Entwicklung einer wendbaren Turbine für Gezeitenkraftwerke

Development of a turnable turbine for use in barrage type tidal power plants

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The paper presents a novel design approach for a low-head hydro turbine to be used in barrage-type tidal power plants. For maximum production, the turbines of such plants need to be capable of four quadrant operation, i.e. turbine mode in both ebb and flood power generation as well as pumping mode in both flow directions. Conventional Kaplan bulb turbines suffer from an inherently reduced efficiency in those two operational quadrants where the flow is reversed in respect of the normal flow direction. The turnable turbine concept presented herein avoids this disadvantage by allowing the turbine to be swiveled around an axis perpendicular to the rotation axis of the runner.

A turbine based on this concept is being designed and model tested within the Safe*Coast research project. As a first step in this process, the main boundary conditions were identified. The two major approaches of exploiting tidal energy, barrage type tidal power plants and tidal current turbines, are described, and a review of the characteristics of turbines in existing barrage type tidal power plants is given.

Subsequently, a concept study for the new turbine was conducted, the main aspects and conclusions of which are presented in this paper. First, operational strategies for tidal power plants and their influence on turbine operation modes are presented. Modes where a turnable turbine is beneficial are identified and laid out. Then, the resulting design demands for the turbine are derived and outlined in a short summary. Subsequently, the systematic analysis of different turbine configurations is described. In the concept study turnable and non-turnable versions of conventional bulb turbines with fixed or adjustable runner blades and guide vanes and counter rotating turbines were assessed. The resulting constraints and demands for the guide vane and runner blade shapes were determined by performing a systematic analysis of the flow kinematics based on studying the velocity triangles in the different operational modes. Possible configurations of guide vane and runner blade shapes and edges were evaluated. The results of this study were compiled in a comparative evaluation matrix, which will be given in the paper along with an excerpt explaining the methodology used.

The investigations performed show that a turnable turbine has a high potential for tidal applications which rely on four quadrant operation. The concept study confirms that the technology of the proposed new turbine concept is feasible and that additional development could lead to an innovative and promising product.

1 Introduction

The main objectives of the project Safe*Coast are to combine active flood protection, tidal power generation and traffic infrastructure improvement. In order to achieve these goals, a new concept of a tidal turbine with the capability of four quadrant operation will be developed. Turbine mode is possible during ebb from a reservoir to the sea as well as during flood from the sea to a reservoir. To maximize the power output, the turbine will be able to pump in both directions. The pump mode can also be utilized for active flood protection by lowering the water level of the separated basin. Hence, increased capacities are available to decrease the impact of an incoming storm surge. Moreover, it is possible to use the barrage for infrastructural projects. The combination of these three goals in one project is a challenging task. The Safe*Coast project is funded by Eurostars, a joint programme between EUREKA and the European Commission.

An important part of the project is the design of a water turbine that meets the special requirements mentioned above. A feasibility study was carried out to evaluate different options of how to accomplish the targets set. A detailed turbine kinematics study was conducted. In the design process of the water turbine, CFD simulations will be performed in order to optimize its performance. Subsequently, a prototype in model size will be built and a performance map as well as cavitation investigations of the turbine will be compiled.

2 Tidal Energy

The cyclic rise and fall of the water level during a tidal cycle allows two fundamentally different options for generating electrical power. It has to be distinguished between the vertical movement of the water level and the tidal currents generated by this phenomenon [Clark, 2007]. Both approaches are described in the following.

2.1 Comparison of barrage and tidal current power plants

Classical tidal power plants use a basin or estuary which is separated from the ocean by a dam. During a tidal cycle the sea water level oscillates between ebb and flood. Thus, by controlling the flow between the two water bodies, a hydraulic head can be created. The potential energy of the water reservoir with the higher water level can be extracted using a water turbine as shown in the operating diagram depicted in Figure 1. This energy conversion can be performed in both flow directions, basin to sea or sea to basin. By pumping the water levels up or down during suitable times the overall energy output of the tidal power plant can be further increased.

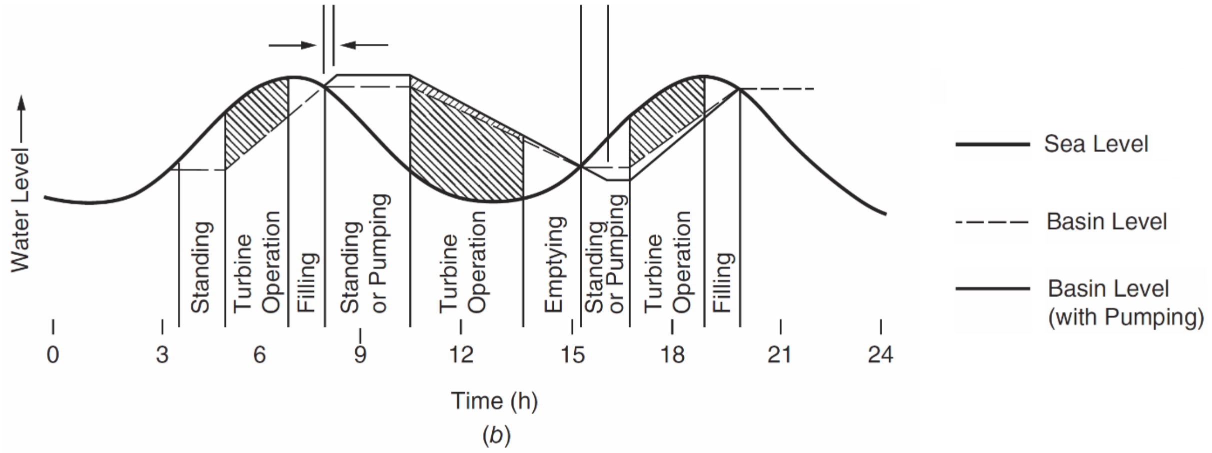

Figure 1 Water levels of a single basin, two way operation mode with pumping [Clark, 2007]

A different approach is to exploit the kinetic energy of tidal currents. Similar to wind power, hydrokinetic turbines are placed in spots with high flow velocities. This is the case where either natural formations or artificial contractions accelerate the flow. The major advantage of tidal current power plants is that only little civil engineering effort is necessary without the need of a total blockage of the flow. Another advantage is that there are almost no constraints to shipping traffic. However, the power output of tidal current turbines is very limited, and there are not many potential sites where the flow velocities are high enough to promise an economically successful operation.

2.2 Existing Tidal Power Plants

Literature states that the world potential for tidal energy is similar to the hydro potential of rivers [Lempérière, 2009]. Nevertheless, only a small number of tidal power plants were built compared to the number of run-of-the-river hydro power plants. The reasons for that are mainly of political, economic and environmental nature. Since fossil fuels are still a cheap and reliable source for energy production, it is difficult to attract investors to fund tidal power plants. The environmental impact, especially of barrage type facilities, is another important reason to consider. Nevertheless, generating energy from tides is a renewable resource that is, in contrast to solar or wind power, completely predictable.

Table 1 summarizes the characteristics of the turbines installed in the main existing barrage type tidal power plants. The installations at La Rance, France and Sihwa-Ho, South Korea are by far the largest regarding power output. The remaining power plants were mainly built for experimental purposes. The power plant in Annapolis Royal, Canada is the only big scale tidal power plant with a Straflo type turbine. In the tidal power station Kislaja Guba, Russia, a Kaplan bulb turbine with s-shaped blades was initially installed. Turbine, pumping and water passing modes were possible in both directions [Bernshteĭn, 1996]. The Kaplan turbine was later on replaced by two orthogonal turbines [Rushydro, 2011]. The power plants La Rance, France, Sihwa-Ho, South Korea and Jiangxia, China are equipped with Kaplan bulb turbines.

Table 1: Characteristics of existing turbines in barrage type tidal power plants

	D [m]	H [m]	Q [m³/s]	n x P [MW]	type
La Rance[1]	5.35	rated head: 5.65 head range: 1 – 11	max: 275 rated: 275	24 x 10.0	Kaplan bulb
Annapolis[1]	7.60	rated head: 5.50 head range: 1.4 - 7.1	max: 407.5 rated: 378	1 x 19.6	Straflo
Kislaja Guba old[2]	3.30	rated head: 1.28 head range: 0.5 - 2.5	n/a	1 x 0.4	Kaplan bulb
Kislaja Guba new	2.50 5.00	n/a	n/a	1 x 0.2 1 x 1.5	Ortho-gonal
Sihwa-Ho[3]	7.50	rated head: 5.82 head range: 2.0 – 6.0	max: n/a rated: 482	10 x 25.4	Kaplan bulb
Jiangxia[4]	2.50	rated head: 3.0 head range: 1.2 – 5.5	max: n/a rated: 34	1 x 0.545 1 x 0.655 4 x 0.760	Kaplan bulb

3 Concept study

In order to understand how the new turbine can satisfy the project requirements, a concept study was carried out. In a first step, the requirements were compiled and assessed regarding

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[1] Clark, 2007

[2] Bernshteĭn, 1996

[3] Bae et al, 2010

[4] Zhengwei et al, 2010

their importance. Then, technical measures for their implementation were identified and reviewed. The goal of the study was to find the most promising way to develop the new turbine.

The main requirement is that the turbine must be capable of operating in all four quadrants with a high efficiency. Four quadrant operation means that both head and discharge can be positive or negative. This results in four modes of operation that are presented in Figure 2:

- Forward turbine operation (discharge positive, head positive)
- Reverse pumping operation (discharge negative, head negative)
- Reverse turbine operation (discharge negative, head positive)
- Forward pumping operation (discharge positive, head negative)

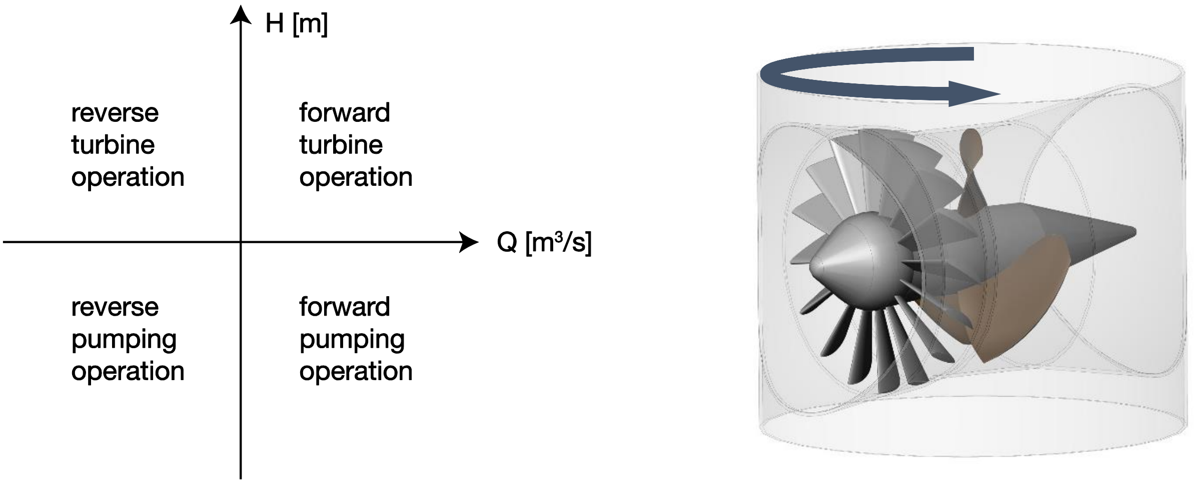


Figure 2 Four quadrants of turbine operation [figure adapted from Bernshteĭn, 1996, p.144] (left) Turnable Turbine concept (right)

The majority of existing low-head hydro turbines are capable of operating in forward turbine operation only since they are installed in run-of-the-river hydropower plants. The same applies for the turbines installed in the Sihwa-Ho tidal power plant. There are also axial pump-turbines that can operate in forward mode as a turbine as well as in reverse mode as a pump. These turbines are used in waste water treatment plants to generate electricity when water is discharged from the plant or to pump the wastewater into the receiving water when its level is higher during floods. The challenge in designing a turbine capable of operating in all quadrants is that each mode has a distinct combination of flow direction and direction of energy transfer. This leads to conflicting requirements regarding the blade shape and the general turbine configuration.

There have been experimental turbines with straight blades, s-shaped blades or blades capable of pitch changes beyond 180°. With these concepts, however, high efficiencies can only be achieved in two quadrants, while efficiencies in the remaining two remain relatively low. The turbines used in the La Rance tidal power plant for example have peak efficiencies of up to 87 % in the forward and 73 % in the backward turbine mode as well as 66 % and 58 % in the forward and backward pumping mode respectively (Bernshteĭn, 1996). In recent years concepts that use two counter rotating runners have been suggested. The turbine concept proposed in this study uses a setup where the whole turbine can be pivoted by 180°. In this way a conventional two-quadrant axial pump-turbine can be used in all four quadrants. Hence, turbine blades and general construction are less complex and can be optimized for one flow direction.

3.1 Operation strategies

Different operation strategies for tidal power plants have been proposed in the past and some of them have been implemented. By increasing the complexity and the degrees of freedom of flow and energy transfer direction, a higher portion of the available energy in the basin can be utilized.

Figure 3 summarizes several possible tidal power schemes and their necessary turbine operation quadrants. The simplest barrage type tidal power plant concept consists of a single pool and is equipped with turbines that work in one direction (e.g. from the pool to the sea). In this concept turbine operation is required in the first quadrant only. If pumping is included this scheme, the third quadrant is added. If a two-way operation (dual mode) is implemented, a non-rotatable turbine would operate in the first and second quadrant. When adding pumping to the dual mode single pool scheme all four modes become relevant.

A turbine that can be turned around would reduce the number of quadrants required in some modes. In the single mode operation, a turning would give no benefits, regardless whether pumping is added or not. In the dual mode, however, the necessary quadrants would be reduced from two to one. If dual mode with pumping is considered, the number of quadrants reduces from four to two. In addition to single pool schemes, twin pool configurations have been suggested. These schemes allow for a more continuous electricity production, but there a very few potential sites where they can be economically implemented. For the two main suggestions of such configurations, no benefits for a turnable turbine could be identified. Nevertheless, with the target to develop a turbine which is giving a high efficiency in all the operating phases occurring in a single pool dual mode scheme, a turnable turbine shows distinct advantages compared to conventional turbines.

Two out of the existing barrage type tidal power plants, namely La Rance and Jiangxia, are capable of dual mode operation with pumping. However, only moderate efficiencies are achieved. Furthermore, Kislaja Guba is capable of dual mode without pumping. Sihwa-Ho and Annapolis are capable of single mode without pumping.

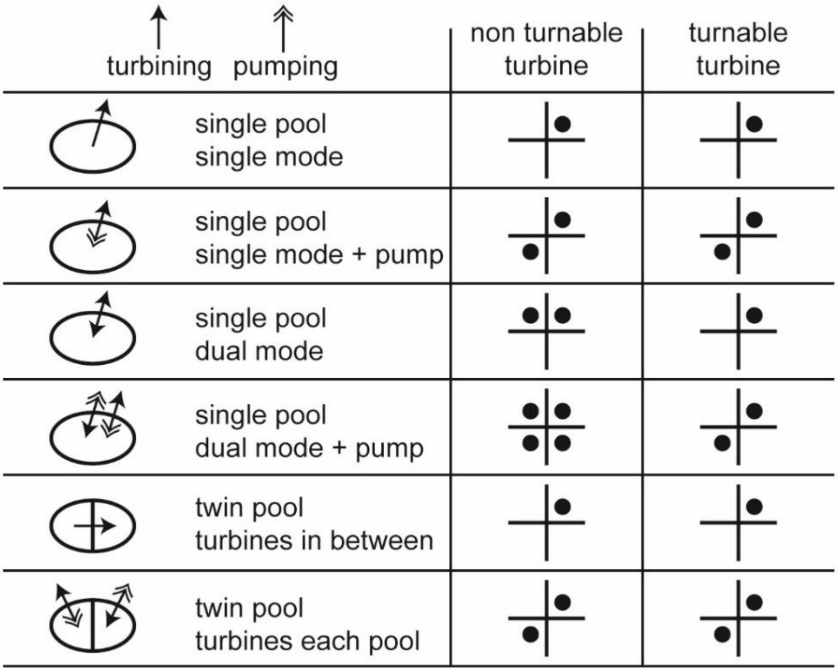


Figure 3 Tidal power schemes and necessary turbine operation modes

3.2 Turbine requirements

In order to reach the maximum energy output of tidal power plants, the turbine under development shall be capable of dual mode with pumping. As a result, some requirements have to be met in order to enable a successful operation. These requirements are described in the following.

In a tidal barrage power plant, there are operating phases where any water flow between the pool and the sea has to be prevented. Thus, one basic requirement is that the turbine can completely shut off the discharge in its closed position. As the turbines operating range is concerned, the hydraulic head between the basin and the pool is usually low. At sites with very high tidal amplitude, the maximum head is approximately nine meters [Aelbrecht, 2014], but the operating head varies greatly during the daily and the monthly tidal cycle. Thus, the turbine should be capable of operating within a wide head range with high efficiency. Due to the low heads and high discharges involved, it is also essential that the turbine has a high unit discharge. This means that, in relation to the head and diameter of the turbine, high flow rates and sufficient power output can be achieved. Mechanical simplicity is another favorable property. The less moving parts the turbine consists of, the easier and cheaper it is to manufacture and to maintain. In general, the risk of failure is reduced if a lower number of bearings, seals, gears and parts are implied. Functional safety also plays a major role. The turbine has to be designed to withstand the structural loads occurring during a runaway condition. In the case of a power outage the water flow has to be shut down in a short time, e.g. through an emergency stop that closes the guide vanes of the turbine. This can be achieved by an actuating drive powered by gravity, hydraulic pressure or springs. Another turbine requirement is that cavitation does not occur within the normal operating range. Cavitation causes not only noise and vibration, but also material erosion on the turbine blades. Moreover, it reduces the overall performance in both turbine and pump mode. Ultimately, the main motivation of the development is to achieve a high efficiency in all four quadrants.

3.3 Turbine kinematic study

In the development of tidal turbines, many variations have been suggested and investigated in the past. Turbines with up- and downstream bulbs have been designed, as were runners with s shaped and straight blades [Cotillon, 1973]. Moreover, guide vanes on either side of the runner were evaluated. Two options were, however, not suggested: turbines that can be swiveled around, as in the proposed concept, and turbines with two counter-rotating runners. By sketching velocity triangles for different turbine concepts, one can derive the flow angles required to achieve the desired energy conversion in the four different operating modes. Moreover, the limitations, advantages and disadvantages of different general runner and guide vane blade shapes can be analyzed. Drawbacks and advantages can be discovered for each combination and unfeasible modes can be identified. To gain a systematic overview of the various possibilities an evaluation matrix was compiled. A conventional tubular turbine was studied as well as a turbine with counter rotating runners. For these turbine types a variety of blade configurations was investigated, see Figure 4. The blade profile could be either curved or straight. Moreover, two variants of blade edges were considered, namely blades with elliptical leading edge and cutoff trailing edge as well as blades with elliptical leading and trailing edge.

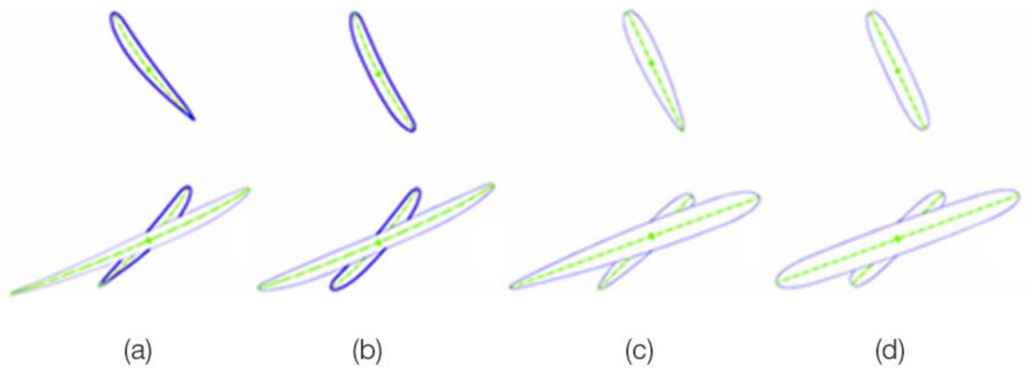
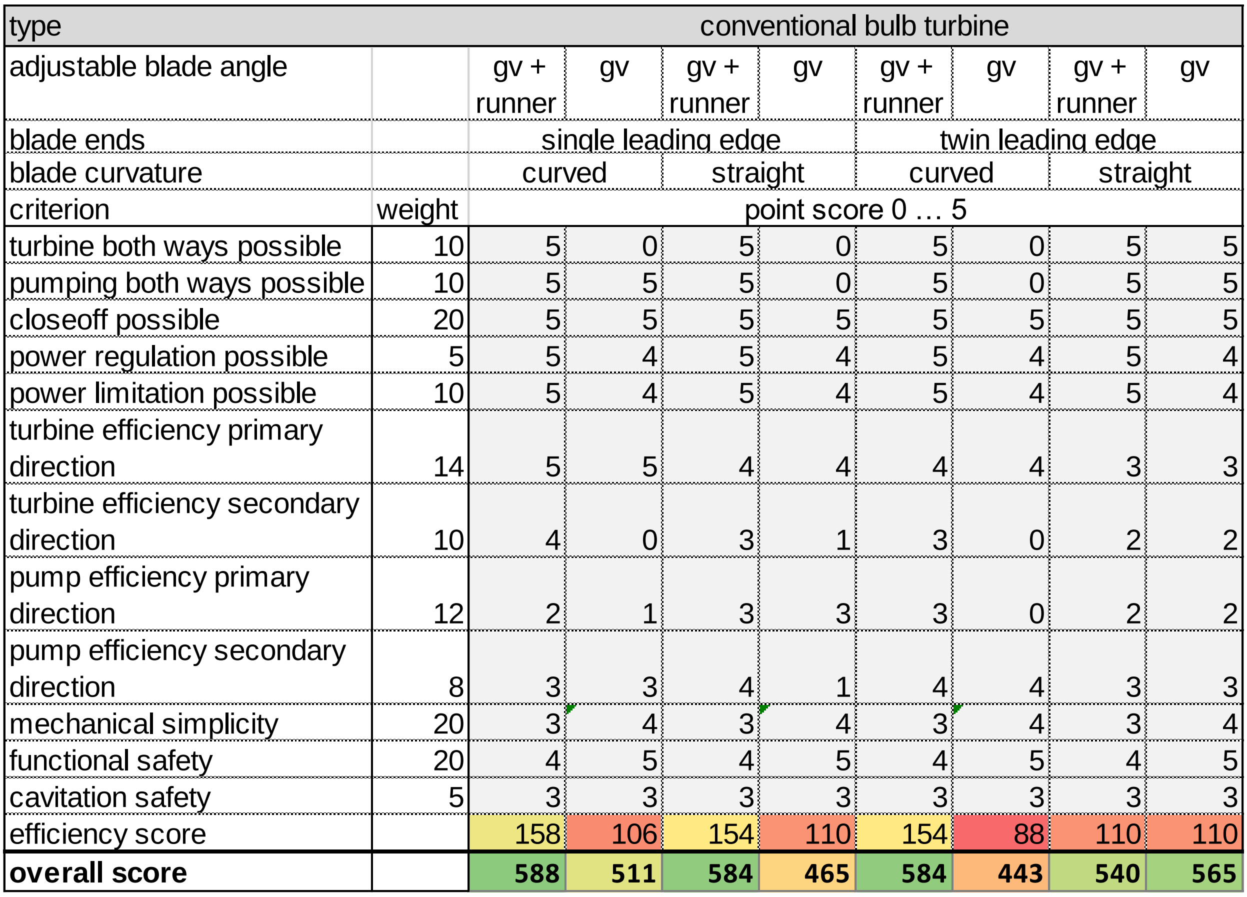


Figure 4 Blade variants in the kinematic study (a) curved, single leading edge; (b) curved, double leading edge; (c) straight single leading edge;(d) straight double leading edge

Furthermore it was distinguished between adjustable and fixed runner blades. Another differentiation was whether the whole turbine can be turned around or not. All those alternatives lead to 32 possible configurations that were included in an evaluation matrix. A detailed rating was assigned to each configuration based on several criteria, like efficiency in different operation modes, mechanical complexity, cavitation susceptibility, functional safety and shutdown possibility. Figure 5 shows an excerpt from the matrix for the evaluation of a conventional bulb turbine.



type		conventional bulb turbine							
adjustable blade angle		gv + runner	gv	gv + runner	gv	gv + runner	gv	gv + runner	gv
blade ends		single leading edge				twin leading edge			
blade curvature		curved		straight		curved		straight	
criterion	weight	point score 0 … 5							
turbine both ways possible	10	5	0	5	0	5	0	5	5
pumping both ways possible	10	5	5	5	0	5	0	5	5
closeoff possible	20	5	5	5	5	5	5	5	5
power regulation possible	5	5	4	5	4	5	4	5	4
power limitation possible	10	5	4	5	4	5	4	5	4
turbine efficiency primary direction	14	5	5	4	4	4	4	3	3
turbine efficiency secondary direction	10	4	0	3	1	3	0	2	2
pump efficiency primary direction	12	2	1	3	3	3	0	2	2
pump efficiency secondary direction	8	3	3	4	1	4	4	3	3
mechanical simplicity	20	3	4	3	4	3	4	3	4
functional safety	20	4	5	4	5	4	5	4	5
cavitation safety	5	3	3	3	3	3	3	3	3
efficiency score		158	106	154	110	154	88	110	110
overall score		**588**	**511**	**584**	**465**	**584**	**443**	**540**	**565**

Figure 5 Excerpt from the evaluation chart of the kinematic study (conventional bulb turbine)

The analysis was based on velocity triangles sketched for the different modes of operation. Figure 6 shows the velocity triangles for a conventional bulb turbine with ordinary blading. In the turbine mode, water flows from the top to the bottom while the runner blade moves to the right. The runner axis is oriented in vertical direction. At first, circumferential speed is created by the guide vanes. The vertical (i.e. swirl-free) approach flow c_1 is deflected by the curvature of the guide vanes, which adds a circumferential component to the runner inlet flow c_2. As the water passes the runner, the direction of the relative flow w is deflected by the curvature of the runner blades and the circumferential component is reduced again, while its momentum is transferred to the runner shaft. A swirl-free runner outlet flow c_3 is thus achieved and the overall flow condition is likely to provide high efficiency.

In the pumping mode, guide vane and runner blades have to be adjusted in order to reverse the direction of the energy transfer. The water is flowing from the top to the bottom and passes the guide vanes that increase velocity and induce a swirl, similar to the turbine mode. Then, the flow hits the runner blade at its former trailing edge which, in this case, has not been modified to have a rounded edge. This can lead to flow separation, thus causing efficiency drawbacks. Moreover, the guide vanes decrease the static pressure at the runner inlet that now acts as a pump impeller. In general, a decrease in pressure on the suction side of a pump impeller makes it more prone to cavitation. The sharp leading edge and higher cavitation susceptibility determine penalties for the pump efficiency in primary direction as well as cavitation safety in the evaluation matrix in this case.

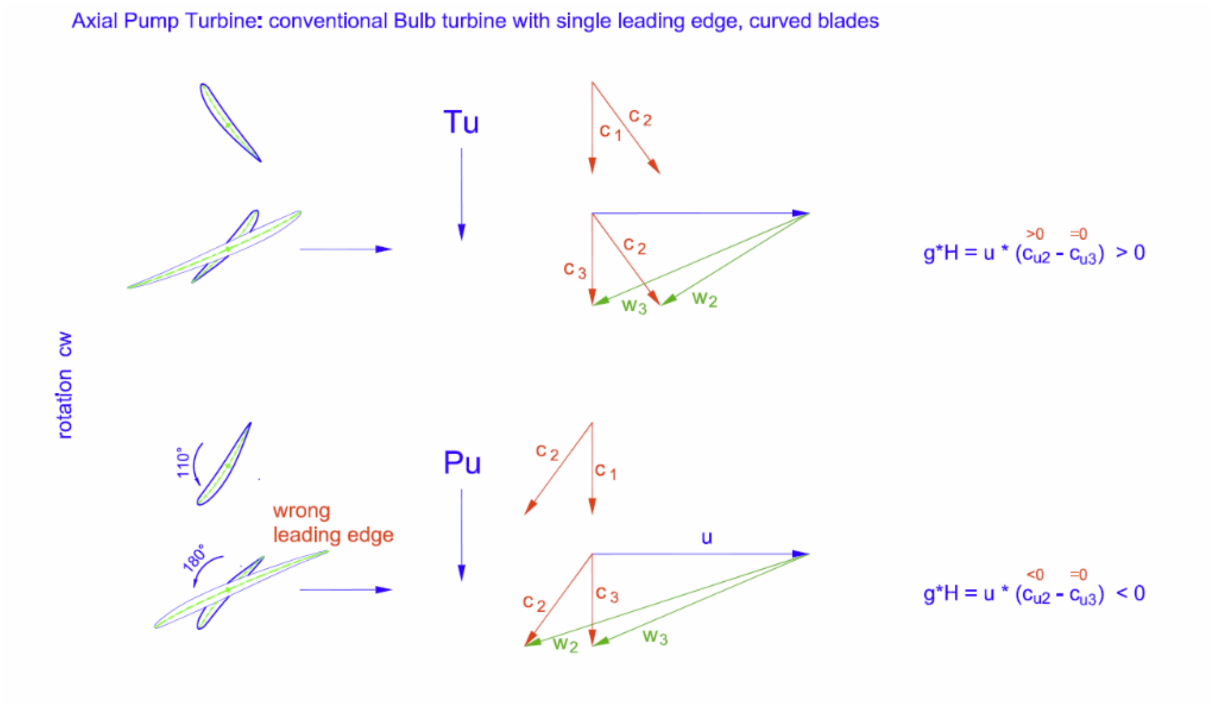


Figure 6 Velocity triangles for a conventional bulb turbine with curved blades and single leading edge

As the circumferential blade speed decreases linearly from the blade tip to the hub and the axial flow velocity is constant, the flow angles near the hub are much bigger than at the blade. To take this into account, the inclination of the blade profile at the hub must be higher than at the shroud, resulting in a twist of the blades. Switching from turbine to pumping mode can be done by reversing the runner blades. In some cases however, reversing the runner blades leads to a wrong orientation of the twist, where the profile inclination is lower near the hub. Those operation modes were ruled out.

4 Conclusion and outlook

As a result of the analysis a conventional turbine that has adjustable guide vanes, fixed runner blades, variable runner speed and can be turned around was considered the most promising turbine configuration. This concept has achieved the highest number of points in the evaluation matrix. It offers good efficiencies in all operation modes and allows for discharge regulation and shutoff. Moreover, the mechanical complexity is reduced by avoiding adjustable runner blades. Conventional turbines that cannot be turned around are also a feasible option but they have major efficiency drawbacks. Counter-rotating turbines are in principle feasible, but offer no pronounced advantages that are sought for in tidal applications. In order to work satisfactorily in all modes either the runner blades or the turbine as a whole have to be reversed.

The next steps in the turbine development are to define a turbine geometry including meridional section, blade profiles and draft tube. From an engineering point of view, it is important to define a geometry that can be manufactured and that is structurally sound.

With the help of CFD simulations, the geometry will be optimized until a satisfying solution is found. The main focus during the optimization is to reach high efficiencies in both, the turbine and the pumping mode. The cavitation risk will be considered as well. The CFD simulations will give a first estimate on the turbine performance under various conditions.

Thereafter, a model turbine will be built and investigated in a closed loop turbine test rig at the chair of hydraulic and water resources engineering at TUM. The model tests will be compared to the numerical predictions and give more insight into the turbine performance, allowing potential design flaws to be disclosed, evaluated and eliminated. If all the expectations are met, the model tests will act as a proof of concept for the new design.

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