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Evaluation criteria for velocity distributions in front of bulb hydro turbines

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ABSTRACT

General guidelines are available for the design of intake structures in river power plants. Nearly all existing criteria are limited in scope to a (rectangular) control section near the trash rack. In this section, a homogeneous flow with negligible wall influence is defined as the ideal condition. 3D numerics can simulate the complete velocity field up to the turbine, and therefore inform investigations of different inflow structure variations. This paper presents a review of six existing criteria and a modification of the Fisher-Franke criterion. All criteria are tested for both theoretical pipe flow conditions and artificial biased velocity distributions, for which different simplified obstacles in front of a turbine are investigated with the help of the 3D numerical software ANSYS-CFX. The best results could be achieved using the evaluation of the kinetic energy flux coefficient as well as the new modified criterion. Both can be recommended for the geometry optimisation of the intake structure.

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1. Introduction

1.1. Overview

An intake structure is the upstream connection of a river or reservoir to a hydraulic system, in which the water is used for drinking, cooling, or producing energy. For energy production, different types of turbines are used, depending on the available energy head and discharge [1]. Liu et al. [2] summarise the improvements over the last years in the field of hydraulic turbines, which have overall led to a very high rate of energy production efficiency with hydro power turbines. Further investigation has focused on Kaplan turbines, which are used for comparable small heights, and are sometimes used in combination with large discharges as the first choice. These can be installed without additional structures, for example as tidal turbines [3–7]. However, under normal conditions, the intake structure guides the water to the rotor blades. Different investigations focus on the draft tubes (downstream the turbine) for vertical [8–12] and horizontal axis turbines [5,13,14]. Energy generation can be further enhanced by inlet guide vans [1,15]. For example, Fernando and Rival [16] investigated different intake structures for very low head conditions and Ferro et al. [17] focused on the influence of inlet guide vans for mini hydro turbines, which should allow the use of hydro power with low investment costs. In general, a well-designed structure can help to reduce the construction costs associated with hydro power plants, and should ensure good inflow conditions, which help to guarantee turbine durability and high energy production efficiency [18–21].

The main goal of intake structure design is to achieve good hydraulic performance. Therefore, head loss should be minimised, and the pressure line must decrease continuously with increasing velocity in the flow direction [18,21]. The design should ensure that as much water as possible can flow to the turbine, including as few impurities as possible. Therefore, trash racks are installed to remove floating debris or other incoming objects from the inflow [22], as well as fish [23]. Based on built-in components [24,25] and reservoir considerations [26–29], the amount of suspended sediment should be reduced as much as possible. An additional vital topic is the prevention of swirls and air entrainment in the

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structure [30–33]; these can lead to turbine damage or efficiency reductions [20]. Under special conditions, ice plugging [34] may also need to be considered. For water-pump intakes, additional criteria must be applied [35,36], particularly if multiple intakes are planned [37].

In addition to the experience and good practice of the designer, two different primary tools can be used to investigate and optimise such construction: (a) numerical simulations and (b) scale model laboratory tests. The latter is often used to investigate sediment or check if free surface vortices will occur. This method is limited by scale effects [38,39], as well as the fact that preparing and testing different geometries can be very costly and time intensive. Particularly for significant variations in geometry, the use of 3D numerical tools is a vital alternative. Various previous studies and validation experiments showed good method usability and accuracy [40–44]. A further advantage of the 3D numerics is that distributed pressure and velocity results are available up to the turbine at a very high resolution. This allows for the further verification and evaluation of existing criteria for fully developed pipe flow conditions upstream of turbines, which are used as target values for the optimisation of intake structures.

1.2. Key aspects

In general, distorted inflow conditions can cause reductions in energy production and lead to vibration-induced turbine damage [19]. Godde [45] compared different existing evaluation criteria (Sec. 2.2). The main weakness in previous work was that nearly all studies were limited to the cross section near the trash rack. This control section is accessible in both scale model tests and nature. For these areas, homogeneous flow conditions and very small wall influences are characteristic. Ideal conditions, which must be indicated by design criteria, differ in cases of downward optimisation in this section; therefore, wall effects are no longer negligible. This paper shows which existing criteria can be used for such pipe flow conditions. It also presents a new modified criterion that allows the control section to be moved near the turbine. In a second step, artificial biased velocity distributions (VDs) are used to further investigate each criterion. This allows for the extension of the geometry optimisation process up to the turbine and helps reduce losses and increase energy production.

2. Methodology

2.1. Concept

Based on a literature review, seven widely used and well known requirements from different turbine manufacturers are summarised in Section 2.2 and a new modified criterion is presented in Section 2.3. In a first step, a data set based on different theoretical VDs in fully developed pipe flow conditions (Section 2.4) is used to evaluate those criteria. The second part of the paper is focused on biased VD in front of an exemplary simplified bulb turbine. Therefore, different theoretical obstacles, which are presented in Section 2.5, are investigated with the help of 3D numerical simulations using ANSYS-CFX. A comparison of these standardised disturbances with real inflow conditions can improve understanding of each individual criterion and classify the actual VD in future projects. The direct connection with possible reductions in energy production is an on-going research topic. Therefore, further investigations and experiments on real turbines are needed.

2.2. Existing criteria

The inflow condition criteria for Kaplan turbines are not standardised, and so each turbine manufacturer can individually specify such criteria. The most common requirements can be classified into the following groups of criteria [19,45]:

- $C0$ – **General conditions**: Vortices, flow separation, air entrainment, and rotation in the flow should be avoided.
- $C1$ – **Discharge**: The complete section is typically divided in half or in quadrants, and the local maximum deviation of discharge in these parts should be smaller than 5% of the total discharge.
- $C2$ – **Angle of the velocity vector**: The maximum deviation measured from the axial direction should be smaller than 5°.
- $C3$ – **Cross flow**: The orthogonal velocity components should not extend 5% of the average velocity.
- $C4$ – **Velocity distribution**: The deviation in local velocity magnitude should be in a range of 5% or 10% of the average value.
- $C5$ – **kinetic energy flux coefficient** α: The correction factor for the velocity head with respect to kinetic energy should be as small as possible.
- $C6$ – **Fisher-Franke-criterion**: The mean velocity of testing sections is normalised by the global mean velocity. This value should fall between the defined upper and lower boundaries, depending on the size of the testing section (Table 1) required to meet the criterion.

The **kinetic energy flux coefficient** α corrects the real kinetic energy $E_{kin,real}$ of an investigated control section in relation to the theoretical value $E_{kin,theo}$. This value is multiplied with the velocity head $u_m^2/(2\cdot g)$ in the basic Bernoulli's equation to take into account a non-uniformity of the velocity profile, and is calculated based on the local velocity u and mean value u_m as presented in Eq. (1) [46,47].

$$\alpha = \frac{E_{kin,real}}{E_{kin,theo}} = \frac{1}{A}\cdot \int_A \left(\frac{u}{u_m}\right)^3 dA \tag{1}$$

The coefficient α is always larger than or equal to 1, which represents a completely uniform velocity profile. For turbulent flow conditions, a value of 1.2 is typical. In the case of laminar conditions α equals 2 (parabolic profile) [46]. These correction terms must be considered, particularly for the calculation of local head losses with different sections before and after loss [42]. For the present work, the kinetic energy flux coefficient α (criterion $C5$) is also used to check the density of evaluation points in the control section. This is needed to generate the data set based on the theoretical velocity distributions (Sec. 2.4).

Fisher and Franke [19] proposed criterion $C6$ to identify acceptable velocity profiles based on various scale model tests. Therefore, different testing areas of the control section in the intake structure are cut out, and a local mean value of the velocity in this smaller testing area is calculated. This local mean value $u_{m,part}$ is normalised by the global mean value u_m for the complete control section. All testing areas result in a value of 1 [-] for a perfect flow condition. Different boundaries B_{lo} and B_{up} are defined depending on the percentage of each investigated local testing area with respect to the total control section. Table 1 shows the boundary values defining the conditions (Eq. (2)) that satisfy criterion $C6$ in

Table 1
Boundary conditions for Fisher-Franke-criterion [45].

A_{part}/A [%]	0	20	50	100
upper value $B_{up}[-]$	1.25	1.1	1.05	1.05
lower value $B_{lo}[-]$	0.75	0.9	0.95	0.95

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