is no evidence based method to quantify potential damage. It is acknowledged, however, that the resulting damage is usually much lower than that of blade strike. Still, it is advised to minimize any adverse effects.

A number of potential causes of damage in the Turbulent hydro turbine, other than blade strike, were identified:

1. *entrapment of fish in the tip clearance between a rotor blade and the stationary casing or wear ring*
2. *fish being scissored between a rotating blade and the stationary tubular casing while leaving the turbine through the side gaps below the runner*
3. *grinding of fish along rough, concrete surfaces or protruding bolts and nuts*

5.1 ENTRAPMENT IN CLEARANCES

The runner is shrouded with a cylindrical metal plate that covers the full axial extent of the blades (figure 6). Since the shroud co-rotates with the runner and connects to the tip of the blades, tip clearances are absent.

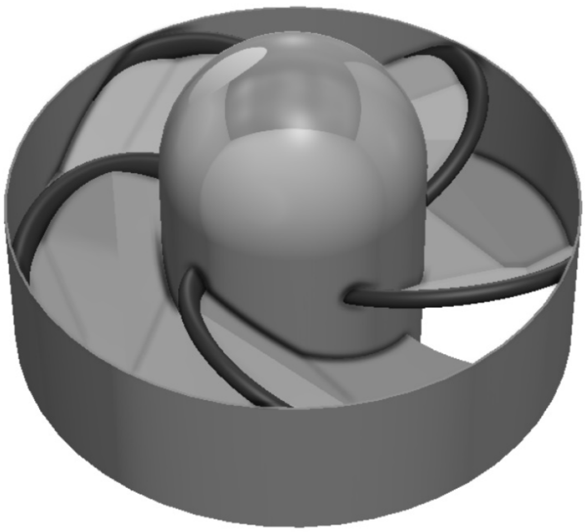

Figure 6: Runner with welded, co-rotating shroud

Still, a leakage gap exists between the rotating shroud of the runner and the tubular casing. The direction of the leakage flow is downwards and promotes fish getting caught in this gap.

Turbulent decided to add a metal ring that covers the leakage gap between the runner and the tubular casing (figure 7). This will be an effective means to prevent the fish from entering.

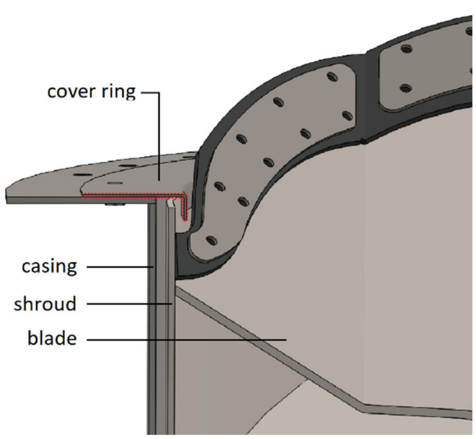

Figure 7: Cover ring shielding the leakage gap between the shroud and the casing.

5.2 SCISSORING BETWEEN RUNNER AND STATOR

Below the runner of the turbine, the water exits through four oval shaped holes in the tubular casing, called the cradle. This cradle acts as a support for the motor and the runner (figure 8). The exit of the runner blades is in close proximity to the holes. Long fish, like eel, that exit the runner can make contact with the sides of these holes while still being swept by the blades. Since the holes are cut in the steel-plated casing, the sharp edges can severely damage fish even if velocities at the runner exit are usually low.

Turbulent decided to add a rubber protective layer onto these edges thick enough to prevent cuts (figure 9).

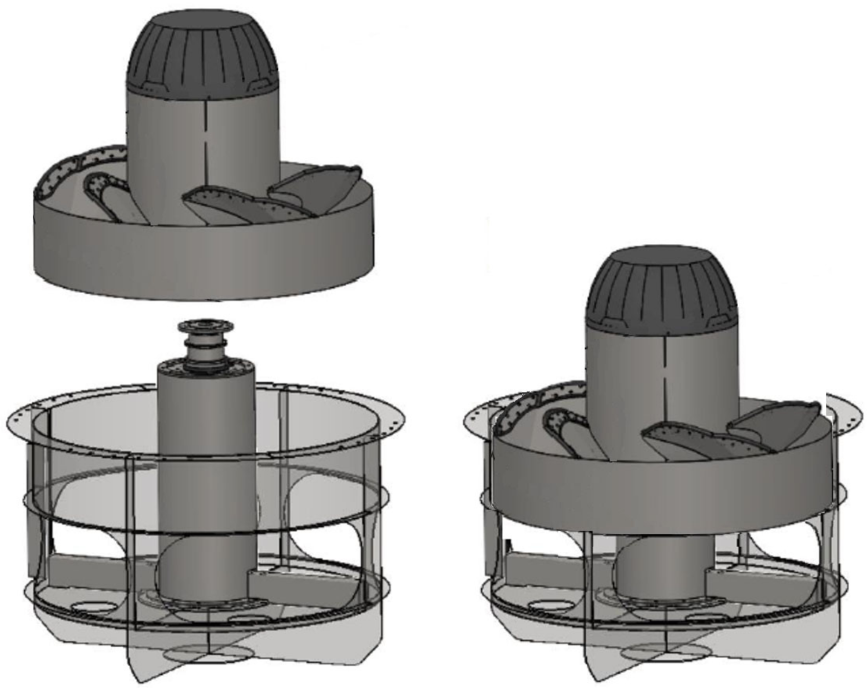

Figure 8: Support structure (cradle) holding the motor and the runner.

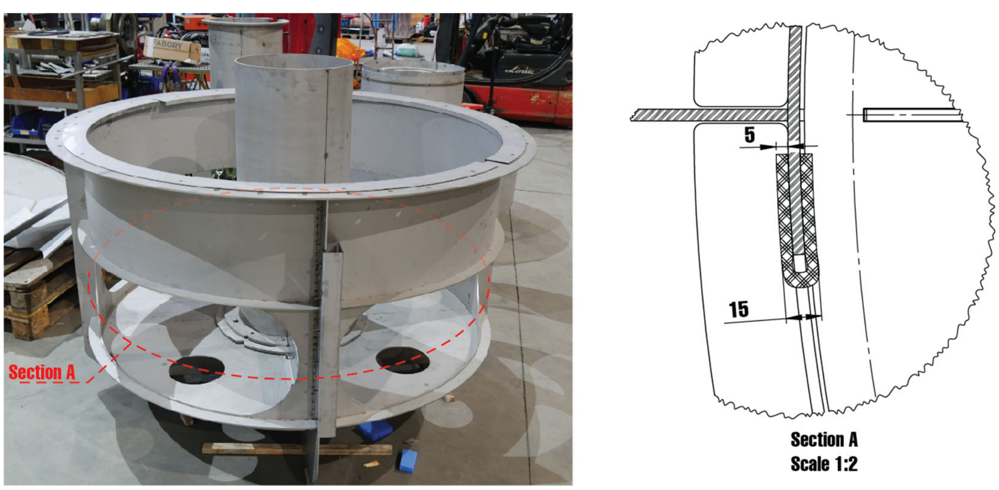

Figure 9: Rubber protective layer onto the edges of the side holes of the cradle

5.3 GRINDING ALONG ROUGH SURFACES

Rough surfaces, like concrete walls or plates with protruding bolts, can lead to scale loss, cuts, or other skin damage when fish move closely along these surfaces. Turbulent stated that there will be no such walls or obstacles at the Denver turbine site.

6. CONCLUSION

A theoretical fish survival assessment is done for the Turbulent® hydro turbine at Denver sluice, following the Dutch NEN 8775 standard for fish safety in pumps, Archimedean screws, and hydro turbines (2020). The turbine is of axial-flow, propeller type, has five blades, and a runner diameter of 1.5 m.

The probability of severe damage caused by blade strike is computed for the duty operating point of the turbine:

- *system head* : $H_{sys} = 1.1$ m
- *capacity* : $Q = 1.1$ m^3/s
- *shaft speed* : $N = 52$ rpm

The probability of a blade strike depends on the length of the fish and ranges from 2.7% for a small length of 20 cm, to 100% for a fish of 100 cm. In the calculation it is assumed that fish align with the flow and expose their full length to the blades, which results in a worst-case estimation.

Even though strike probability can be high, no severe strike damage to fish or to eel of any length is to be expected. Based on the results of CFD calculations, the strike velocity between a blade and a fish that moves passively with the flow, is below approximately 1 m/s regardless the location of the strike along the leading edge. According to the NEN standard, such strike velocities are not likely to cause severe damage.

Secondary causes for fish injury were also considered, i.e. entrapment in clearances, scissoring between runner and stator, and grinding along rough surfaces. It led to appropriate changes in the design in order to mitigate the potentially negative consequences.

REFERENCES

NEN 8775:2020(en) Fish safety - Method for determination of the fish safety of pumps, Archimedean screws and confined water turbines used in pumping stations and hydroelectric plants

Amaral, S.V., Hecker, G.E., and Dixon, D.A. 2011. Designing leading edges of turbine blades to increase fish survival from blade strike. In EPRI-DOE, Conference on Environmentally-Enhanced Hydropower Turbines, EPRI Report No. 1024609

Bevelhimer, M.S., Pracheil, B.M., Fortner, A.M., Saylor, R., and Deck, K.L., 2019, Mortality and injury assessment for three species of fish exposed to simulated turbine blade strike, Canadian Journal of Fisheries and Aquatic Sciences, Vol. 76 (12)

Cada, G. F., Coutant, C. C., and Whitney, R. R. 1997. Development of biological criteria for the design of advanced hydropower turbines. , DOE/ID-10578, U.S. Department of Energy, Idaho

Cook, T.C., Hecker, G.E., Amaral, S.V., Stacy, P.S., Lin, F., and Taft, E.P. 2003. Final Report - Pilot scale tests Alden/Concepts NREC Turbine. Alden Research Lab. inc., Holden, MA

EPRI (Electric Power Research Institute). 2008. Evaluation of the effects of turbine blade leading edge design on fish survival. Prepared by Alden Research Laboratory, Inc., EPRI Report No. 1014937

EPRI (Electric Power Research Institute. 2011. Fish passage through turbines: application of conventional hydropower data to hydrokinetic turbines. Prepared by Alden Research Laboratory, Inc., EPRI Report No. 1024638

Krakers, L.A., Kruyt, N.P., and Rutjes, H.A., 2015, Full-scale validation of a comprehensive criterion to predict fish-friendliness of pumps, AJKFluids2015-216450, AJK Joint Fluids Engineering Conference, July 2015, Seoul, Korea

Turbulent Hydro, Fish friendliness clarifications, 20-09-2021

Turnpenny, A.W.H., Clough, S., Hanson, K.P., Ramsey, R., and McEwan, D. 2000. Risk assessment for fish passage through small low-head turbines. Report No. ETSU H/06/00054/REP. Energy Technical Support Unit, Harwell, United Kingdom

Van Esch, B.P.M. 2012. Fish injury and mortality during passage through pumping stations. J. Fluids Eng. - Trans. ASME 134(7), 071302. doi: 10.1115/1.4006808

Van Esch, B.P.M., Spierts, I.L.Y., 2014, Validation Of A Model To Predict Fish Passage Mortality In Pumping Stations, Canadian Journal of Fisheries and Aquatic Sciences, 10.1139/cjfas-2014-0035