ECOLOGICAL HYDROELECTRIC CONCEPT "SHAFT POWER PLANT"

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Abstract: At the Department of Hydraulic Engineering of the Technische Universität München an innovative hydropower concept was developed; the "Shaft Power Plant," in which the power plant unit is located entirely under water in a shaft and the turbine water supply is carried out via a horizontal intake plane. The system requires only a low building volume and has in particular environmental benefits given the integration of a convincing fish protection and migration passage in the hydraulic design. For larger sites, the system “multishaft power plant” was conceived.

1 Motivation

Suitable hydropower able to cover base load is in many countries essential for the generation of electricity and contributes significantly to a secure fulfilment of the demand. In most industrialized countries, however, the hydropower potential is largely extended and new hydropower plants must fulfil strict environmental regulations. For instance, in the German Water Management Act of 2010, the protection of the fish population is required and connected with the binding condition for admissibility § 35 (hydropower utilization). In other words, a permission or an approval may not be granted, or a plan may not be authorized if the required appropriate measures for the protection of the fish population are not taken, or do not guarantee success. On the other hand, it is necessary to prevent that fish are sucked into the hydropower turbines during their migration, thus killed or injured [1]. The EU Water Framework Directive includes an additional restriction through the prohibition of the ecological deterioration. Therefore constructions of new run-of-river power plants are mostly limited to existing weir sites, where often difficult boundary conditions prevail.

At existing weirs, hydropower utilization is implemented in conventional technology mostly in the form of a classic bay power plant, in which, depending on the system, a large structural effort with significant bank intervention is required. Compared to the actual state, no major water level rise, generated from the often silted-up barrage constructions, shall be made, in view of the unfavourable conditions of low flow for the power plant intake. The intake must, therefore, be designed and dimensioned such that the natural broad-based wetted section is diverted with minimum losses in the compact wetted section of the bay route. In order to ensure the minimum hydraulic requirements, a large excavation of the river bed must be therefore made directly in the discharge area. Additionally for bedloadcarrying rivers, upstream basins must be arranged to allow sediment deposition and flushing-sluice. At the same time, the requirements of the fish protection must be taken into account; in particular, huge intake structures shall comply with the maximum velocity of approach.

Due to these challenging conditions, it is hard for Germany and many other countries with conventional power plant technology to fulfil the environmental constraints and to achieve economic viability, especially with rather small fall. The main challenge of the modern and sustainable use of hydropower is therefore to promote practical, efficient, and in particular ecological hydropower technology with integrated fish protection. Consequently, a successful development of technology in this sense is also particularly desirable, because it would lead to the availability of environmentally sound solutions for the large hydropower potential in developing countries.

The innovative concept of the “Shaft Power Plant” (SPP) was designed in 2009 at the Technische Universität München (TUM) for a cost-effective and nature-compatible use of the run-of-river power plant; it was experimentally investigated within the scope of a ZIM-research project. Since 2013, a prototype system with natural conditions is available for research purposes in the Laboratory of Obernach. The patent-pending system types “Shaft Power Plant / Multishaft Power Plant” are suitable for new structures and can also be integrated into existing weirs.

2 Hydropower Plant Concept of the Shaft Power Plant

2.1 Functional description

The basic idea of the new concept; “Shaft Power Plant,” is aimed to integrate the power plant in the weir (Fig. 1) in order to avoid a classic discharge and recirculation of the turbine water, with all constructional and environmental disadvantages.

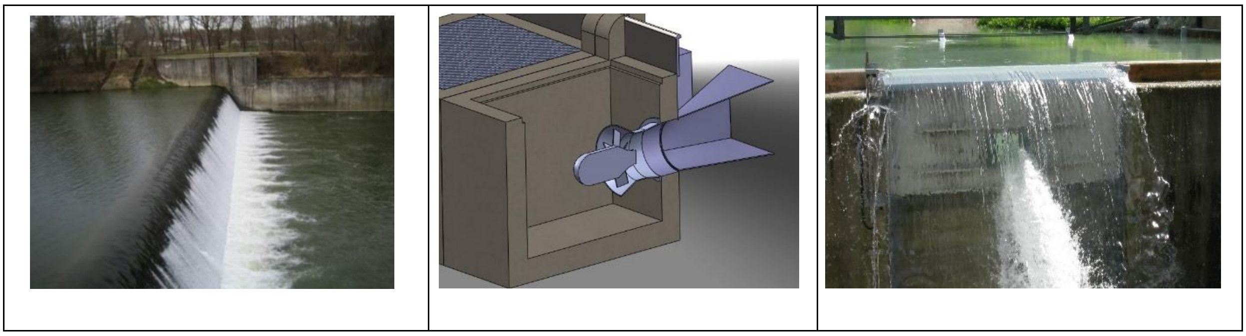

Fig. 1: “Shaft power plant” concept installed in a fixed weir body

The developed approach comprises the arrangement of a horizontal intake plane with a complete mechanical tailwater layout in a shaft, which can be enabled by the new technology of dive-turbines. A vertical flow of the turbine supplies the power plant inflow. The connection to the tailwater is possible via the suction pipe through the weir body, see Fig. 2. The intention of the hydraulic considerations was to control the necessary 90° flow deflection through a large sized intake area and by a permanent overflow of a front-mounted gate (reduces the vortexes). With these hydraulically required intake components a migration corridor for the fish descent can be provided in the inlet area. The other operational functions could be covered with further options for the gate configuration, for instance; a slit for rack cleaning and full lowering to the driftwood and sediment discharge.

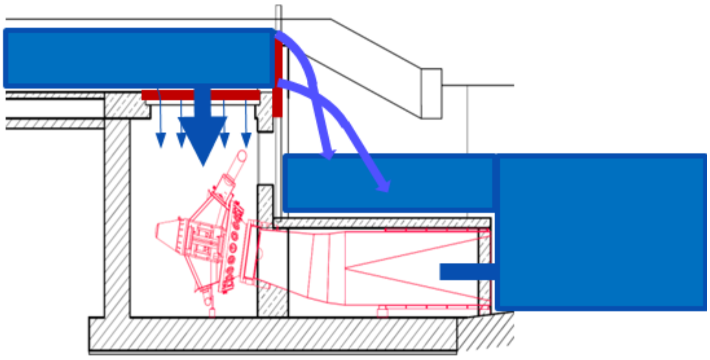

Fig. 2: overflowed panel gate (l.) and turbine waterway (longitudinal section)

2.2 Test results of the Power Plant Model

A physical model was built at the research institute in Obernach (Fig.3) within the framework of the Central Innovation Program (ZIM), funded by the TUM, to verify and optimize the functionality of the described concept and to generate hydraulic performance curves. The power plant model (Q_T = 200 l/s, h = 1.2 m) was equipped with a functioning “Dive-Turbine” from the company Fella and a hydraulically controlled gate device such that any flow state can be studied and demonstrated [2].

The conducted experiments confirm clearly the expected hydraulic and operational processes, so that the basic functions of the power plant concept could be already confirmed. In summary, the following results were found:

Via the horizontal intake plane with the enforced vertical deflection of the turbine-water, a vortex is produced when the flow changes from a free-surface to a pressurized state. The intensity of this vortex depends primarily on the velocity of approach and the overlap (= height difference between shaft overflow and weir crest), and is mitigated by the rack bars. A relative small gate overflow prevents the development of critical vortexes, even at low flow depths. The velocity measures conducted with a 3-D ADV probe confirm that a homogeneous velocity profile at the rack plane can be generated by an appropriate dimensioning of the intake area (v_m < 0.5 m/s), see Fig. 3. All other basic operational functions can be covered with the required hydraulic configuration of the gate:

Under high flow conditions or in case of a flood event, the gate panel up to the intake area is closed such that a drawdown surface forms above the rack plane, creating a sufficiently large drag force to cause flushing of solid matter (Fig. 4). Sediment fractions smaller than the interior spacing of the rack bars are discharged through the turbine into the tailwater.

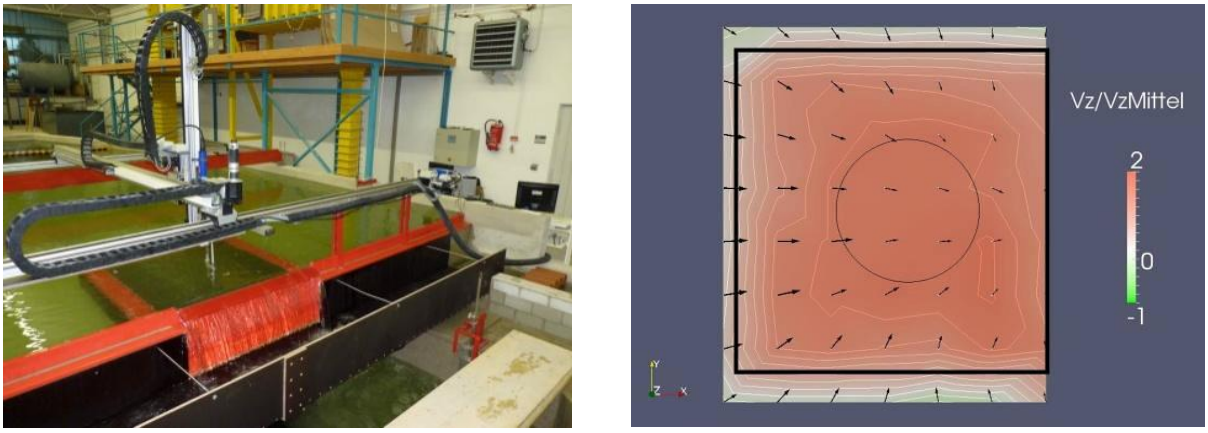

Fig. 3: Velocity measuring device in the power plant model (l.) and velocity distribution over the horizontal rack field (r.)

For normal cleaning, a rail with rake is moved over the rack and by temporarily lifting the gate device, the collected material is delivered directly into the tailwater (Fig. 4). In order to ensure a rapid accessibility in case of malfunctions and inspection works, stop logs are provided, which can be set both manually and automatically movable.

Fig. 4: Operating states: KW-operation (l.), Rack cleaning (m.) Bed-load and HW flushing (r.)

2.3 Results of the investigation with the Prototype Plant

As a consequence of completely underwater arrangement, a high quality standard for all mechanical parts of the power plant is demanded. In order to evaluate and demonstrate the practical suitability under near-natural conditions, i.e. increased driftwood and sediment discharge, a power plant prototype was constructed in the open area of the Oskar von Miller- Institute in Obernach, and equipped with a submersible Kaplan turbine (runner diameter 75 mm, four blades, 333 rpm) of the company Geppert. The shaft power plant is designed for a developed flow of 1.5 m³/s (accurate discharge measurement by means of an upstream Rehbock-flume) and a head of 2.5 m. The 2m x 2m rack area was developed by the company Muhr and is equipped with two rack panels (each special profile with a 20 mm interior rack bar spacing), in which different functional and underwater rack cleaning concepts were developed and tested. All relevant operating conditions (rack cleaning, sediment flushing, efficiency curves) could thus be studied and demonstrated without scale effects with the double adjustable 35 kW system. A major research focus is the migration of fish especially juveniles.


Fig. 5: Prototype plant with technology building (l.), overfall with fish descent window (r.)



Fig. 6: Turbine installation (l. & m.), view from the Shaft to the top (r.)

The particular technical challenge is the development of a reliable rack cleaning technique since, due to the system, the sediment transport is carried out via the rack plane. Therefore, the technique has to be designed in such a way that areas of the inlet, which are not hydraulically flushed, can be cleaned mechanically. In addition, driftwood and other solid matter are to be transported into the tailwater. Also, the system is to be dimensioned for large rack areas, which is why panel supports are considered.

The tested rack cleaning techniques have shown that the form of all structural components must be carried out such that deposits of bed-load particles are avoided in the cleaning device. A widening of the cross section in the flow direction must take place in the concept of the plant and the geometrical adjustment such that no deposition and trapping of solid matter can occur. This requirement must also hold for the geometric shape of the rack bars: Instead of a rounded, streamlined bar profile, a T-shaped profile must be used such that fine gravel and smaller solids can fall in the shaft. The onward movement is guaranteed by the turbine discharge. Sediment deposits in the shaft corners are not a problem because they do not cause flow losses. Currently, an electrically driven cleaning bar is being optimized and developed to maturity. The system is designed such that the entire drive technology is integrated protected in the shaft. Special guide and slide rails ensure an accurate, synchronic movement of the trash racks, and the direction of movement and the driving power can be varied load-dependent by programming.

For efficiency reasons, the concept of the shaft power plant was aimed at simple geometric forms because, compared to conventional plant technology, significantly lower flow velocities are present in the intake-flow area, and only low hydraulic losses can result due to the system. The first approximate measurements of the plant efficiency with values of 86% at full load and 88% at partial load (0.6 * development outflow) confirm the selected hydraulic intake concept. Since the generator is also in the water body and is thus optimally cooled, there is an additional positive influence on the efficiency.

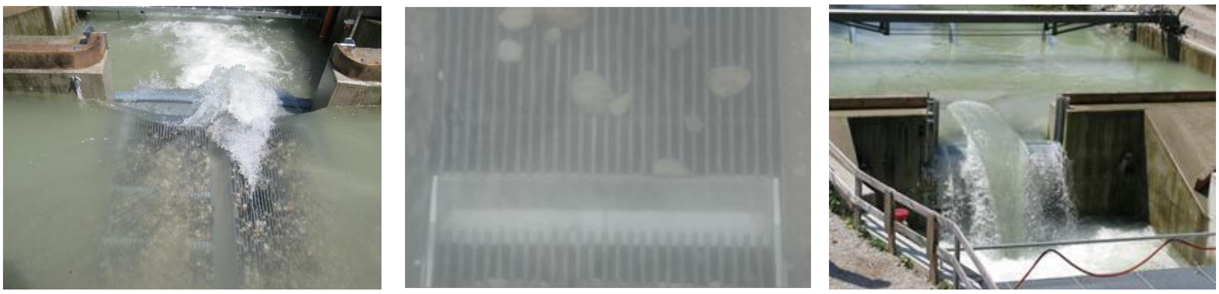

Fig. 7: Sediment flushing with the assistance of the rack cleaning

3 Fish protection

3.1 Methods and achieved results

As explained in more detail in Section 2.2, the hydraulic approach of the "shaft power plant" requires a low velocity of approach in the intake plane and a finely woven rack plane, as well as a superficial current over the closing gate to avoid vortices,. In the conceptual idea, this non-usable energy outflow (approximately 3-5% of QT) should also be important for the fish migration. In the dimensioning, all of the influencing hydraulic variables were specially designed for a functional fish protection. The horizontal rack area and the installation depth (water overlap) are dimensioned such that low flow velocities with a homogeneous distribution are guaranteed. The maximum speed can be adapted to the respective fish population and their swimming abilities. The descent takes place via special openings in the gate (one or more descent windows in a different arrangement, Fig. 2), producing a direct water route with the tail water body. To ensure a harmless immersion of the fish, a water cushion with a minimum depth of 90 cm or one quarter of the head must be maintained.

The fish behavior in the "Shaft Power Plant" system was investigated in 2011 (fish bigger than interior rack spacing) without a turbine but with exact compliance of the power plant inflow, and from 2013 with the complete prototype system. Since all hydraulic and operational processes were available without scaling effects, a comparison of the different configurations was ensured under near-natural conditions. The studies delivered differentiated records of fish distribution and damage according to the specie, size and experimental design (different descent window, variable speeds), where all the migration and drift events were adequately captured [3] [4]. The research results were of particular interest because fish behavior patterns for downward flow forms were previously not known. The underwater video images of all the investigated species revealed that the fish has a slanted position over the inlet plane (Fig. 8). Virtually no contact was established with the rack and an active swimming behavior against the curved flow was monitored. Furthermore, the expectations for the fish pass were fully met, and a descent rate of about 60% was observed in tests of 24 hours on average. These studies have thus shown that an absolute barrier effect is obtained with the studied species and fish larger than the interior bar spacing of the rack, because these individuals, which are particularly important for the reproduction of the population, are fully protected against a turbine passage.

Fig. 8: Fish movement over the horizontal rack plane (l. chub, m. barbe, r. juveniles)

The studies with fishes that are smaller than the bar spacing of the rack showed that the rack can also work as a behaviour barrier and that common-rack fish can get safely to tailwater through the downstream fish passage (fraction of the investigation 2013: 51 – 86 %). There were different injury rates for the turbine passage, namely; brook trout (6/16), grayling (2/13), and bullhead (0/18). The magnitude of the share depends heavily on the fish size and type. The flow velocity at the rack influences the migration distribution and can be selected on the basis of the study results such that the passage through the rack plane and turbine can be strategically reduced. Further tests were conducted in 2014 in order to achieve higher statistical robustness of the detailed statements.

Fig. 9: Used bullhead (l.), small fishes (m.), trouts at the descent (r.)

3.2 Evaluation

Considering all mechanisms, namely; total protection of the fish > bar-distance, significantly lower mortality with a larger runner and lower rotational speed, the fish ladder concept; “Shaft Power Plant,” can be assessed positively by the current state of knowledge as the system includes with simple structural elements a safe migration corridor into the tailwater and complies with the velocity of approach of v_{max} < 0,5 m/s. Due to the horizontal intake plane, the required large rack area can be generated for moderate flow velocities exclusively through an appropriate dimensioning of the shaft area and the overlap. Thus, the required low bar spacing of the rack (≤ 2 cm) and unfavourable flow profiles can be implemented without substantial hydraulic losses. The structural dimensions can be easily adapted to the location and thus to species-specific ratio, whereby a temporal gate control can enhance the ecological continuity.

4 Multiwells Concept

4.1 Basic system

The technical concept of the "Shaft Power Plant" requires the use of dive-turbines due to the complete underwater arrangement, and is therefore currently limited to a maximum discharge per shaft of approximately 20 m³/s due to hydraulic, operational and turbine technical aspects. To enable a high degree of expansion, even at sites with larger discharges, an in-line arrangement of several individual shafts can be made, which can be advantageous to integrate ecological elements. In this way an innovative and complete solution was developed for the inclusion of the upstream migration of fish and other aquatic organisms [4]. The concept of "Multishaft Power Plant" is based on the module "Single Shaft" with a horizontal intake plane, a turbine-/generator-unit in underwater arrangement, and a movable intake gate with fish migration windows. By this construction, the functions of damming body, flow control, energy conversion, and passage are met with the following tasks:

- Shaft structure = weir: Through the geometric dimension and the constructive integration of the shaft blocks (cut-off walls before and after the structure), the shaft forms the support body including the discharge pipe connection.
- Shaft Power Plant gate = control weir system: In addition to the power plant functions (removal of the debris when the flow passes below the gate in the cleaning process, permanent overflow to prevent vortex), a controlled water level, a flow control system and fish migration are guaranteed.
- Outlet structure= stilling basin: Water or solids over the draft tube and the ramp after the draft tube’s end and the river bed serve as a stilling basin and, thus, for energy conversion.

The special hydraulic engineering element consists of a so-called "ecological connection channel", which is incorporated upstream between the shaft blocks, and can be structured in different sizes and designs. With a spacious design, the channel with frontal apertures achieves a near-natural habitat with varied flow structures, and can therefore also act as substitute habitat, because Multi Shaft Power Plants also allow water levels that are discharge-conditioned and dynamic. In addition, ascending facilities can be arranged near the banks. The system has the particular advantage that the access points can be optimally aligned without any dead-end areas to the power plant outlet, and can easily provide accessible connecting paths along the full width of the river for all living creatures, see Fig. 10.

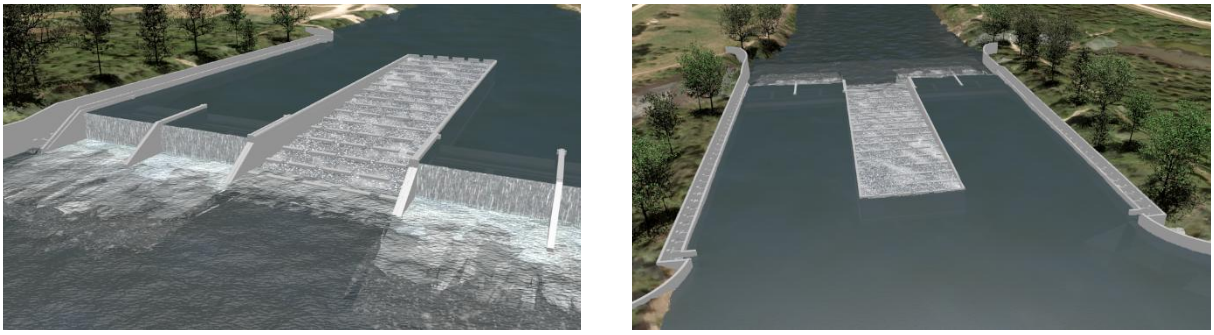

Fig. 10: Multishaft Power Plant: view from downstream (l.), view from upstream (r.)

4.2 Structure design and application

In the geometric and structural design, the basic system "Multishaft Power Plant" unites integrated power plant units with a combined weir-power plant body, which is preferably perpendicular to the main flow direction and enables a wide direct waterway over, and through the weir. With the gates, a discharge-dependent water level control can be generated for ensuring compliance with the minimum flow rates in the upper water according to ecological requirements. The system acts as a combined weir in case of flood discharge, because the long lateral partition walls of the connection channel act as a solid and powerful spillway. It should be noted that the structural design and dimensions must be aligned to the complex energy conversion processes, due to different filling levels.

The casing depth of the shafts, or rather, the overlap and the area of the horizontal intake plane act in accordance with the developed design specifications for flow rates and, where appropriate, the discharge capacity in the lowered gate state. The system allows the use of unregulated dive-turbines in horizontal-to-vertical position as a result of the multi-turbine equipment. The assembly of the turbine/generator unit is carried out by means of a truck-mounted crane. The Multishaft Power Plant is primarily equipped with the operation technology of the individual shaft plant. However, since at Multi Shaft Power Plants only a unilateral inflow is present, the intake area of the horizontal rack plane must be enlarged to comply with the maximum flow velocity. This directed inflow offers the advantage that the intake can be segmented by piers, and blocked with unilateral gate elements. The “Multishaft Power Plant” concept can be implemented as a part of or as a completely new structure and is suitable, for instance, as an alternative for existing weirs in wide rivers.

5 Economic Evaluation

The complexity of hydroelectric power plants makes general and simple evaluations of the economic efficiency, and profitability difficult because compared to other techniques, a larger number of water management factors and functions should be met or considered. A cost estimate can, therefore, only be conducted in a location-dependent way. In addition to the physical base value of the flow supply and head of water, different questions should be taken into consideration, e.g.: the building structure, the technique of existing weirs, the accessibility, flood and bed-load characteristics, the infrastructure, and particularly the ecological significance. These general assessment criteria must also be included in the profitability analysis of the "Shaft Power Plant," whereby the large number of influencing variables does not allow for transparent power plant costs. Therefore, a statement should be made in a comparative analysis with a conventional bay design with similar technical equipment, which must be based on the fact that also in the conventional design, the ecological demands (identical size of the rack area, descent bypass system) are at least theoretically met.

The essential difference of both types of systems is that a Shaft Power Plant, due to the installation in the weir body with integrated fish ladders, requires only compact construction and less steel hydraulic structure elements. In previous investigations was established that the construction volume can be reduced to about 25-30%, and due to the tailwater configuration, an extra qualitative technical cost of about 10% must be taken into account. Since the shaft structure must be created in the water body with complex construction pits, and a limited penetration of the weir bodies is required, the specific costs result higher than with bay power plants. Assuming that the SPP specific construction costs are twice as high as those of bay power plants, the construction costs are still reduced to 40-50%. Thus, by considering the additional cost of 10% for mechanical and electrical engineering (M+E), the following comparative cost factor can be calculated:

$$\textbf{Costs}_{\textbf{SPP}} = [½*0,5 * B_{BayPowerPant} + ½*1,1* (M+E)_{BayPowerPlant} \mathbf{= 0,80}_{\textbf{BayPowerPlant.}}$$

Shaft Power Plants can be built with an approximately 20% lower price in comparison with conventional power plants. In case of larger dams, the cost benefit is significantly higher.

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