Experimental research on a hydrokinetic turbine model

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Abstract. The renewable energy policy strongly encourages the use of all renewable sources of energy. ICPE-CA starts to develop a new hydrokinetic turbine to be implemented in small rivers or water channels with a low investment cost. In a first step, the characterization of a laboratory reduced scale turbine model is performed. The hydrokinetic turbine model is implemented in a free surface water channel. The produced power for many flow rates and rotation speed of the turbine, as well as the detailed flow characterization (PIV measurements) are presented.

1. Introduction
Run-of-river hydroelectricity can be easily harnessed using river-based hydrokinetic turbines without the need for water storage, which need specific works to preserve the environment. On the other hand, a small hydroelectric power plant without reservoir is subject to seasonal river flows, thus the plant will operate as an intermittent energy source. This kind of installations are suitable for low power generation systems in remote areas where other energy sources, including renewable, are not available. Their conversion efficiency is limited at a maximum theoretical value of 59% as stated by Betz law and the power output can be increased only by using different types of shrouds that provides a local velocity increase. Compared to large hydroelectric power plants, the hydrokinetic turbines cannot benefit from the water head and must rely only on the kinetic energy of the flow. Recently, some advances were made on the rotor design, including blade optimization and the use of various shroud shapes which aimed to increase the power coefficients [1]. Different studies and research focus on identifying the most suitable technical solutions and operating conditions that lead to an increased power extraction.

Harnessing the kinetic energy of water is the subject of numerous studies and papers which analyse different scientific, technological and economic aspects related to kinetic turbines use, reviews focusing on the current development and challenges of this technology were published [2].

However, hydrokinetic turbines are still in early stage of development and many enhancements are needed in order to become feasible solutions on the market in the near future.

From the hydrodynamic perspective, the diffuser augmented turbines have promising results [3-5] and in terms of power handling and electrical engineering, the use of Maximum Power Point Tracking charging controllers can provide an increased conversion efficiency. Such devices adapt the load
resistance and keep the rotational speed of the electric generator in a well-defined range ensuring the operation within the maximum point of the power curve [6, 7]. Thus, continuous improvements are made to minimize the drawback of such devices which is their sensitivity to water flow and rotational speed variations, since the rotor is placed directly into the water current.

2. Energetic performances study

The experimental model of the hydrokinetic turbine was tested at a water velocity ranging from 0.7 m/s up to 1 m/s, and different rotation speed, on a free surface water channel (Figure 3). The closed-circuit hydraulic stand is provided with a transparent viewing area of 375 x 300 x 1015 mm as well as an adjustable water velocity system in the range of 0.05 – 1.1 m/s. The mechanical power is measured using a torque transducer and an electromagnetic particle brake. By loading the electromagnetic particle brake, the power output could be extracted using a torque transducer that also measured the rotational speed. The output data allows plotting the power curves depending on the rotational speed for each considered water velocity. The mechanical power at the turbine shaft is determined as:

\[ P = M \cdot \Omega \]  

(1)

where \( P \) [W] is the mechanical power, \( M \) represents the torque measured by the torque transducer and \( \Omega \) is the angular velocity and can be calculated as:

\[ \Omega = \frac{\pi \cdot n}{30} \]  

(2)

where \( n \) [rpm]– is the rotational speed of the rotor, determined also with the torque transducer which has an integrated counter that allows the measurement of the rotational speed.

The main sizes of the experimental turbine are: rotor diameter: 137 mm, shroud inlet diameter: 142 mm, shroud outlet diameter: 170 mm, turbine/generator diameter: 80 mm, shroud length: 155 mm (Figure 1).

Figure 1. Rotor view a) upstream b) downstream

3. Flow characterization using PIV measurement

3.1. PIV set-up

Particle Image Velocimetry (PIV) measurements were carried out using a Dantec system composed of a Litron of 200 mJ laser and a FlowSenseEO_4M-32 CCD camera with resolution of 2072×2072 pixels. A BNC 575 synchronizes the laser with the camera. A total of 500 image pairs were recorded by camera for each studied case. The time interval between two laser beams was set 700÷2000µs depending on the
speed of the water flow. The laser beam was parallel to the flow and CCD camera is placed perpendicular to the measurement plane (figure 2).

As tracers, S-HGS particles - silver coated hollow glass spheres of 10 μm in diameter and density of 1.4 g/cm³, are used.

DynamicStudio software was used for configuration, data acquisition, and post-processing.

Many analysis modules were applied to transform the double frame images in a set of velocity vector fields, from these Average Correlation analysis show more relevant results.

Figure 2. PIV set-up

3.2. Data post processing

Further post processing was done by importing the resulting vector maps from DynamicStudio into Matlab. The mask defined in DynamicStudio was used to help filter out areas outside the flow, as well the problematic areas to avoid negative impact on the results.

To compare the flow rate between the upstream and downstream PIV measurements, the following formula was used

\[ Q = \int_{y_{upp}}^{y_{low}} u dA = \text{constant}, \]  

(3)

where \( Q \) [m³/s] is the water flow rate, \( u \) is the velocity component, parallel with the direction of the flow and \( A \) [m] is the area element but applied differently depending on the flow characteristics.

Upstream the turbine, the flow is quasi uniform, and the relation (3) is applied under the assumption the velocity distribution is similar in all the layers parallel with the measurement plan.

In downstream of the turbine, the flow is highly turbulent with vortex generation.

To compute the flow rate in this case, two flow zones were considered, a central one (zone 1, Figure 4 and 5) where the rotational flow shows an axisymmetric aspect and an exterior zone (zone 2, Figure 4 and 5) where the flow is considered under the same assumption as the upstream zone.

To find the separation between zones, streamlines were considered, due their property that the flow rate between two streamlines is constant at each cross-section. The streamlines were seeded from points placed on a line on turbine side of the flow (Figure 4). Selection of the streamlines which separates these areas (marked with purple line in Figure 5) was made considering the positioning of the turbine shroud which is marked by two sudden drops in cross section velocity profile. To exemplify, the separation line illustrated in Figure 5 with purple line is marked with purple dots in Figure 6.
To evaluate the flow rate in the zone 1 is used the

\[ Q_{cen_i} = \int \limits_{y_{cen0}}^{y_{cen1}} U \mathrm{d}A \]  

(4)

where

\[ dA_j = \frac{\pi}{2} (r_{j+1}^2 - r_j^2) \]

(5)

\[ r_j = \left| y_j - \frac{y_{cen0} + y_{cen1}}{2} \right| \]  

(6)

\( y_j \) is the y coordinate of the speed vector, \( y_{cen0} \) and \( y_{cen1} \) are the y coordinate of the streamlines delimiting the central zone, \( i \) and \( j \) are indexes corresponding to \( x \) and respectively y coordinates. Flow rate in zone 2 was evaluated using

\[ Q_{ext_i} = \left( 0.3 \cdot (y_{surf_i} - y_{bot_i}) - A_{cen_i} \right) U_{avg_i} \]  

(7)
where 0.3 is the channel width, $A_{cen,i} = A_1 + A_{end}$ from eq. (5), is the central area of the zone 1 for cross-section $i$ (constant $x$), and $U_{avg,i}$ is the average velocity of zone 2 at cross-section $i$, $y_{surf,i}$ and $y_{bot,i}$ are $y$ coordinates given by flow limits (bottom and surface) at $x_i$.

The surface area was determined by position of the minimum in the velocity length differential (Figure 7a) on each cross-section (Figure 7b) and interpolated with a 3rd degree polynomial.

**Figure 7.** Detection of surface from vector field, a) velocity length differential; b) cross-section

Similarly, for measurements in the upstream of the turbine, expression (8) was used to obtain the flow rate

$$Q_i = 0.3 \cdot (y_{surf,i} - y_{bot,i}) \cdot U_{avg,i}. \quad (8)$$

**Figure 8.** Water flow rate aspect at operation regime **d** ($v = 1\text{ m/s}$)

**Figure 9.** Histogram of velocity component $U$ in downstream of the turbine, at operation regime **d** ($v = 1\text{ m/s}$)

For comparison of the flow rates obtained upstream and downstream, a synthetic value was calculated for flow rate and used as reference (dotted line in Figure 8):

$$Q_{ref} = 0.3 \cdot (\bar{y}_{surf} - \bar{y}_{bot}) \cdot U_{peak}, \quad (9)$$

where $\bar{y}_{surf}$ and $\bar{y}_{bot}$ are mean values for the surface and bottom limits, and $U_{peak}$ is the velocity with the highest occurrence in histogram of $U$ in upstream flow (Figure 9).
4. Results

The measurement was performed for rotational speed and water mean velocities to characterize the operating range of the turbine. The power outputs of the turbine results are presented in Table 1, across the power curves (Figure 10).

Table 1. Power measurement reported to the mean water velocity

| Operation regime | Water velocity $v$ [m/s] | Rotational speed $n$ [rpm] | Mechanical Power $P$ [W] |
|------------------|--------------------------|---------------------------|--------------------------|
| a                | 1.0                      | 340                       | 0.12                     |
|                  |                          | 270                       | 1.02                     |
|                  |                          | 190                       | 1.4                      |
|                  |                          | 150                       | 1.32                     |
| b                | 0.9                      | 310                       | 0.13                     |
|                  |                          | 250                       | 0.7                      |
|                  |                          | 190                       | 1                        |
|                  |                          | 140                       | 1                        |
| c                | 0.78                     | 230                       | 0.11                     |
|                  |                          | 190                       | 0.22                     |
|                  |                          | 150                       | 0.38                     |
|                  |                          | 115                       | 0.42                     |
| d                | 0.68                     | 180                       | 0.1                      |
|                  |                          | 160                       | 0.21                     |
|                  |                          | 140                       | 0.28                     |
|                  |                          | 110                       | 0.32                     |

Another objective was to measure the main velocity field and observe the velocity distribution and water level evolution, both upstream and downstream the turbine. An example of velocity field upstream and downstream the turbine is presented in Figure 11.

The upstream flow is uniform and insure ideal operation condition for the turbine intake. The velocity fields for many operation regimes downstream the kinetic turbine are presented in Figure 12. A vortex is appearing after the turbine with lower mean velocity and an increase of the velocity in the upper and lower part of the channel is obtained. The surface level is decreasing due to the
global speed increasing in the section. This information is important not only for flow analysis, but for implementation purposes due to additional erosion effects in the river/channel.

Figure 12. Velocity field downstream the kinetic turbine for different flow speed.

5. Conclusions
By an experimental model test in a free surface channel, the power output of a new kinetic turbine was obtained. Many flow speeds and rotational speeds of the turbine were investigated to have an extended operating range. By extensive PIV measurements, the velocity field upstream and downstream was obtained. This gives helpful information’s for the site implementation. Future analysis of the velocity field will help to improve the turbine design and implementation.

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