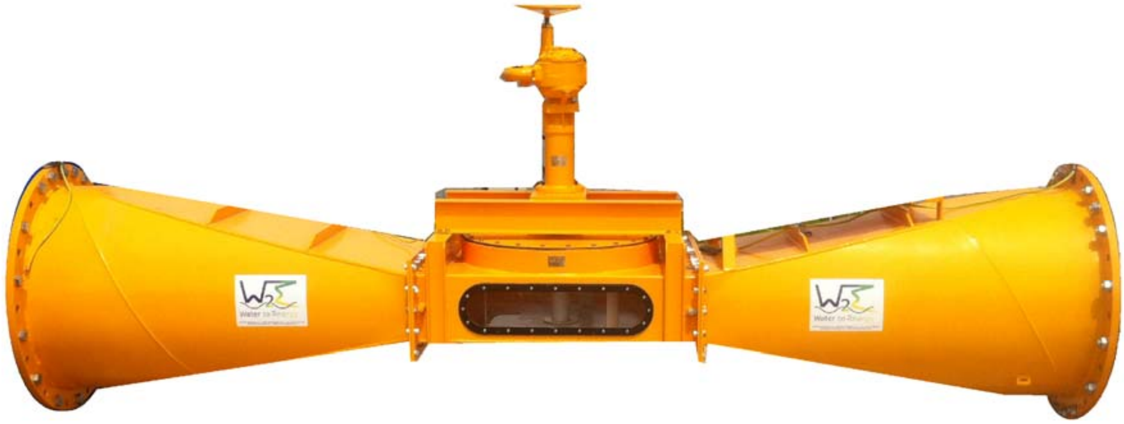
PRO-TIDE-NL

Pilot Tidal Turbines

Testing for Performance



Article

Pro-Tide work package WP1A2

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This project has received European Regional Development Funding through INTERREG IV B.

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1. EXECUTIVE SUMMARY

Within the Dutch Pro-Tide project a test-rig was designed, realised and operated, specifically for testing of scale 1:10 pilot tidal turbines on performance and fish friendliness.
Power performance (efficiency) testing is executed for a vertical axis active blade pitch controlled tidal turbine developed by the company Water-2-Energy (W2E).

The findings of this project work package can be summarised as:

1. The test-rig designed, build and operated within the Dutch Pro-Tide project provided a well controlled test environment for testing of performance of scale model turbines: Flow rate and head were controllable within the desired range (1 m^3/s and 1 m respectively), with adequate accuracy and resolution.
2. Hydraulic power supply is measured using an ultrasonic flow meter on the supply tube, and pressure transducers. Mechanical power is derived from the turbine shaft torque measurement and the momentary shaft speed (rpm).
3. The test procedure comprising controlled deceleration of the turbine at fixed hydraulic power supply, proved to be a very easy and fast method. Continuous logging of the relevant parameters (for hydraulic input and mechanical output) enabled easy a posteriori data-processing.
4. Efficiency is derived from mechanical power and hydraulic input. Depending on the flow rate, hydro-mechanical machine efficiency ranged from 30- to 48 %.
5. When hydraulic losses in the entire system are taken into account, the measured machine efficiencies translate to system efficiencies around 20 %.
6. Scaling to full size turbines is done on the basis of Reynolds scaling, accounting for the relative importance of blade and wall friction in small scale devices, compared to full scale devices. When adopting conservative scaling parameters, full scale system efficiencies can be expected in the range of 30 %.
7. The 30 % efficiency indication shows that there is room for improvement of the W2E-turbine. Given the low tip speed ratio of around 1,2 for the three bladed machine, one suggestion would be to apply more (e.g. 6-8) turbine blades (possibly to be determined using Computational Fluid Dynamics). The effect on fish friendliness should of course need to be taken into account.
8. Quite remarkably, for ducted, ultra low head application, the 3-bladed vertical axis machine with active blade pitch control proves to be much more efficient than a similar machine with fixed, non-angled blade position, which is frequently used in free stream applications.

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2. LAYOUT OF THE TEST-RIG AND PILOT TURBINES

2.1 Layout of the test-rig

For testing fish friendliness and power production of tidal turbines, within the framework of Pro-Tide a test-rig is designed, realised and operated (Berkel, 2015-a,b).
The test rig is designed for testing tidal turbines on scale in the range 1:10. To facilitate testing for fish friendliness the layout is in accordance with guidelines that are formulated within this project (Vriese, 2015a). To assure water quality (temperature and composition), the test-rig comprises an open loop layout with continuous supply of fresh river water, see figure 2.1

Figure 2.1 Aerial (top) view of Pro-Tide-NL's test-rig at Maurik, The Netherlands. Circulation of fresh river water is clock-wise.

A submerged pump delivers water to a 13 m^3 header tank (shown top-left), designed to stabilise the flow to the turbine, and also facilitate introduction of life fish in the turbine's supply flow. The turbine discharges water to a 16 m^3 sink tank (shown top-right), also designed to stabilise the exit flow and facilitate collection of the fish after turbine passage. The dimensions (length x width x height) of the tanks is further selected to provide adequate submergence both at the turbine exit (cavitation) as well as the turbine's entrance (avoidance of air entrainment). Perforated baffle plates provide dissipation of large turbulent eddy's and uniform flow distribution. In the sink tank a weir is positioned to control the water level in the test-rig.

The test-rig was designed for a flow rate of 1 m^3/s at a gross turbine head of 1 meter. During testing, a maximum flowrate of 1.1 m3/s was measured. Maximum head measured was 1,2 meter.

The test-rig itself is installed at the premises of Nuon/Vattenfall's hydropowerplant at Maurik, NL. For a more detailed description see Berkel,2015-a,b.

2.2 Pilot turbines

Two pilot model tidal turbines were tested in the test-rig, see figure 2.2.

Figure 2.2 Pilot turbines: Left: Nijhuis horizontal axis bi-directional tidal turbine (50 cm rotor diameter) and right: W2E vertical axis tidal turbine, 70 cm rotor diameter (28 cm rotor height).

Both turbines were selected in accordance with the advice of the Pro-Tide-NL's R&D advisory board (Klip, 2015). Within Pro-tide, both turbines are tested for fish friendliness, see Vriese 2015b. As the turbine of Nijhuis was already tested extensively for performance prior to the Pro-Tide tests, within this project, performance tests concentrated on the W2E turbine. Figure 2.3 gives a 3-dimensional view of the W2E-turbine. Special feature of this turbine is the active blade pitch control, adjusting the positioning of the blades to a specific optimal tip speed ratio.

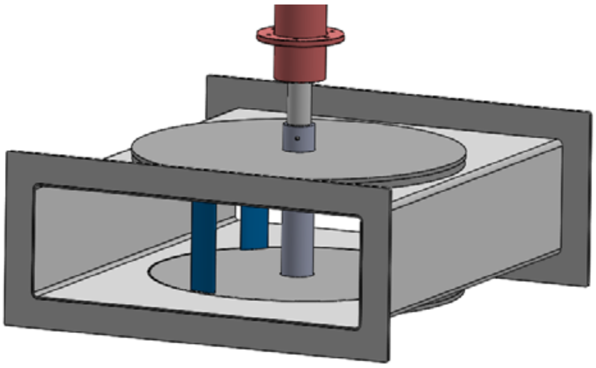

Figure 2.3 W2E's vertical axis turbine, with in blue the runner blades. Not visible is the blade pitch control mechanism.

The pilot model is a scaled version of a full size device with rotor diameter x height of 7 x 7 m^2, housed in a conduit of 8 x 8 m^2. The diameter is scaled with a factor 10, resulting in a pilot rotor diameter of 70 cm. To allow safe passage of fish, clearance with the conduit wall is maintained at 10 cm, which gives a conduit width of 90 cm. To limit water usage (to max. 1 m^3/s) the cross section of the turbine house is also limited by selecting a conduit and rotor height of 28 cm. The pilot turbine cross section area thereby is a factor 254 smaller than its full scale equivalent. The ratio of rotor area/conduit area is 0,77 both for the pilot as well as for the full scale version. Table 3.1 summarises the main dimensions of W2E's turbine.

Table 3.1 Main dimensions for W2E's vertical axis turbine.

	Full scale	Scale
Rotor diam. x height [m^2]	7 x 7	0,7 x 0,28
Housing cross section [m^2]	8 x 8	0,9 x 0,28
Flow velocity @ Brouwersdam [m/s]	4	4
Flow rate [m^3/s]	256	1
RPM [-] @ 2 Tip Speed Ratio (TSR)	22	220
Power output [kW] @ Cp=0,2	315	1,3

As first indication of power production is based on an assumed 20 % efficiency (Cp), see table 3.1. More detailed power prediction for the W2E-turbine is done following insight derived from free stream vertical axis (Darrieus-type) turbine (Ginter, 2007). As this analysis however concerned fixed (symmetrically) positioned blades it was used to get an indication only. Final conclusions concerning the power production of W2E's turbine is to be derived from the tests at Maurik.

2.3 Measurement equipment

For determination of technical performance (turbine efficiency) the test-rig is equiped with measurement equipment:

1. Ultrasonic flow meter, connected to the DN1000 supply pipe (just before entering the header tank)
2. Gross head measurement meters (manual reading)
3. Turbine net head pressure meters.
4. Turbine shaft torque meters.
5. Turbine shaft speed (rpm) meters.

Except for the gross head meters, all readings are logged to a measurement computer, at a rate of 100 Hz. Figures 2.4 to 2.6 give an impression of the measurement equipment.

Figure 2.4 W2E's vertical axis turbine shaft measurements: Left Torque sensor with strain gauges and wire-less transmitter and right: optical shaft speed meter.

Figure 2.5 Hydraulic measurement equipment: Left: pressure transducers for static pressure across the turbine and right: one of the Ultrasoninc flow transmitters/receivers attached to the DN1000 supply tube.

Figure 2.6 Data logging and measurement computer console.

During measurement, all relevant signals were logged to a measurement computer, for data processing at a later stage. Results became available in (amoungst others) .xls or .csv-format.

During power measurements, mechanical power generated by the turbine is dissipated in a hydraulic brake, consisting of a pump, with adjustable throttle valve, see figure 2.7.

Figure 2.7 Hydraulic braking system

Prior to deployment, all equipment was calibrated and checked for accuracy, see further (Stam, 2015).

3. PILOT TURBINE POWER MEASUREMENT RESULTS

3.1 Measurement procedure

During the initial stage of a performance test, flow rate through the turbine was adjusted to the desired value by means of the frequency controlled submerged pump, with the (pump) brake throttle valve fully open, enabling the turbine to run at maximum speed. Turbine head follows from the flow rate set with the pump and the hydraulic resistance of the turbine.

During the actual data-logging period, the (pump) brake throttle-valve was gradually closed resulting in the turbine slowing down, until the throttle valve was fully closed and the turbine ran at minimum speed. During turbine deceleration, all relevant parameters were logged (sample rate 100 Hz). Care was taken to decelerate the turbine at a rate sufficient to establish quasi-steady conditions. Each test typically took 5 minutes to complete.

Performance tests are done for three blade pitch control settings (A, B en C) and as a reference the fixed (symmetrical) blade position (Darrieus-type, test series "D"). On the basis of the tests, the choice was made to test the turbine for fish friendliness with blade control "A", of which the performance results will be given here.

3.2 Measurement data (pilot turbines)

Figure 3.1. and 3.2 gives the measurement data and relevant calculated parameters of the two tests conditions also selected for fish friendliness testing and thereby providing a coherent set of turbine performance data.

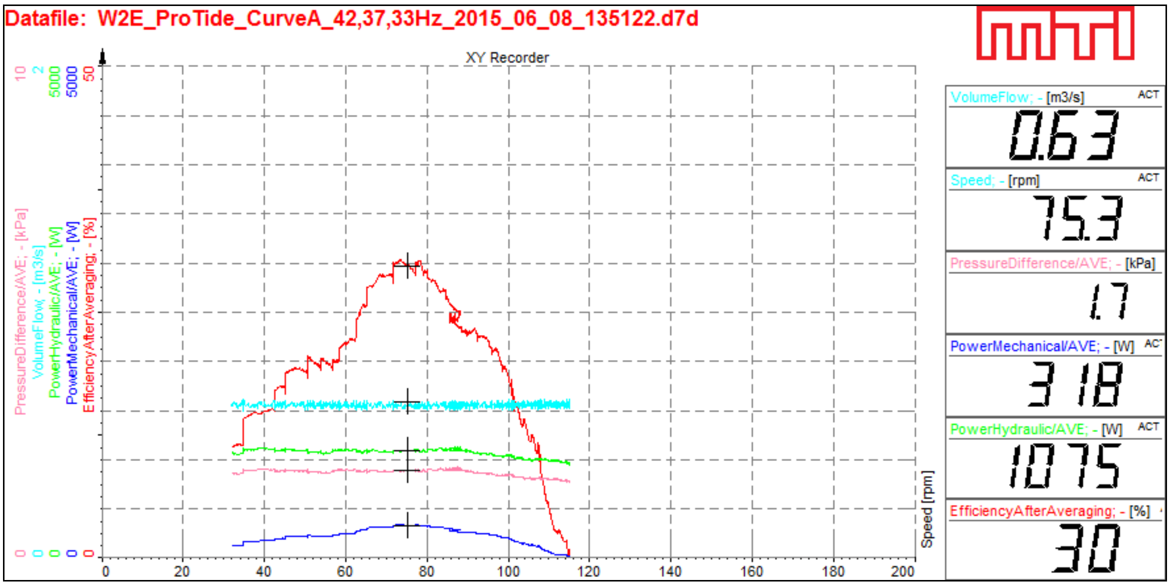

Figure 3.1 Measurement data and relevant calculated parameters of test condition I (0,63 m³/s)

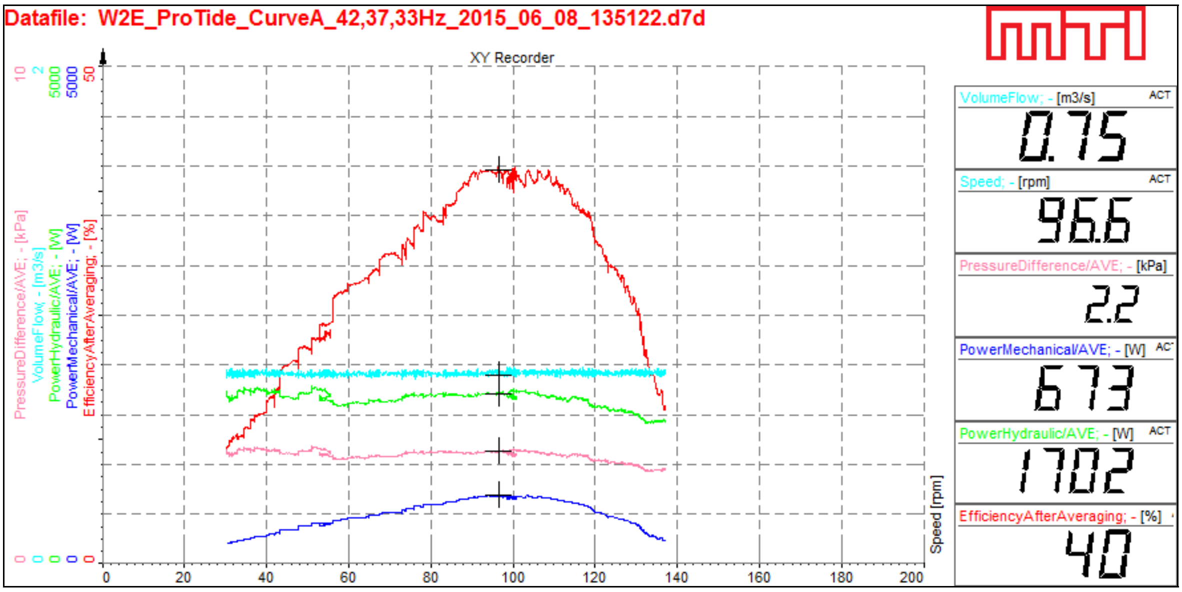

Figure 3.2 Measurement data and relevant calculated parameters of test condition II ($0{,}75\ m^3/s$)

A third measurement at 0,94 m^3/s, resulting in a higher efficiency (48 %), was not adopted for further (fish) testing because of the anticipated high mortality rate.
The most relevant data of the tests taken into account is summarised in table 3.1.

Table 3.1 Measured and relevant data, test conditions I and II.

Performance test W2E-turbine, blade control "A" dd. 08-06-2015		
	Test condition I	**test condition II**
Flow rate @ max efficiency [m3/s]	0,63	0,75
Net turbine pressure @ max efficiency [kPa]	1,7	2,2
Average gross head [m] (manually recorded)	0,30	0,42
RPM @ max efficiency [/min]	75	95
Flow velocity @ max. efficiency [m/s]	2,50	2,98
Maximum machine efficiency [%]	30	40
Tipspeedratio @ max. efficiency [-]	1,10	1,17

The efficiency given in table 3.1 is machine efficiency, defined as mechanical power, devided by hydraulic power (product of flow rate and pressure difference across the turbine). More relevant is the system efficiency, defined as mechanical power, devided by hydraulic energy input (based on flow rate and water level difference in header- and sink tank). System efficiency accounts for unavoidable losses outside the turbine like entrance losses, conduit losses and exit losses. As can be derived from table 3.1, for the test-rig and pilot turbine the system static pressure head is about half the turbine net pressure difference. Hence system efficiency is about half the value given in table 3.1 (15- and 20 % for condition I and II respectively).

Quite remarkably, tests series "D" with the fixed, non angled blade configuration (which is frequently used in free-stream applications), performed not well in ducted application. The turbine was found to be self-starting only for the highest flow rate (0,92 m^3/s), and barely capable to overcome the friction of bearings and seals and non-activated brake. Maximum speed attained was 58 rpm and maximum power generated 23 W, indicating a machine efficiency of less than 1 %.

This indicates that for ducted, ultra low head operation, the machine with active blade control perfoms significantly better than for the same machine without active blade control (fixed, non-angled blade position).

4. PROGNOSIS FOR FULL SCALE TURBINE EFFICIENCY

Knowing the power output of a small scale turbine, the power output of the full scale device can be predicted by means of a standard Reynolds scaling (Wright 2010):

$$\frac{(1-\eta_{turbine})}{(1-\eta_{model})} = \left(\frac{Re_{model}}{Re_{turbine}}\right)^n \qquad [-] \qquad (4.1)$$

Reynolds scaling is based on the assumption that (friction) losses due to wall and blade roughness scale with the Reynolds number (which represents the ratio of inertia to friction forces). Efficiency is assumed to increase with the Reynolds number.
Of course there is a limit to the efficiency increase; Above some level (Reynolds number) the flow will hardly be affected by wall roughness any more. In addition, some losses, like exit losses, do not scale with roughness.
Hence Reynolds scaling here is interpreted with care. In literature values for the exponent n (see eq. 4.1) roughly vary between 0,1 to 0,25. The conservative value of 0,1 is used here.
The efficiency of the full scale equivalent of the pilot turbine, operating in the Brouwersdam system at 1 meter head is estimated following the calculating scheme in table 4.1:

Table 4.1 Full scale efficiency calculation

Efficiency scaling W2E turbine blade control "A"	
Pilot scale, condition II	
Pilot machine speed [rpm]	95
Pilot machine efficiency @ BEP [%]	40
Gross head H [m]	0,42
Net turbine pressure @ BEP [kPa]	2,2
System efficiency, based on gross head	21,0
Flow velocity @ BEP [m/s]	2,98
Velocity coefficient C [-] V=C Sqrt(2 g ΔH)	1,04
Tips speed ratio @ BEP	1,17
Full scale (rotor diameter 10x)	
Head [m]	1
Anticipated velocity @ 1 m head and 1,04 velocity coeff.	4,60
Full scale speed@ TipSpeedRatio=1,17 [rpm)]	15
Full size / Pilot size Reynolds number	15,4
Machine effciency @ full scale, using Reynolds scaling	0,54
System efficiency, accounting for 0,5 m full scale head loss	0,27

Note that the 27 % efficiency prediction (rounded up to 30 %) in principle holds for a 1:10 scaled turbine, with a rotor height of 2,8 meter and not for a 7 meter high rotor.
As stated, the 30 % efficiency estimate should be interpreted with care. It nevertheless does indicate that there is room for improvement of the efficiency of the W2E turbine. Given the fact that the tip speed ratio is close to 1, one direction would be to install more runner blades as to attain the better coverage of the water flow. For max. efficiency, a three-bladed machine normally would operate at a tip speed ratio of 2-3 (Ginter, 2007). If (avoidance of) blade-blade interaction and wake-effect is the torque & speed determining principle, a machine operating at tip speed ratio around 1, in principle could have a double number of blades (6-8), which would in principle generate a double torque. The increase of blades may of course have an adverse effect on fish friendliness, which needs to be determined accordingly.

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