



Evaluation of Fish Injury and Mortality Associated
with scale models of the
Pentair Fairbanks Nijhuis Modified Bulb turbine
and the
Water2Energy Cross Flow turbine

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1 INTRODUCTION

With a growing demand for 'green' energy, the interest for hydro power installations has increased worldwide. As recently fish safety has become an important issue (the Dutch government issued a guideline permitting a maximum mortality rate of 0,1% per passage), manufacturers strive to produce fish friendly innovative turbine solutions. Strike models and Computational Fluid Dynamics are used to predict the degree of fish friendliness of these new installations. Also, testing with live fish is done to ascertain fish mortality rates of new concepts under different conditions.

The project Pro-Tide is aiming on the development, testing and promoting of tidal energy in coastal and estuarine areas. The project is led by the province of Zeeland, together with sub partners province of Zuid-Holland and the Dutch Ministry of Infrastructure and the Environment (RWS). Other partners are The Isle of Wight Council, Dover Harbour Board (English partners), ULCO Université du Littoral – Côte d'Opale (French partner) and Waterwegen en Zeekanal N.V (Belgian partner). Within the project a further development of hydrokinetic turbines and low head tidal turbines is strived for. Themes for the project are technology, ecology, economy and public-private partnership. The Dutch project within Pro-Tide, Pro-Tide-NL, is trying to identify Best Available Technology (BAT) for the conditions that are envisaged for the Brouwers dam tidal power plant: extreme low head (~ 1 m average) and large discharges (2,500 m³/s average). As similar conditions can be present in river deltas, hydrokinetic turbines are also taken into account.

With the purpose to identify BAT, the first step was to make an overview of available technologies that might be suitable. By using a Multi Criteria Analysis, the R&D advisory board has made a prioritization of available technologies (Van Berkel, 2015-a). Based on this study it was advised to conduct further research on the following topics:

1. To perform fish safety test with a modified bulb turbine;
2. To do a performance test with a hydrokinetic turbine and also a fish safety test;
3. To perform a desk study on the costs of the VETT technology.

Pro-Tide selected the Pentair Fairbanks Nijhuis modified bulb turbine and the cross flow turbine of Water2Energy to be tested for fish safety. ATKb was commissioned to perform the fish safety tests at a location near Maurik, for among others important species like salmon and eel.

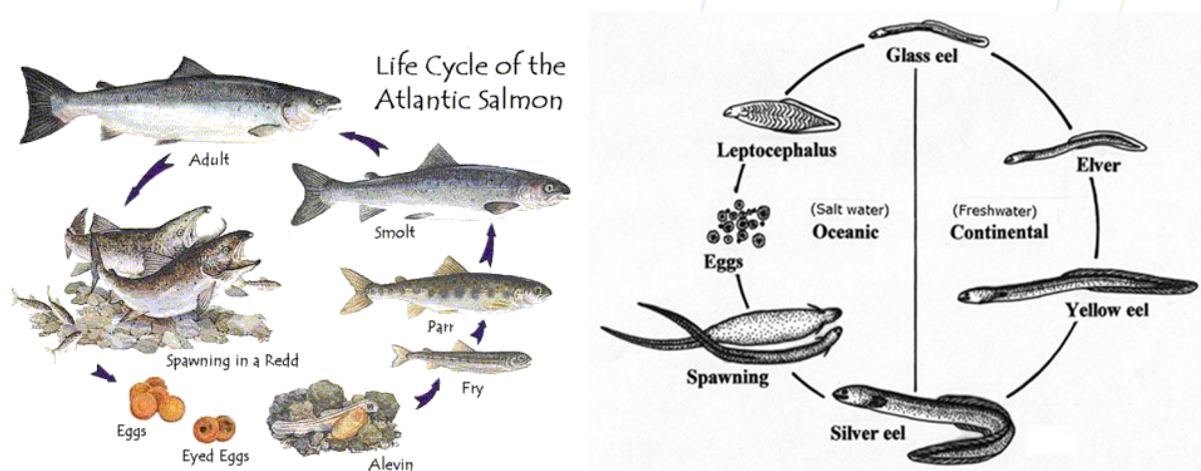


Figure 1. Life cycle of long distance migrants

2 PROJECT ORGANISATION, METHOD AND MATERIALS

2.1 Project organisation of the live fish tests

The project is led by Pro-Tide-NL, in the person of Jacob van Berkel. Pro-Tide-NL commissioned parts of the project to other parties, does the management and supervision and also coordinates the test set-up, design, assembly and removal at the site. Bart van Esch (BE Engineering, also affiliated to TU Eindhoven) is involved for, modelling the fish safety of the different turbine types, applying turbine scale laws etc. André Breukelaar of RWS is involved because of his expertise on the subject of fish migration and the impact of hydro power installations. Nuon (Jan Smink and Wim van Lent) has been facilitating the project by supplying a location to perform the tests (and other facilities: electric power, accommodation etc.). Pentair Fairbanks Nijhuis delivered the modified bulb turbine and gave assistance during the tests (operator Raymond Meijnen). Water2Energy delivered the cross flow turbine and Reinier Rijke operated this turbine during the tests. Other companies involved in the preparations were MC-welding, Rental Pumps, Mammoet, GP-infra and Pavert steigerbouw. ATKB was asked to prepare guidelines for the fish safety tests and to perform these test (Tim Vriese, Jochem Hop, Stefan Oskam and Jan Wullink). Before the actual testing took place there were several meetings to discuss the design of the test rig, test conditions and modelling of the fish mortality for scaled turbines and full scale turbines. The results of fish mortality model were promising, so that it was deemed safe to perform the tests with live fish.

2.2 Method and materials

2.2.1 Test species and method

The guidelines for performing the fish safety tests are published in another report (Vriese, 2015). Only a short description will be given here. The chosen turbines will be tested at two different conditions (head, discharge, rpm). Originally, it was the idea to perform the test with 4 fish species (pike perch, salmon smolts (or rainbow trout), eel and flounder). The first three species were available from commercial suppliers (Viskweekcentrum Valkenswaard). The flounder had to be caught by a commercial fisherman. However, during the preparation of the tests, it turned out that it was not possible to obtain enough juvenile flounder in good condition. As a result, testing was done with only three species. When evaluating fish mortality associated with pumps and turbines using live fish, the law on animal testing applies (in Dutch: Wet op de Dierproeven). Regarding this, ATKB has all the necessary licenses and permits and qualified personnel to perform these tests (see appendix 1: license and project permit).

The size of the fish used for testing is dependent on the size of the turbine scale model tested and also on the vulnerability of the appropriate length classes of species (i.e. there is a lower limit in size of the fish tested). An average length of 20 cm for eel, 12 cm for smolts and 16 cm for pike perch was chosen (in practice, there is always a length range of fish present). The number of fish used in the test (N) determines the accuracy of the proportion of fish mortality that is established. Testing fish is a binomial experiment. For each fish there is a probability (p) of success (or in this case the probability of dying). A 95% confidence interval around the proportion of dead fish can be calculated, dependent on the number of fish that passed through the turbine. Due to practical reasons (see Vriese, 2015) a test group of 100 fish was chosen for each of the two test conditions. Also a control group of 100 fish was used. This amounts to 300 fish per species per turbine.

Fish were transported to the test site and stored in a large fish tank (with a continuous water supply) to acclimatise for 24 hours. The next day tests were performed. Beforehand, the 100 individuals were

closely inspected for injuries or abnormalities. If these were present, fish were excluded from the test. The group of 100 fish was divided equally over 4 smaller containers and transported to the test rig.



Figure 2. Fish species of test fish (pikeperch, eel and rainbow trout)

Per container, fish were gently released into the specially designed intake structure (see further) in the high water tank and transported through the turbine. The whole procedure only took several minutes. The water supply via the pump was turned off and the water was drained from the test rig. At the low water tank fish were collected, using small dip nets. Directly after this procedure, small groups of fish were lightly anaesthetized using a solution of benzocaine (40 mg per litre). Fish were closely inspected for damage. Damage was categorized as follows:

1. Non damaged fish;
2. Slightly damaged fish;
 - 2.1 Red and/or enlarged eyes;
 - 2.2 Red and/or damaged fins;
 - 2.3 Slightly scratched and/or scale loss (<20%);
3. Severely (terminally) damaged fish;
 - 3.1 Severe scale loss (>20%, Main & Sangster, 1990);
 - 3.2 Cuts, lacerations and/or severed body parts;
 - 3.3 Fractures;
 - 3.4 Damaged and/or lost eyes;
 - 3.5 Damaged gills of gill covers;
 - 3.6 Severe bruising/haemorrhaging;
 - 3.7 Abnormal swimming movements;
4. Dead fish.

Fish of category 3 were euthanized directly (humane endpoint) by immersion in a solution of benzocaine (200 mg/l). Fish of category 3 and 4 was photographed. The healthy fish (categories 1 and 2) were transported back to the storage facility and kept there for another 48 hours. After 48 hours fish were checked for delayed mortality. Fish belonging to the control group were not transported through the turbine but released with the same intake structure in the low water tank, receiving the exact same handling as the fish from the test groups.

2.2.2 Test site and test rig

The location of the tests was situated near the village of Maurik at the Nederrijn on grounds belonging to the power company Nuon, that operates a hydro power station there (see figure 3).



Figure 3. Right hand side (above): red dot, location of Maurik in the Netherlands. Left hand side (above): aerial view of sluices, hydro power station and fish way near Maurik. Down: view of terrain before construction of the test rig (figure courtesy of J. van Berkel)

Designing and building the test rig took quite some effort from all parties involved (Van Berkel, 2015-b, 2015-c). The test rig consists of two large tanks, a high water tank and a low water tank, connected by a large pipe in which the turbine was installed. A large pump in the river supplied water for the test rig. Dimensions were chosen to obtain a water flow velocity in the pipe leading to the turbine of approximately 1,5 m/s, to prevent fish from swimming back to the high water tank. In both tanks perforated baffles were present to ensure a uniform flow of water. The specially designed intake structure consists of a funnel with its own water supply, leading into a curved smaller pipe that ends in the large pipe leading to the turbine. The water velocity through the intake structure matches the water velocity in the large pipe, to ensure a swift insertion of the fish into the main water flow. All surfaces, pipes, transitions etc. were finished very smoothly to protect the fish from injuries. All netting used was knotless for the same reason. The next figures give an impression of the design and building of the test rig and intake structure.

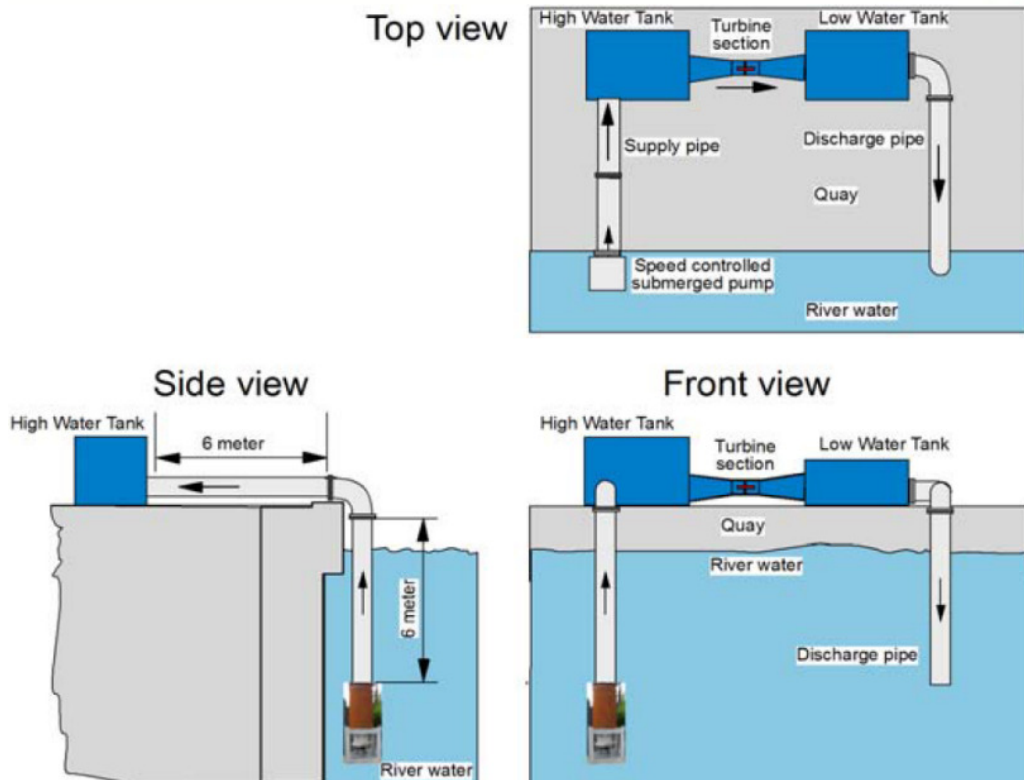


Figure 4. The test rig (top view, side view and front view) (figure courtesy of J. van Berkel)

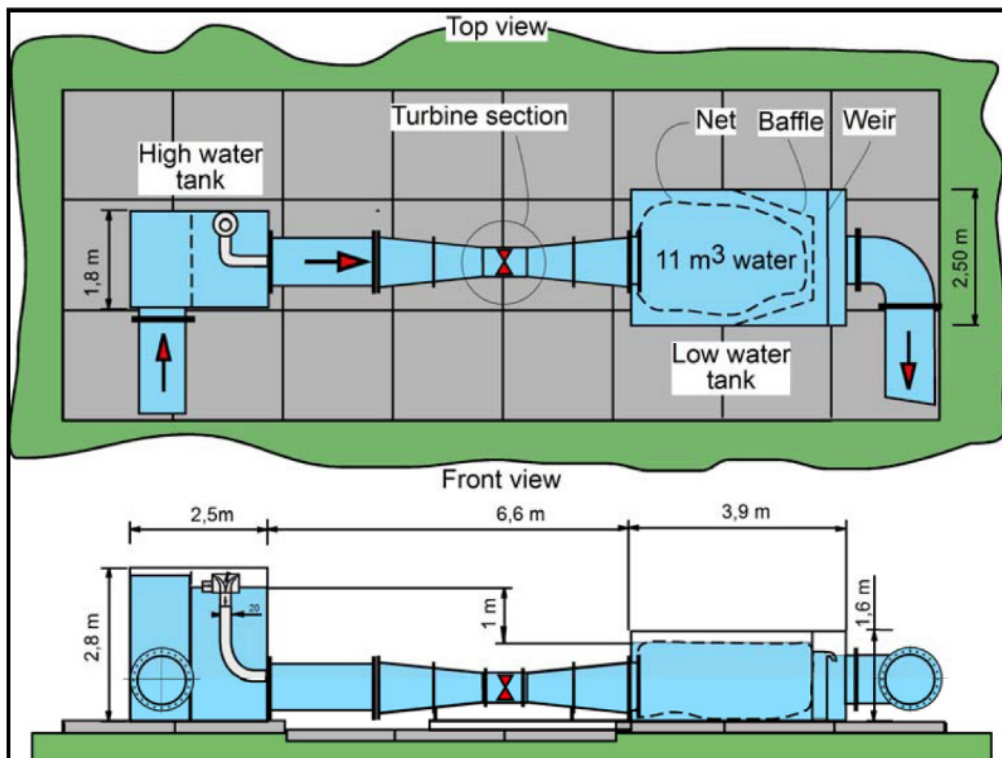


Figure 5. Design of the test rig (figure courtesy of J. van Berkel)



Figure 6. Building test rig on site



Figure 7. Side view of test rig

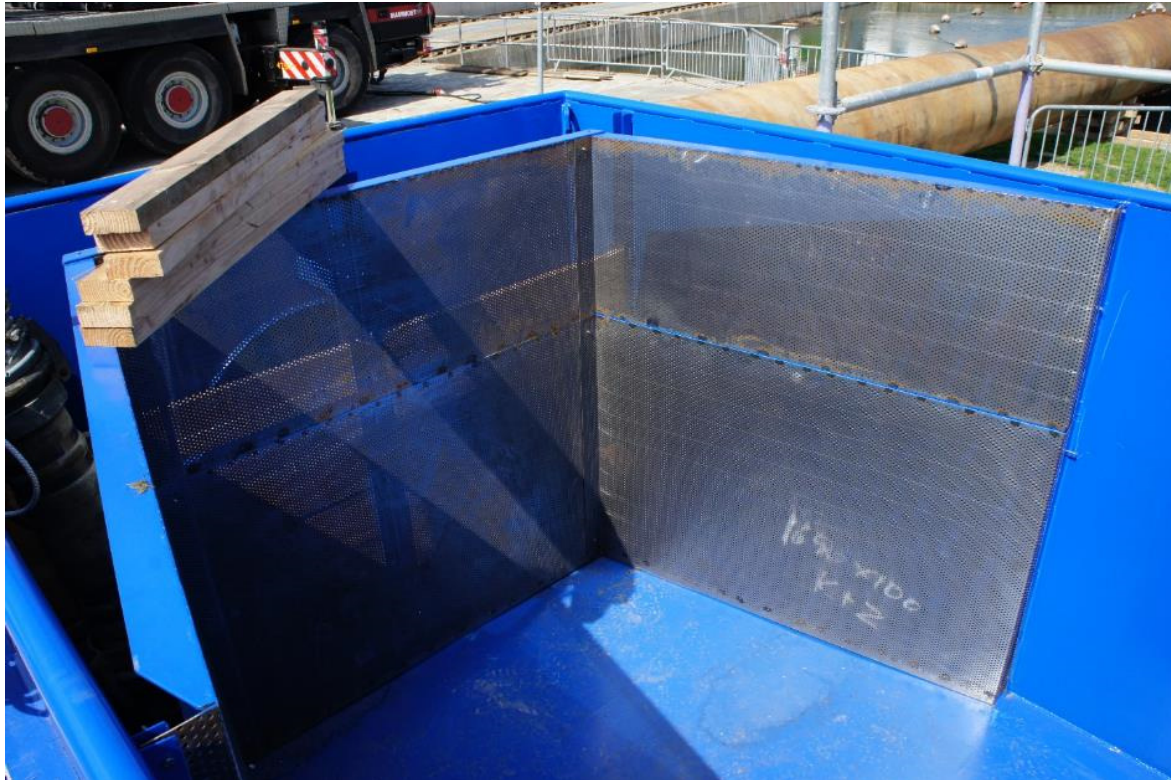


Figure 8. Baffles in the low water tank

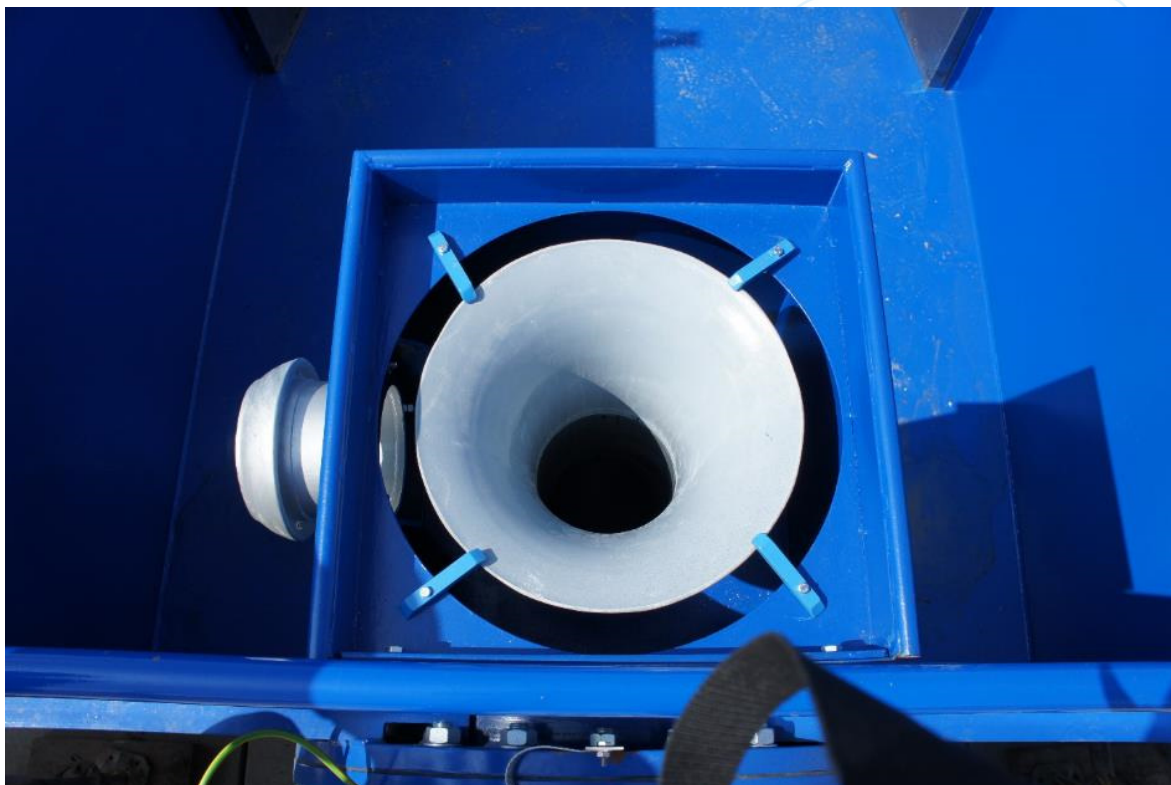


Figure 9. Intake structure (top view)



Figure 10. Intake structure (front view)



Figure 11. View into high water tank with mount for intake structure and pump for water supply

2.2.3 Turbines

Turbines to be tested are scale models of the bi-directional Pentair Fairbanks Nijhuis modified bulb turbine and the Water2Energy cross flow turbine.

Pentair Fairbanks Nijhuis modified bulb turbine

This turbine is especially designed for low head tidal utilisation as it can rotate both turbine blades (bi-directional). This turbine also has no guide vanes. Table 1 summarizes some characteristics of the turbine and the scale model.

Table 1. Characteristics of full scale and scale model of the Nijhuis turbine

Nijhuis turbine	Full scale	Scale model (1:16)
Rotor diameter (m)	8	0,5
Nominal head (m)	1	1
Nominal flow rate (m ³ /s)	250	1
RPM	14	245
Power output (kW)	~2000	~8

Testing was done at two different conditions:

- 1). Head 0,82 m; discharge 0,8 m³/s; shaftspeed 190 rpm
- 2). Head 0,51 m; discharge 0,7 m³/s; shaftspeed 175 rpm

The control group was tested at the same conditions as under 1.

On the next page a photo of the Pentair Fairbanks Nijhuis bi-directional turbine with two tapered ducts to be connected to the pipes leading from the high water tank and to the low water tank. In the centre there is a Perspex section through which fish passing through the turbine can be observed and filmed with a high speed camera.

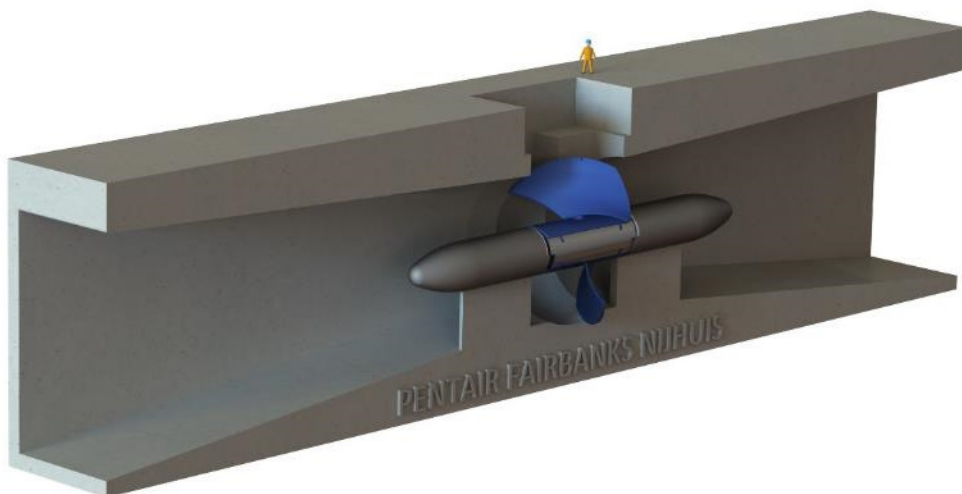


Figure 12. Cross section full scale bi-directional Nijhuis turbine



Figure 13. Pentair Fairbanks Nijhuis scale model turbine as tested in Maurik

Water2Energy cross flow turbine

The Water2Energy cross flow turbine is a Darrieus type turbine, with its axis at a right-angle to the flow direction of the water. It has three vanes flush mounted at top and bottom.

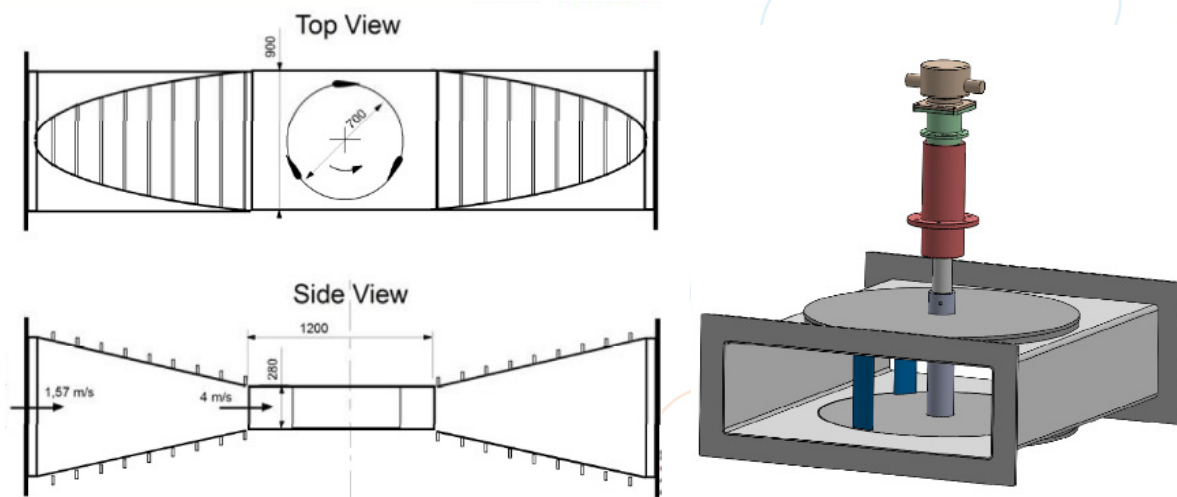


Figure 14. Water2Energy cross flow turbine

Table 2 summarizes some characteristics of the turbine and the scale model.

Table 2. Characteristics of full scale and scale model of the Water2Energy cross flow turbine

W2E turbine	Full scale	Scale model
Rotor diameter x height (m)	7 x 7	0,7 x 0,28
Housing cross section (m)	8 x 8	0,9 x 0,28
Flow velocity @ Brouwersdam	4	4
Nominal flow rate (m ³ /s)	256	1
RPM @ 2 Tip Speed Ratio (TSR)	22	220
Power output (kW) @ C _p =0,4	820	3,2

Testing was done at two different conditions:

- 1). Head 0,41 m; discharge 0,78 m³/s; shaftspeed 95 rpm
- 2). Head 0,30 m; discharge 0,60 m³/s; shaftspeed 75 rpm

The control group was tested at the same conditions as under 1.



3 RESULTS

3.1 Pentair Fairbanks Nijhuis bi-directional turbine

3.1.1 General

Testing the Pentair Fairbanks Nijhuis turbine was done on the 12th and 13th of May and on the 28th of May 2015. Fish always arrived on the test site the day before the test to acclimatise to the existing conditions. On the 12th of May pike perch was tested, on the 13th of May rainbow trout was used and on the 28th of May yellow eel was tested. The first test was always the test with the more extreme conditions (higher discharge and head). Control testing was done under the same conditions as the first test. During tests 1 and 2 on the 12th of May the intake structure was mounted on the high water tank, to insert the fish. At the end of this day the intake structure was taken down and mounted on the low water tank to perform the control testing. Control group fish did not pass through the turbine but were kept for the same period as test fish in the low water tank to experience the ambient conditions (turbulence, flow velocity, netting etc.). After each test was performed fish were checked for damage and stored in separate keepnets in the river, to be kept for another 48 hours (delayed mortality testing). Testing on the 13th of May started with the control test group to minimize the amount of labour necessary to disassemble the intake structure and reassemble it on the high water tank. Testing on the 28th of May started again with test 1 with the more extreme conditions and the intake structure mounted on the high water tank.



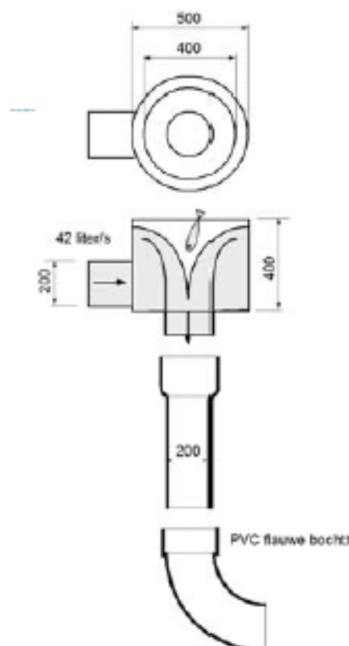
Figure 15. Low water tank with collection net for fish

A collection net was used in the low water tank to prevent fish from escaping to the river. A heavy frame prevented the net from moving to and fro and thus possibly damaging the fish. Fish could escape to the river through a small opening below the baffles, hence the collection net was necessary. The net was not necessary for removing the fish because it turned out to be just as easy to go into the

tank (when the water was drained) and remove the fish one by one using a small hand held dip net, thus treating the fish with utmost caution. When fish had passed through the turbine and entered the low water tank they directly displayed controlled swimming and schooling behavior. Fish seemed not to be disoriented in any way. The turbulence in the low water tank was minimal, as can be seen in figure 16.



Figure 16. Water flow in low water tank



The specially designed fish intake structure turned out to work very well (figure 17 and 18). The structure had its own water supply (42 l/s) by smaller pumps in the high water tank and in the low water tank. The water enters the top end of the structure and then flows over the edge into the funnel. Water with fish can be added from above and the constant flow takes the fish away down through the insertion pipe (diameter 0,2 m) in a very gentle way. The horizontal part of insertion pipe was actually somewhat longer than depicted in figure 17 and reached well into the large pipe leading to the turbine, to prevent fish from swimming back to the high water tank. The flow velocity in the insertion pipe and the large pipe was approximately 1,5 m/s, fast enough to carry the fish to the turbine. The distance from the insertion point to the turbine however, was long enough to give fish time to orientate themselves in the flow. From high speed camera footage it could be concluded that most fish, passing through the turbine, performed controlled swimming. Only very few fish succeeded in swimming against the current and reaching the high water tank.

Figure 17. Intake structure for fish



Figure 18. Intake structure supplied with water

3.1.2 Pike perch tests (12th May 2015)

Test 1-1 (0,82 m head; 0,80 m³/s discharge)

100 pike perch;
average length 17,2 cm;
maximum length 22 cm;
minimum length 13 cm;
standard deviation 1,7 cm.

After performing test 1-1 it became obvious that there were several instant mortalities as a small number of fish was floating in the low water tank. In total 6 dead fish were counted with severe bruising/fracturing, damage to the eyes and haemorrhaging.



Figure 19. Dead pike perch, with severe bruising, damage to the eyes and haemorrhaging

In total 8 fish showed some light damage (scratches, scale loss and bruises). Mortality after 48 hours was zero.

On the 6 dead fish autopsy was performed. The results are given below.

Pike perch 21 cm: haemorrhaging and bruising on lower part of the head, haemorrhaging above anal fin; discoloration right flank, left pectoral fin inverted, pale gills, heavy internal bleeding, ruptured artery following the Bulbus arteriosus, ruptured swim bladder.

Pike perch 17 cm: no external damage, left pectoral fin inverted, haemorrhaging and bruising on lower part of the head, pale gills, heavy internal bleeding, ruptured artery following the Bulbus arteriosus, swim bladder intact.

Pike perch 15 cm: no external damage, haemorrhaging within the brain, swim bladder intact.

Pike perch 21 cm: bruising/ haemorrhaging left flank near dorsal fin, pale gills, heavy internal bleeding, ruptured artery following the Bulbus arteriosus, ruptured swim bladder.

Pike perch 15 cm: bruising/ haemorrhaging top of both flanks near dorsal fin, pale gills, heavy internal bleeding, ruptured artery following the Bulbus arteriosus, ruptured swim bladder.

Pike perch 16 cm: suffered a severe blow between head and dorsal fin, bruising/ haemorrhaging in front of dorsal fin, pale gills, heavy internal bleeding, ruptured artery following the Bulbus arteriosus, ruptured swim bladder.

In general all 6 fish show the same type of lethal damage, likely due to collision with turbine blades. Death was probably instant, due to severing the artery from the Bulbus arteriosus, causing heavy internal bleeding resulting in pale gills, rupturing of the swim bladder.

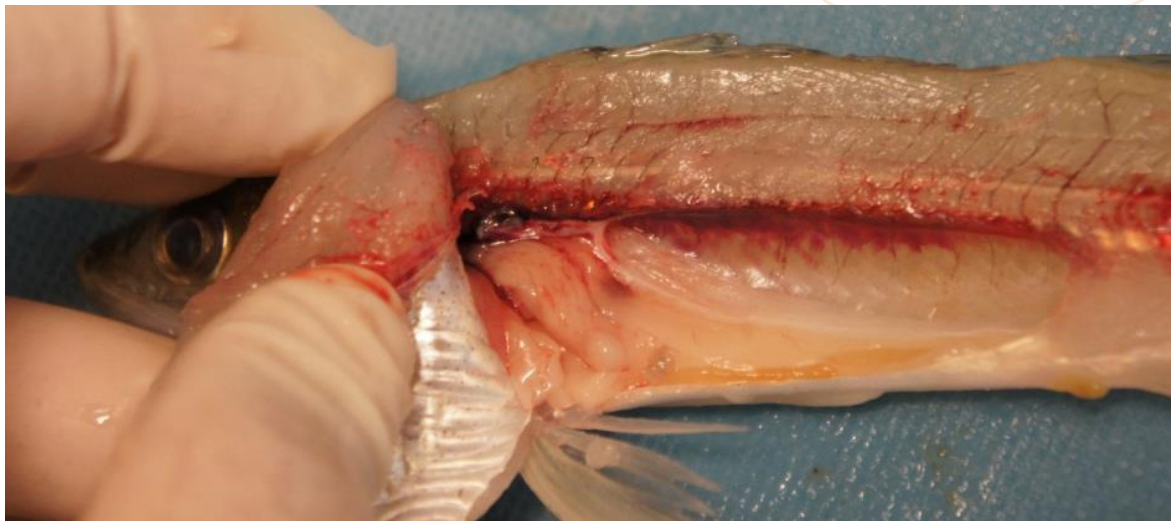


Figure 20. Pike perch with severe internal bleeding due to rupture of artery

Test 1-2 (0,51 m head; 0,70 m³/s discharge)

98 pike perch (amount of pike perch was less than ordered, so sometimes groups were smaller);
average length 17,2 cm;
maximum length 23 cm;
minimum length 14 cm;
standard deviation 1,7 cm.

Test 1-2 , under milder conditions, resulted in fewer fatalities (2 dead pike perch). Type of damage was the same (severe bruising/fracturing etc.). In total 5 fish showed some light damage (mainly some slight bruising). Mortality after 48 hours was zero.

Test 1-control (control test, fish in low water tank; 0,78 m head; 0,80 m³/s discharge)

89 pike perch;
average length 16,7 cm;
maximum length 21 cm;
minimum length 12 cm;
standard deviation 1,8 cm.

The control group had no fatalities and no damage at all. Mortality after 48 hours was zero. Table 3 shows the results in terms of percentage of (delayed) mortality (and upper and lower limits) of all tests with pike perch.

Table 3. Mortality of pike perch associates with the Pentair Fairbanks Nijhuis turbine

Direct mortality								
Turbine	Date of test	Test nr.	Fish species	N dead fish	N passed	% mortality	Lower limit%	Upper limit%
Nijhuis modified bulb	12-5-2015	1-1	Pikeperch	6	100	6,00	2,23	12,60
		1-2	Pikeperch	2	98	2,04	0,25	7,18
		1-control	Pikeperch	0	89	0,00	0,00	4,06
Direct + 48 hour mortality								
Turbine	Date of test	Test nr.	Fish species	N dead fish	N passed	% mortality	Lower limit%	Upper limit%
Nijhuis modified bulb	12-5-2015	1-1	Pikeperch	6	100	6,00	2,23	12,60
		1-2	Pikeperch	2	98	2,04	0,25	7,18
		1-control	Pikeperch	0	89	0,00	0,00	4,06

3.1.3 Rainbow trout tests (13th May 2015)

Test 2-1 (0,80 m head; 0,80 m³/s discharge)

98 rainbow trout (some trout succeeded in swimming back to the high water tank, so not all fish could be collected after the experiment);
average length 17,2 cm;
maximum length 20 cm;
minimum length 13 cm;
standard deviation 1,4 cm.

Test 2-1 resulted in 1 fatality. This rainbow trout suffered a blow to the head, resulting in a crushed skull and one eye missing. In total 6 fish showed some slight damage, light bruising, scratches and discoloration (black spots). Mortality after 48 hours was zero. Also important to mention, the discoloration had disappeared after 48 hours and fish were in a good condition.

Test 2-2 (0,48 m head; 0,70 m³/s discharge)

97 rainbow trout;
average length 17,4 cm;
maximum length 21 cm;
minimum length 12 cm;
standard deviation 1,7 cm.

Test 2-2, under milder conditions, resulted in zero fatalities. In total 7 rainbow trout suffered minor injuries (scratches, some scale loss, discoloration). Mortality after 48 hours was zero. Discoloration had disappeared.

Test 2-control (control test, fish in low water tank; 0,75 m head; 0,80 m³/s discharge)

100 rainbow trout;
average length 17,2 cm;
maximum length 21 cm;
minimum length 12 cm;
standard deviation 1,7 cm.

The control group had no fatalities and no damage at all. Mortality after 48 hours was zero. Table 4 shows the results in terms of percentage of (delayed) mortality (and upper and lower limits) of all tests with rainbow trout.

Table 4. Mortality of rainbow trout associates with the Pentair Fairbanks Nijhuis turbine

Direct mortality								
Turbine	Date of test	Test nr.	Fish species	N dead fish	N passed	% mortality	Lower limit%	Upper limit%
Nijhuis modified bulb	13-5-2015	2-1	Rainbow trout	1	98	1,02	0,03	5,55
		2-2	Rainbow trout	0	97	0,00	0,00	3,73
		2-control	Rainbow trout	0	100	0,00	0,00	3,62
Direct + 48 hour mortality								
Turbine	Date of test	Test nr.	Fish species	N dead fish	N passed	% mortality	Lower limit%	Upper limit%
Nijhuis modified bulb	13-5-2015	2-1	Rainbow trout	1	98	1,02	0,03	5,55
		2-2	Rainbow trout	0	97	0,00	0,00	3,73
		2-control	Rainbow trout	0	100	0,00	0,00	3,62

3.1.4 Yellow eel tests (28th May 2015)

Test 3-1 (0,85 m head; 0,80 m³/s discharge)

88 eel;
average length 25,1 cm;
maximum length 32 cm;
minimum length 17 cm;
standard deviation 3,2 cm.

Test 3-1 resulted in zero fatalities and no damage at all. All eel were in perfect condition. Mortality after 48 hours was zero.

Test 3-2 (0,54 m head; 0,70 m³/s discharge)

99 eel;
average length 24,6 cm;
maximum length 34 cm;
minimum length 14 cm;
standard deviation 3,4 cm.

Test 3-2, under milder conditions, resulted in zero fatalities and no damage at all. All eel were in perfect condition. Mortality after 48 hours was zero.

Test 3-control (control test, fish in low water tank, 0,78 m head; 0,80 m³/s discharge)

94 eel;
average length 24,9 cm;
maximum length 31 cm;
minimum length 15 cm;
standard deviation 3,4 cm.

The control group had no fatalities and no damage at all. Mortality after 48 hours was zero. Table 5 shows the results in terms of percentage of (delayed) mortality (and upper and lower limits) of all tests with eel.

Table 5. Mortality of yellow eel associates with the Pentair Fairbanks Nijhuis turbine

Direct mortality								
Turbine	Date of test	Test nr.	Fish species	N dead fish	N passed	% mortality	Lower limit%	Upper limit%
Nijhuis modified bulb	28-5-2015	3-1	Eel	0	88	0,00	0,00	4,10
		3-2	Eel	0	99	0,00	0,00	3,66
		3-control	Eel	0	94	0,00	0,00	3,85
Direct + 48 hour mortality								
Turbine	Date of test	Test nr.	Fish species	N dead fish	N passed	% mortality	Lower limit%	Upper limit%
Nijhuis modified bulb	28-5-2015	3-1	Eel	0	88	0,00	0,00	4,10
		3-2	Eel	0	99	0,00	0,00	3,66
		3-control	Eel	0	94	0,00	0,00	3,85

3.2 Water2Energy cross flow turbine

3.2.1 General

On the first of June 2015 the Pentair Fairbanks Nijhuis turbine was removed from the test rig and afterwards the Water2Energy cross flow turbine was installed. Testing of this turbine with live fish was done on the 11th and 12th of June and on the 16th of June 2015. Species were tested in the same order as with the first turbine. The first test was always the test with the more extreme conditions (higher discharge and head). Control testing was done under the same conditions as the first test. Control group fish did not pass through the turbine but were kept for the same period as test fish in the low water tank to experience the ambient conditions (turbulence, flow velocity, netting etc.). After each test was performed fish were checked for damage and stored in separate keepnets in the river, to be kept for another 48 hours (delayed mortality testing). Procedures that were followed, were exactly the same as described in § 3.1.

3.2.2 Pike perch tests (11th June 2015)

Test 1-1 (0,43 m head; 0,77 m³/s discharge)

100 pike perch;
average length 18,3 cm;
maximum length 23 cm;
minimum length 14 cm;
standard deviation 2,0 cm.

Test 1-1, with the cross flow turbine, led to 6 fatalities. One of these fish had a fractured spine just posterior of the head (figure 21). The other fatalities were also collision victims, suffering from severe bruising in the region of the head mainly, haemorrhaging (figure 22) and some damage to pectoral fins.

Three pike perch suffered some slight damage in the form of bruising near the head or in the dorsal area. Mortality after 48 hours was zero. Although no autopsy was performed, due to the nature of the damage and injuries, same causes of death are likely. Severe bodily trauma due to collision with moving parts of the turbine.



Figure 21. Pike perch with fractured spine just posterior of the head



Figure 22. Severe bruising and haemorrhaging near head

Test 1-2 (0,31 m head; 0,65 m³/s discharge)

100 pike perch;
 average length 17,7 cm;
 maximum length 23 cm;
 minimum length 13 cm;
 standard deviation 2,1 cm.

Test 1-2 , under milder conditions, did not result in significantly fewer fatalities as 5 pike perch were instantaneously dead. Type of damage was the same (severe bruising/fracturing etc.). In total 2 fish showed some light damage (mainly bruising). Mortality after 48 hours was zero.

Test 1-control (control test, fish in low water tank; 0,43 m head; 0,78 m³/s discharge)

74 pike perch;
 average length 18,4 cm;
 maximum length 23 cm;
 minimum length 15 cm;
 standard deviation 1,8 cm.

The control group had no fatalities and no damage at all. Mortality after 48 hours was zero. Table 6 shows the results in terms of percentage of (delayed) mortality (and upper and lower limits) of all tests with pike perch.

Table 6. Mortality of pike perch associates with the Water2Energy cross flow turbine

Direct mortality								
Turbine	Date of test	Test nr.	Fish species	N dead fish	N passed	% mortality	Lower limit%	Upper limit%
Water2Energy Cross flow	11-6-2015	1-1	Pikeperch	6	100	6,00	2,23	12,60
		1-2	Pikeperch	5	100	5,00	1,64	11,28
		1-control	Pikeperch	0	74	0,00	0,00	4,86

Direct + 48 hour mortality								
Turbine	Date of test	Test nr.	Fish species	N dead fish	N passed	% mortality	Lower limit%	Upper limit%
Water2Energy Cross flow	11-6-2015	1-1	Pikeperch	6	100	6,00	2,23	12,60
		1-2	Pikeperch	5	100	5,00	1,64	11,28
		1-control	Pikeperch	0	74	0,00	0,00	4,86

3.2.3 Rainbow trout tests (12th June 2015)

Test 2-1 (0,40 m head; 0,79 m³/s discharge)

96 rainbow trout;
average length 18,9 cm;
maximum length 22 cm;
minimum length 14 cm;
standard deviation 1,6 cm.

Test 2-1 did not result in any fatalities. All fish survived the testing. Fish could be observed swimming in a controlled way through the turbine. There was one rainbow trout with some discoloration but virtually unharmed. Mortality after 48 hours was zero.

Test 2-2 (0,29 m head; 0,57 m³/s discharge)

86 rainbow trout;
average length 18,6 cm;
maximum length 21 cm;
minimum length 14 cm;
standard deviation 1,6 cm.

Test 2-2, under milder conditions, did not result in any fatalities. In total 4 rainbow trout suffered minor damage (mainly discolorations, slight bruising). After 48 hours the discoloration disappeared. There was, however, one fatality after 48 hours. During the test a rainbow trout could be observed swimming against the water flow through the turbine.

Test 2-control (control test, fish in low water tank; 0,41 m head; 0,79 m³/s discharge)

99 rainbow trout;
average length 18,7 cm;
maximum length 22 cm;
minimum length 14 cm;
standard deviation 1,6 cm.

The control group had no fatalities and no damage at all. Mortality after 48 hours was zero. Table 7 shows the results in terms of percentage of (delayed) mortality (and upper and lower limits) of all tests with rainbow trout.

Table 7. Mortality of rainbow trout associates with the Water2Energy cross flow turbine

Direct mortality								
Turbine	Date of test	Test nr.	Fish species	N dead fish	N passed	% mortality	Lower limit%	Upper limit%
Water2Energy Cross flow	12-6-2015	2-1	Rainbow trout	0	96	0,00	0,00	3,77
		2-2	Rainbow trout	0	86	0,00	0,00	4,20
		2-control	Rainbow trout	0	99	0,00	0,00	3,66
Direct + 48 hour mortality								
Turbine	Date of test	Test nr.	Fish species	N dead fish	N passed	% mortality	Lower limit%	Upper limit%
Water2Energy Cross flow	12-6-2015	2-1	Rainbow trout	0	96	0,00	0,00	3,77
		2-2	Rainbow trout	1	86	1,16	0,03	6,31
		2-control	Rainbow trout	0	99	0,00	0,00	3,66

3.2.4 Yellow eel tests (16th June 2015)

Test 3-1 (0,41 m head; 0,79 m³/s discharge)

99 eel;
average length 26,3 cm;
maximum length 35 cm;
minimum length 20 cm;
standard deviation 3,0 cm.

Test 3-1 did not result in any fatalities among the yellow eel. None of the eel suffered any damage. Mortality after 48 hours was zero.

Test 3-2 (0,29 m head; 0,57 m³/s discharge)

80 eel;
average length 25,8 cm;
maximum length 31 cm;
minimum length 20 cm;
standard deviation 2,8 cm.

Test 3-2 , under milder conditions, did not result in any fatalities. None of the eels were slightly damaged. Mortality after 48 hours was zero.

Test 3-control (control test, fish in low water tank; 0,41 m head; 0,79 m³/s discharge)

96 eel;
average length 25,2 cm;
maximum length 31 cm;
minimum length 19 cm;
standard deviation 2,6 cm.

The control group had no fatalities and no damage at all. Mortality of eels after 48 hours was zero. Table 8 shows the results in terms of percentage of (delayed) mortality (and upper and lower limits) of all tests with yellow eel.



Figure 23. A perfectly healthy eel after testing

Table 8. Mortality of yellow eel associates with the Water2Energy cross flow turbine

Direct mortality								
Turbine	Date of test	Test nr.	Fish species	N dead fish	N passed	% mortality	Lower limit%	Upper limit%
Water2Energy Cross flow	16-6-2015	3-1	Eel	0	99	0,00	0,00	3,66
		3-2	Eel	0	80	0,00	0,00	4,51
		3-control	Eel	0	96	0,00	0,00	3,77
Direct + 48 hour mortality								
Turbine	Date of test	Test nr.	Fish species	N dead fish	N passed	% mortality	Lower limit%	Upper limit%
Water2Energy Cross flow	16-6-2015	3-1	Eel	0	99	0,00	0,00	3,66
		3-2	Eel	0	80	0,00	0,00	4,51
		3-control	Eel	0	96	0,00	0,00	3,77

4 DISCUSSION AND CONCLUSIONS

4.1 Project organisation of the live fish test

On the 9th of July 2015 a meeting was organized with all involved parties to officially end the Pro-Tide-NL project. Several presentations were given and the project was more or less evaluated. All involved parties agreed that the project had been very successful. The cooperation between all parties went well. Though testing with flounders showed to be not possible (see later), commitments were met and the planning was within boundaries. Safety regulations were followed and no accidents happened. No major problems were encountered. Of the project a film was made, which can be used for communication purposes.

4.2 Test species and method

Fish species available from commercial suppliers (pike perch, rainbow trout and eel) were easy to obtain and of very good quality, though costly. It was the intention to also test flounder as a standard for the group of flat fish that can be encountered in a tidal situation, but this proved to be disappointing. Juvenile flounder were caught and delivered by a professional fisherman, but the fish proved to be of very poor quality and testing was not commenced. Although it was not possible to remedy this within the planning of the project, it is felt as an omission that it was not possible to test a flat fish species, especially as this group of fish is quite different in behavior and appearance.

In a trade-off between scaling laws and vulnerability of young fish, average lengths were chosen for the fish species to be tested. For pike perch a length of 16 cm was chosen, for rainbow trout 12 cm and for eel 20 cm. Although fish of these sizes were ordered, the average length of the different species delivered deviated somewhat: pike perch: 17,6 cm; rainbow trout 18,0 cm; yellow eel: 25,3 cm. Fish tend to grow during the year, so the moment of testing is important as it is related to a certain fish size of the species available by commercial suppliers. One batch of fish always has a certain variety in lengths, as has become clear in chapter 3. With regard to possible damage and mortality, these were modelled based on the aforementioned lengths of the different species. As the fish used in the test were larger, a higher mortality might be expected.

Transport of fish and acclimatization went very well as there were no fatalities during the whole period of the turbine tests. The handling and the materials used (knotless netting, dip nets, anaesthesia, storage tanks and pumps etc.) were flawless. Control groups of fish experienced no damages whatsoever.

Insertion of fish in the test rig was very easy and fast. Water with fish could be dosed perfectly and the transport of the fish through the turbine into the low water tank only took seconds. As it turned out, the dimensions of the collection net was not in accordance with the actual size of the low water tank. This proved not to be a great set back as adaptations could be made on site. After the test and collection of the fish from the low water tank, fish were slightly anaesthetized and checked for damage. All damaged fish were photographed. After this procedure fish were stored in vertical keep nets attached to a line with floating buoys (see figure 24). When the experiment had ended, fish were released on site.



Figure 24. Vertical keep net for storage of fish

4.3 Test site and test rig

The location of the test site was near the village of Maurik at the Nederrijn, on grounds belonging to the power company Nuon. The terrain has been especially prepared for the test rig (concrete slabs, electric power supply, extra fencing near water etc.) with the help of Nuon. The area is fenced off and not accessible for unauthorized persons. Strict safety measures apply. The test site proved to be very suitable.

The design of the test rig functioned very well. The large pump supplying the water for the test rig had enough capacity. The high tank could be filled to capacity and the discharge was enough (and more than that) to operate the turbines and achieve a strong enough flow of water (figure 25) through the large pipe to transport the fish. The dimensions of the low tank were large enough as not to cause too much turbulence. The baffles in both tanks functioned properly, straightening out the flow. The collection net did not fit completely but on site adjustments could be made. The frame kept the net in position so it was not moving back and forth possibly damaging the fish. The permeability of the net was enough to accommodate the maximum discharge used. As there were several gaps at the bottom of the baffles the collection net was necessary. In future use, these gaps could be closed and a collection net would no longer be necessary as it was just as easy to enter the drained tank and use small hand held dip nets to collect the fish.



Figure 25. Measuring the water flow coming out of the large pipe with a Flow Mate 2000

As mentioned before the fish intake structure functioned very well. It was easy to inject the fish in a controlled manner (i.e. almost one by one) in a way that is certainly not damaging the fish. Care had to be taken to apply the correct amount of water passing through the intake structure. If the water supply was a low, air was entrained into the water leading to air bubbles passing the viewing chamber and obscuring visibility.

4.4 Test results

4.4.1 Pentair Fairbanks Nijhuis bi-directional turbine

Predictions of the modelling, done BE Engineering (Van Esch, 2015), of fish injury and mortality caused by the scale model of the Pentair Fairbanks Nijhuis bi-directional turbine are quite well in line with the live fish testing that has been executed in this project. It was clear that the scale model would cause some mortality but as it turned out, the mortality of pike perch was slightly higher in the tests than the model predicted and the mortality of smolts was lower than the predicted value, albeit well within the range of accuracy that can be expected. It was predicted that eel would not be damaged by passing through the scale model of the turbine, due to the fact that the tip speed of the scale model (approximately 6,4 m/s) is below the critical strike velocity for eel (8 m/s). As it turned out, there were no mortalities among the tested eel, there wasn't any kind of damage and there was no delayed mortality, completely in line with the predictions regarding eel.

Generally, it is accepted that salmon smolts (or in this case, small rainbow trout) belong to the most vulnerable species with regard to turbine damage. Mortality of pike perch however, was significantly higher than that of rainbow trout (6% in test 1-1 versus 1% in test 2-1 and 2% in test 1-2 versus 0% in test 2-2). Also, the internal damage to pike perch was quite severe (severed arteries, collapsed swim bladder etc.) leading to instant mortality. The reason why smolts did not suffer at least the same kind of damage is not completely clear, especially as both species in the test were practically of the same length (17-18 cm). Several factors might be of influence. Firstly, salmonids are sophisticated swimmers, as they have evolved in fast flowing waters. Probably, they are much more agile and capable to avoid the turbine blades. Pike perch is a species living in deep, dark and slow flowing waters and stagnant lakes and canals. Their swimming ability and agility is probably less than that of salmonids, thus being more prone to be hit by the turbine blades. The maximum swimming speed might also be an indicator of swimming performance through a turbine. Rainbow trout can reach up to 8 m/s and pike perch not even half of that speed (EPRI, 2000). Secondly, a difference in behavior might play a role here.

As stated before, eel was not damaged at all when passing the Pentair Fairbanks Nijhuis turbine. Film footage showed eels being hit by a turbine blade and gently slipping off the blade totally unharmed, indicating that the tip speed was not high enough to inflict damage to this species.

In the test with the Nijhuis turbine pike perch suffered a mortality ranging from 2% in test 1-2 (lower and upper limit respectively 0,25-7,18%) to 6% in test 1-1 (lower and upper limit respectively 2,33-12,60%). Rainbow trout experienced a mortality of 1% in test 2-1 (lower and upper limit 0,03-5,55%) and 0% (lower and upper limit 0,00-3,73%) in test 2-2. Mortality of eel in both tests was 0% (upper and lower limit 0,00-3,66 or 4,10%, depending on the number of eel tested). In none of the test there was any delayed mortality.

4.4.2 Water2Energy cross flow turbine

Pike perch passing the cross flow turbine experienced a mortality of 6% (lower and upper limit respectively 2,23-12,60%) in test 1-1. The second test (1-2, with milder conditions) resulted in a mortality of 5% (lower and upper limit respectively 1,64-11,28%). There was no delayed mortality. It is remarkable that the second test, with milder conditions, showed a mortality which is almost the same as the mortality in the first test. The reason for this is not distinct. The tip-speed-ratio (TSR) of both tests are almost equal ($TSR_{test1-1} = 1,14$; $TSR_{test1-2} = 1,22$). This small difference cannot compensate for the larger difference in collision speed.

Rainbow trout suffered no direct mortality in test 2-1 and test 2-2 (upper and lower limit respectively 0,00-3,77%). In test 2-1 there was no delayed mortality (0%, upper and lower limit respectively 0,00-4,20%) and in test 2-2 one rainbow trout died (1% mortality, upper and lower limit respectively 0,03-6,31%).

The tests with eel showed no direct nor delayed mortality at all and no damage (0%, lower and upper limit 0,00-3,66 or 4,51%, depending on the numbers of eel tested).



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