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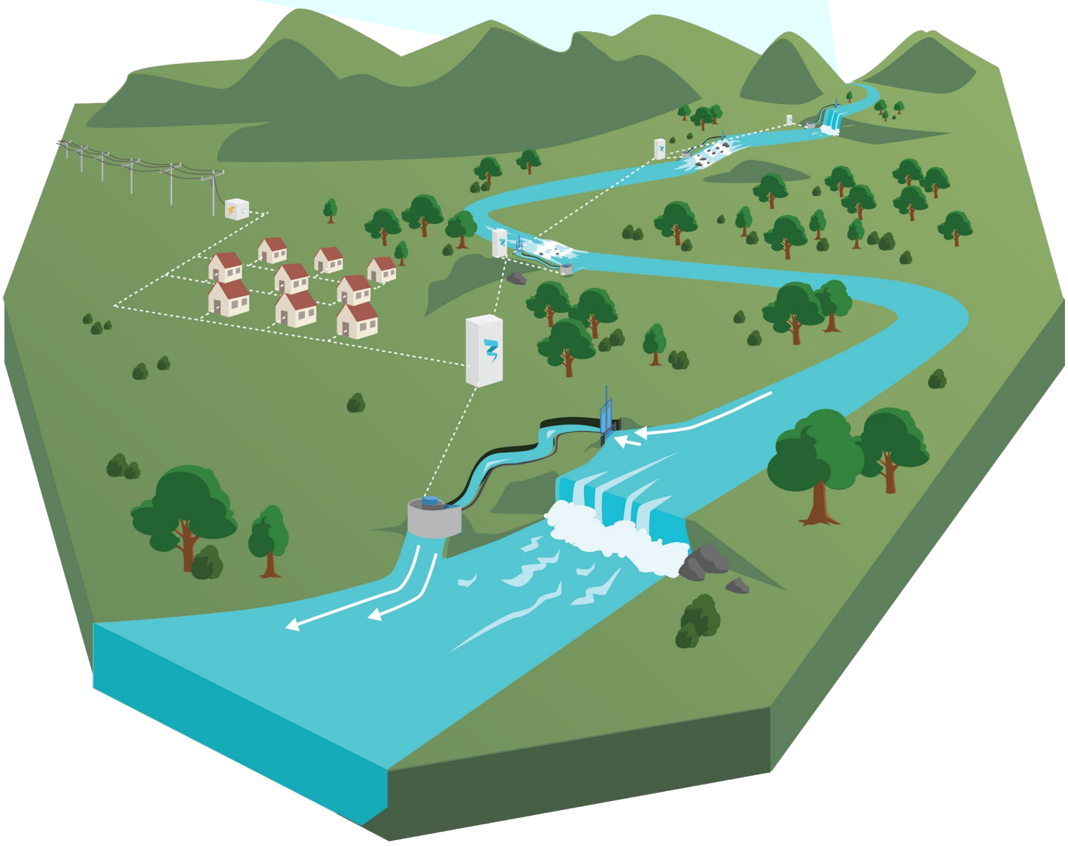
Report on fish friendly design of the Turbulent vortex turbine.



www.turbulent.be
Wijgmaalsesteenweg 6, 3012 Wilsele, Belgium

Contents

1. Introduction

The main objective of this report is to demonstrate that the operation of the turbine doesn't affect the natural fish population letting the fish pass through the turbine unharmed. To validate that assumption we used tried and tested formulas and methods from the "Alden Turbine Labs".

We present a summary of the investigations that were made on turbines showing the values for the operation points that ensure a fish friendly operation for our turbine. In particular, we present also a comparison between the recommended value and the value calculated for the operation of our turbine, in every variable we keep values below the limits that harm a fish.

2. Fish potential damage classification

Potential damage mechanisms are identified in 4 categories; mechanical, pressure, shear, and cavitation (USACE 1995). Mechanical causes include strike, abrasion, and grinding. Pressure fluctuations, shear stress, turbulence, and cavitation are related to flow characteristics.

Mechanical: Abrasion, Grinding, and Strike

The rubbing action of a fish against a turbine system component or objects in the flow field is referred to as abrasion, and can cause damage to the fish (USACE 1995). Abrasion damage is dependent on flow discharge and velocity, number of turbine blades and spacing between them, and the geometry of flow passages (USACE 1995). Data are not available to identify the amount of or to distinguish injury due to abrasion.
Grinding injury can occur when a fish is drawn into small clearances (gaps of sizes close to that of the fish) within the turbine system (USACE 1995). Gaps with high velocity zones that may cause grinding injury are present between the turbine blade leading edge and the hub, the blades and the throat ring, the wicket gates and stay vanes, and between the wicket gates and the

distributor ring (USACE 1995). Grinding injury can be documented by examining the fish's body for localized bruises, deep cuts, and even decapitation.

A fish may be damaged when it collides with (strikes) a turbine system component. The probability of a fish striking parts of the turbine system depends on several factors which include the size of the fish, number of blades and their spacing, turbine speed, flow velocity and discharge, among others. Several equations have been developed to calculate the probability of strike in Francis and Kaplan type turbines (von Raben 1957 and Monten 1985, cited in Cada 1997; USACE 1991, cited in Cook et al. 1997). Also, a new equation, based on the von Raben's model, was derived by the Voith team (Franke et al. 1997). A blade and a fish striking each other (colliding) may cause scale and mucous loss, eye injury, and internal bleeding depending on the velocities involved and the shape of the blade's leading edge (Turnpenny et al. 1992).

Data relating fish mortality to entry into a water body showed that mortality varied between 0% at 20 m/sec and 100% at 44 m/sec. Also, upon impact onto solid objects fish mortality varied between 0% at 4.5 m/sec and 100% at 29 m/sec (USACE 1991, cited in Cook et al. 1997). Data from EPRI (1987) indicated that mortality increases with runner peripheral velocities; minimal mortality could be expected at runner peripheral velocities of 12 m/sec or lower in Francis turbines. The data in EPRI (1987) also showed that more strikes would occur at higher tip speeds and that a peripheral runner velocity of 6 ft/sec or less may eliminate strike mortality.

Pressure

Fish are subjected to rapid pressure changes throughout the turbine system. Damage due to pressure is dependent on the amount and rate of change of pressure experienced by the fish as well as the type of the fish. Physostomous fish, such as salmon and trout, have a pneumatic duct that connects the swim bladder to the oesophagus, which is used, along with the mouth, to rapidly take in or vent gas (Lagler et al. 1962, cited in Cada et al. 1997). Physoclistous fish, such as perch and bass, do not have a pneumatic duct and must adjust their body's gas content by diffusion into the blood. Because this diffusion process may take hours, these fish are more susceptible to damage due to rapid pressure decrease. Pressure changes felt by a fish are relative to its acclimation pressure prior to entering the turbine system. These typically range from 4.6 m of water (21.2 psi or 146 kPa Absolute) at low-head plants to 52 m of water (87.7 psi or 605 kPa Absolute) at high-head plants (USACE 1995). It is believed that fish are more sensitive to pressure decreases than pressure increases, and that pressure-related mortality is due to injury to the swim bladder from decompression (Tsvetkov 1972, cited in Cada 1990 and in Cada et al. 1997).

Swim bladder rupture and embolism are caused by suddenly and severely lowering the pressure from the fish's acclimated pressure (USACE 1991). Theoretical information on mortality in salmonids, relative to pressure changes, indicated that when the minimum pressure is 30% of the acclimation pressure (i.e., Exposure Pressure/Acclimation Pressure ratio is 0.3), or higher, no mortality is expected (USACE 1991).

Large pressure drops over short periods of time can cause gas volumes within the fish to expand excessively, resulting in internal damage. Pressure change rates ($\Delta P/\Delta t$) < 5.5 bar/s (Odeh, 1999). When the flow enters the runner, it accelerates around the entrance edge of each blade, giving rise to the large pressure drops. The pressure change rates rise again along the trailing edge. The blade design on the right has less red area on the trailing edge, but both designs have similar total area with larger pressure drop than the threshold.

Cavitation

The presence of voids in the liquid has a damaging effect on marine and hydraulic turbine propellers (Euler 1754, cited in Odeh 1988). Cavitation is the rapid vaporization and condensation process of liquid. It normally occurs when the local pressure in the liquid drops to or below vapor pressure, and with nuclei present in the liquid vapor cavities (bubbles) are formed. These bubbles grow within the vapor pressure region and then become unstable and collapse as they travel to areas with higher pressures.

A widely used non-dimensional cavitation parameter, , can be defined as the ratio of operating pressure conditions to the available gross hydraulic head, H, on the turbine runner. This is expressed as = (Hatm - Hs - Hv) / H, where Hatm the absolute atmospheric pressure (ft absolute), Hs the turbine runner setting relative to tailwater level (ft), and Hv is the vapor pressure (ft absolute). To avoid cavitation at a hydro plant, its operational must be higher than its critical value, crn where cr is when cavitation starts to be damaging to the turbine. The highest fish survival at the Foster Project occurred when the turbine had an operational almost one-half to one-third the critical value (Bell 1981).

Cavitation can also be minimized by properly designing the runner geometry to minimize parameters governing cavitation, which include high velocity/low pressure zones, surface irregularities, abrupt changes in flow direction, and location or submergence (Cook et al. 1997).

Shear stress

Shear stress in the flow field are a result of the change of velocity with respect to distance, or the rate of deformation of the fluid. Shear stress is expressed as the force acting on an area parallel to its direction (Gordon et al. 1992). The spatial change of velocity can be attributed to both viscous forces and fluid flow properties, or fluid-induced forces due to its acceleration and local turbulence (Franke et al. 1997) The highest values of shear stress are found close to the interface between the flow and solid objects it speeds by, such as the blade leading edges, vanes, and gates.

The highest shear stress is found close to the interface between the flow and solid objects it speeds by, such as the blade leading edges, vanes, and gates. i.e. Salmonids survived at submerged water jet velocities of 30 ft/s or through the 14-inch pipe at nozzle velocities of 67 ft/s and less. Alewives and smelt survived at jet velocities of 30 and 40 ft/s (Odeh, 1999).

Parameter	Threshold	Reasoning
Peripheral runner speed	< 40 ft/s (12.2 m/s) Preferably < 20 ft/s (6.1 m/s)	Reduces strike injury, minimizes shear stresses and vortices between moving and stationary parts
Pressure	> 10 psia (0.7 bar)	Mortality when P drop > 30% of acclimation pressure (typically 30 psia = 2.06 bar)
Rate of change of pressure	< 80 psi/s (5.5 bar/s)	Assuming fish injury at a 160 psi/s (11 bar/s)
Shear stress	< 180 /s (1.8 m/s /cm)	Test of alewives, a fragile fish at 180/s did not cause injury

Summary of flow parameters thresholds (Odeh, 1999):

3. Turbulent technology: design parameters

Taking in count the parameters explained in the previous section, the Turbulent turbine has been designed to ensure that it is harmless for the fish population, below are shown the values of nominal operation.

How abrasion, grinding, and strike is avoided

The rotor of the gravitational vortex turbine developed by Turbulent has a particular geometry (pending patent) that besides of providing a superior efficiency also consists of curved plains and rounded edges, made from glass-fiber with a coating that improves the mechanical properties making it resistant to abrasion. This allows the blade having the same roughness during its lifetime.

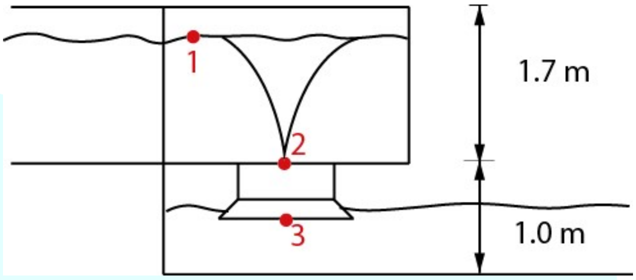
Blade of the 5 kW model, top view.

Blade of the 5 kW model, close up to the attack edge.

Pressure changes on Turbulent turbine

To estimate the rate of pressure change we considered 3 points:

1. in the surface of the inlet
2. just before to enter the rotor
3. point just after leaving the rotor.



Main dimensions of the basin with the study points.

The pressure in those points was estimated according to:

$$P_1 = 101325\ [Pa]$$

$$P_2 = 101325 + 1000 * 9.8 * 1.7 = 117985\ [Pa]$$

$$P_3 = 117985 - 11698 = 106287\ [Pa]*$$

* : calculated according the pressure difference necessary .

For an estimation of the time it takes one particle in the water to travel from point 1 to point 2 and 3. The calculation of the movement of the particle was made in respect to the vertical axis. In this direction, the largest acceleration occurs because of gravity as it is a free vortex.

In this case, the equation that describes the vertical position in any time for a particle it is:

$$_{Y}(t) = \frac{1}{2}\vec{g} * t^2 + \vec{V_0} * t + \vec{Y_0}$$

With:

$V_0 = 0\ ; Y_0 = 0\ ; Y_1 = 0\ ; Y_2 = 1.7\ ; Y_3 = 2.2$ Time

between 1-2:

1. $7 = \frac{1}{2} 9.8 * t^2 \rightarrow t_{1-2} = 0.589\ (s)$

Time between 2-3:

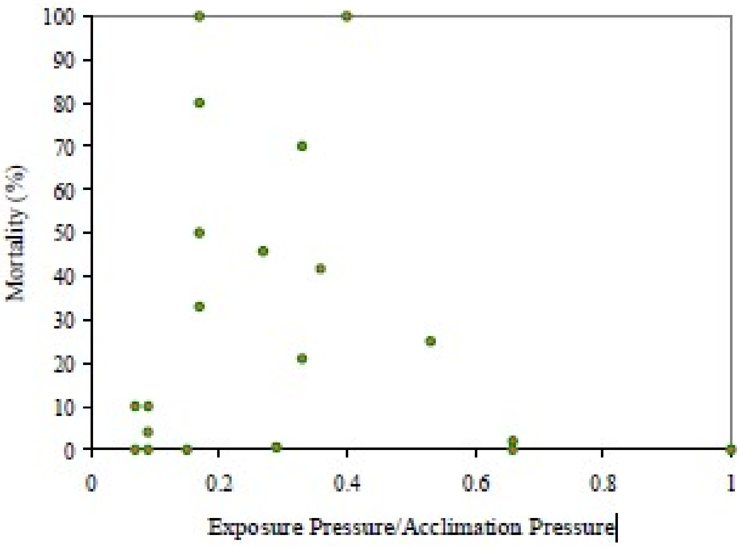
2. $2 = \frac{1}{2} 9.8 * t^2 + \sqrt{2 * 9.8 * 1.7} * t + 1.7 \rightarrow t_{2-3} = 0.08\ (s)$

Then the rate of change of pressure:

$$\Delta P_{12} = \frac{117985 - 101325Pa}{0.589} == 28285 \left[\frac{kPa}{s}\right] \rightarrow 28.3 \left[\frac{psi}{s}\right] \rightarrow 0.28 \left[\frac{bar}{s}\right] 4.1 [\ ] \rightarrow$$

$$\Delta P_{23} = \frac{106287 - 117985}{0.08} = 146225 \left[\frac{Pa}{s}\right] \rightarrow 146.3 \left[\frac{kPa}{s}\right] \rightarrow 21.22 \left[\frac{psi}{s}\right] \rightarrow 1.46 \left[\frac{bar}{s}\right]$$

Also in USACE 1991 it is shown a graph where they illustrate the results of an experiment in which they tested the mortality of salmonids under decompression. Results are rated with the ratio of decompression in comparison with the pressure of acclimation of the fish.



Mortality (%) vs. Ratio of pressures for salmonids.

In our case, the theoretical minimal pressure point can be found on the rotor in the region with the maximum speed. This occurs on the edge of the blade and correspond to 5.88 m/s at 100 rpm. In that scenario, the pressure is:

$$P^2 = 101325 + 1000 * 9.8 * 1.5 - \frac{1}{2} * 1000 * 5.88^2 = 98737.8\ [Pa]$$

Dividing the exposure pressure with the acclimation pressure, which is assumed as atmospheric pressure:

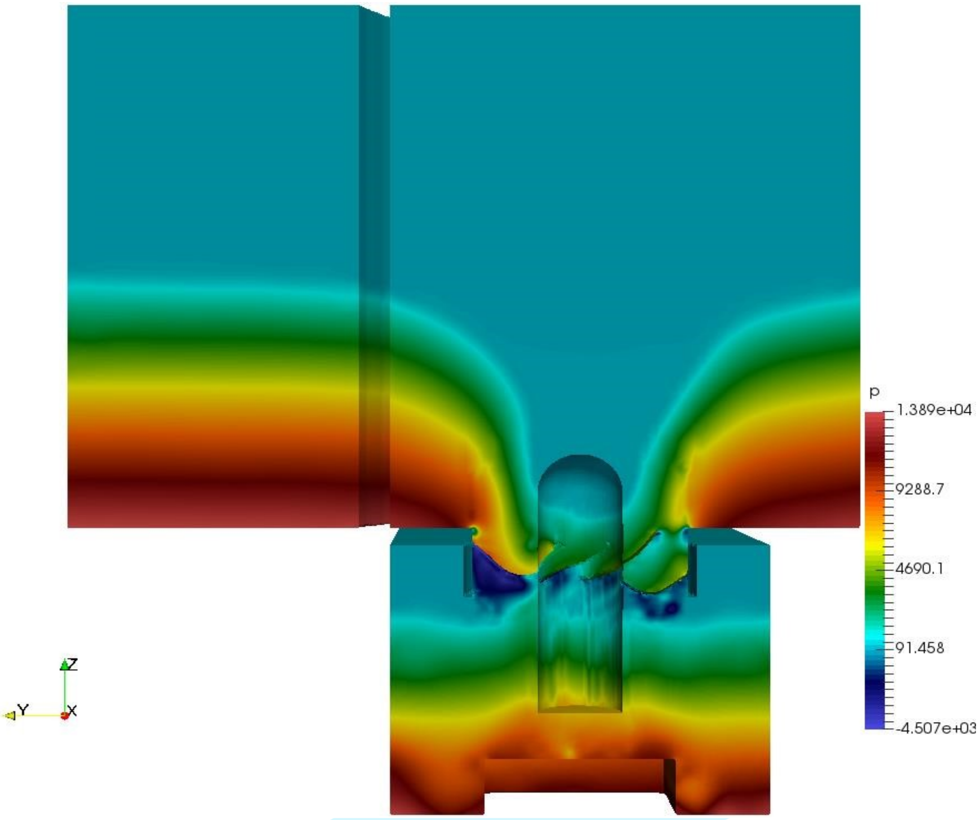
$$Exposure\ Pressure \div Acclimation\ Pressure = \frac{98737.8}{101325} = 0.97$$

The graph shows that our operation point is in the non-deadly zone of operation.

Cavitation

Cavitation is a problem that affects to turbomachinery in general, in the case of the gravitational vortex turbine of Turbulent, the lowest possible pressure was calculated previously and was found to be 98.7 [kPa] absolute pressure. The vapor pressure for water at 21°C is 2500 [Pa] absolute, which means that the operation point of the turbine is almost 40 (39.5) times higher than the vapor pressure, which is the pressure where bubbles of steam start to appear.

On CFD simulations were simulated the gravitational turbine with a draft tube acting as a diffuser on the exit of the turbine, those simulations show minimum points of pressure of 6 [kPa] gauge pressure which means an absolute pressure of 95.3 [kPa] what is also superior than the vapor pressure.



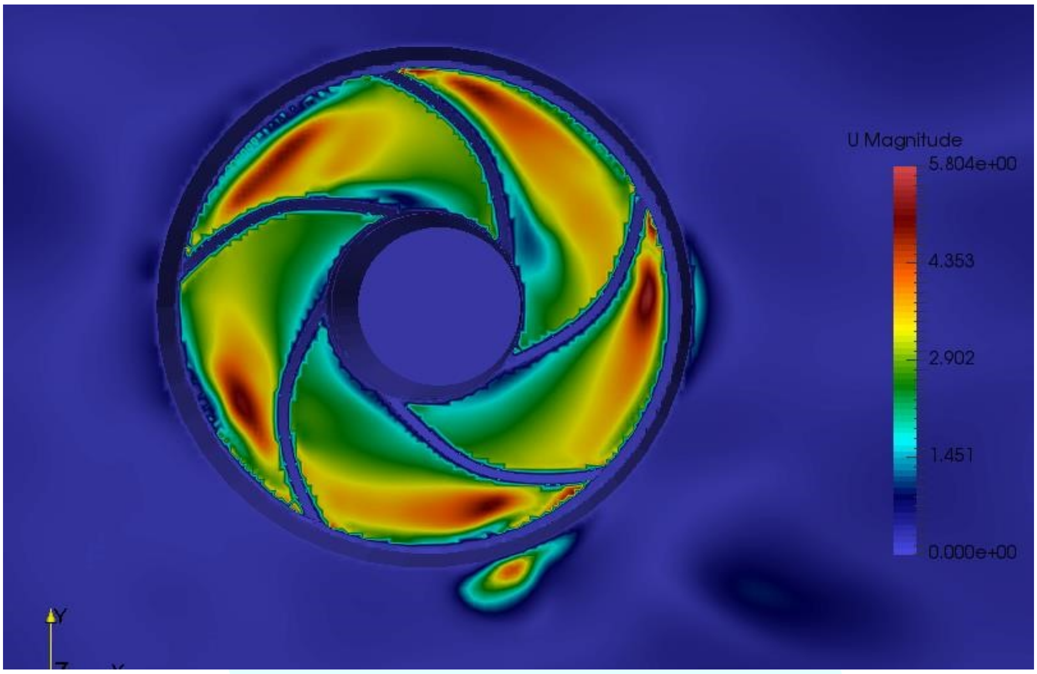
Pressure profile of CFD of the 15 kW model (1.6 m^3/s and 100 rpm). Lowest pressure upper than steam pressure.

Shear stress

For shear resistance forces on fish, the scientific papers show their results expressed as a function of the shear rate. The shear rate is calculated as:

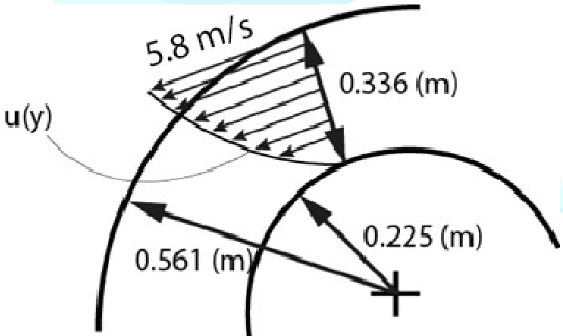
$$\gamma = \frac{du}{dy} [s^{-1}]$$

For that we need the speed distribution, based on the CFD simulations we know the maximum speed on magnitude.



CFD simulation of the 15 kW turbine (1.6 m³/s and 100 rpm)

The assumption that the velocity on the plane x -z has a maximum value of the same that the maximum value with the magnitude is an assumption that will rise the value of the actual shear rate. Assuming a square distribution:



$$u(y) = a * y^2$$

With the values given by the simulation on the image, the a coefficient has a value of 44.28:

$$\gamma = \frac{du}{dy} = \frac{d(44.28 * y^2)}{dy}\Big|_0^{0.336} = 29.7\ [s^{-1}]$$

Comparison between the limit values and Turbulent values

Parameter	Threshold	Turbulent
Peripheral runner speed	< 40 ft/s (12.2 m/s) Preferably < 20 ft/s (6.1 m/s)	5.88 m/s at 100 rpm
Pressure Rate of change of pressure Shear stress	> 10 psia (0.7 bar)	minimum of 13.83 psia (CFD simulations with draft tube)
	< 80 psi/s (5.5 bar/s)	maximum of 1.46 bar/s
	< 180 /s	maximum of 30 /s

4. Conclusions

After the comparison between several scientific research papers, the nominal operational condition for the Turbulent turbine can be assumed to be fish-friendly. The CFD model has been validated in real life in the Donihue (Chile) site, thus we can already state a confirmation of our fish-friendly design. Further research is being conducted together with the University of Concepcion to validate this with actual fish tests.

The advantages of the gravitational vortex turbine in comparison with other micro hydro turbines (with exception of the Archimedes screw), it is that the pressure differences are low because it works with free surface flow and a low height difference. Additionally, the big clearance between blades help to make this turbine fish friendly.

5. References

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