EFFICIENCY MEASUREMENT TECHNIQUES OF HYDRO KINETIC TURBINES: A REVIEW

A.K. Verma and R.P.Saini
Alternate Hydro Energy Centre, IIT Roorkee, Uttrakhand, 247667
Email : ak.verma8819@gmail.com, saini.rajeshwer@gmail.com

ABSTRACT
Among all renewable energy technologies, hydro power generation is considered to be prime choice in terms of contribution to the electricity generation. Lot of hydro potential exists in canals and rivers in India. However, technology to tap this potential has not been successfully developed and readily available. Hydro kinetic turbine is considered to be suitable technology for power generation at such sites which can be used to capture the kinetic energy of flowing water. Hydrokinetic technology is under development and many studies were carried out and available in the literature. This paper presents the review on efficiency measurement techniques for evaluation of performance of hydro kinetic turbines used by various researches.

Keywords: hydro kinetic, Turbines, Efficiency measurement technology

1. INTRODUCTION
There are different kinds of renewable technologies, such as biomass, wind, solar, hydro and geo thermal, which are clean and reliable to reduce greenhouse gas emission that leads to global warming. Water is an abundant renewable resource covering 75% of the planet and its primary form of energy is potential energy of elevation. Among different renewable energy technologies, hydro power generation (large and small scale) is the prime choice in term of contribution to the world's electricity generation [1-2]. Hydropower offers an advantage over fossil fuels because it uses water as a renewable fuel source. Water is a clean fuel and does not release any particulate into the air [3]. The production of electricity from falling water, due to the gravitational force, accounts for 16% of global electricity generation and is expected to increase about 3.1% each year over the next 25 years [4]. Electrical demands, rising diesel fuel prices, as well as fossil fuel-based energy is limited and in fact is depleting [5], and subjected to use of renewable technologies. Conventional hydropower utilizes the potential energy of water through the construction of dams or reservoirs. An estimated potential of about 20,000 MW of small hydro power projects exists in India. Ministry of New and Renewable Energy has created a database of potential sites of small hydro and 6,474 potential sites with an aggregate capacity of 19,749.44 MW for projects up to 25 MW capacity have been identified. It is concluded that in India there is a scope to develop small hydro power station at remote area to make better life of people and fulfill their requirement. However, this requires a large capital investment and technology development and can have significant consequences on the local aquatic environment [6]. Potential in hydro are of two which can be harnessed to generate electricity i.e. hydrostatic and hydrokinetic. Hydrostatic is the potential energy of a water body due to its height with respect to a reference ground. Conventional hydropower plants use dams and reservoirs to store water with a large amount of hydrostatic energy in
order to harness the energy in a controllable manner to generate electricity. Hydrokinetic technology has the potential to generate a great amount of electricity with a minimum impact to the environment [7]. Hydrokinetic is the kinetic energy of a water mass due to its movement. The faster the water velocity, the larger hydrokinetic energy it contains. There are two types of hydrokinetic energy result from two popular types of water movements: current-based and wave-based hydrokinetic energy. Current-based hydrokinetic energy can be found in river streams, artificial waterways, irrigation canals, dam head/tailrace, tidal and ocean currents. This movement of water can be utilized to generate electricity by a hydro mechanical conversion device that is turbine. Generally these are called as river current turbine (RCT) or hydro kinetic turbines. Many investigators investigated various types of hydrokinetic turbines and presented their performance under different conditions. The performance of hydrokinetic turbines was analyzed theoretically and experimentally under different studies. Under this paper attempt has been made to present a literature review on efficiency measurement of hydrokinetic turbines carried out by different investigators.

2. HYDROKINETIC TURBINES

As widely known in the literature, the hydrokinetic power theoretically available in a river segment, having velocity V, flowing through a cross section and can be expressed as:

\[ P = \frac{1}{2} \rho A V^3 \]  

Where, \( \rho \) is the density of water. Fresh water has a density of 1000 kg/m³ at 5°C [8]. Hydrokinetic power resource evaluation has been done in different parts of the world. Although the theoretically available power is high, the technically recoverable power is much lower.

The function of hydrokinetic turbines is to capture the kinetic energy of flowing water current and transfer it into a shaft. Hydrokinetic turbines can only capture a fraction of the kinetic energy in the water that pass through its cross section. The fraction is known as power coefficient, \( C_p \). The power captured by a hydrokinetic turbine can be expressed as:

\[ P_{\text{actual}} = C_p \times P_{\text{theory}} = \frac{1}{2} \times C_p \times \rho \times A \times V^3 \]  

Similar to wind turbines, the power coefficient, \( C_p \), of a hydrokinetic turbine depends on Tip-Speed Ratio. By definition, tip-Speed Ratio (TSR), \( \lambda \) is the ratio of the speed of the blade, at its tip, to the speed of the flowing water [9]. It expressed as:

\[ \lambda = \frac{\omega R}{2xV} \]  

The relation between TSR and power coefficient \( C_p \) can be understood intuitively. If the turbine’s blades spin too slowly, then most of the water will pass through the rotor without being captured by the blades. However, if the turbine spins too fast, then the blades will always travel through used, turbulent water. There must be enough time lapses between two blades travelling through the same location so that new water can enter and the next blade can harness the power from that new water, not the used, turbulent water [10].
Helical Savonius rotor with shaft has the lowest coefficient of power of 0.09 at a TSR of 0.9. Helical Savonius rotor with a lower aspect ratio of 0.88 shows a higher performance than rotors with an aspect ratio of 0.93 and 1.17 [33]. Gilbert and Foreman (1983) found $C_p = 2.51$ in an experiment of ducted hydrokinetic turbine [11]. Gaden (2007) used computational fluid dynamic simulation to study the effect of a duct to the flowing fluid [10]. He found that the velocity of a fluid inside a duct could be more than double the outside fluid velocity. Double in velocity means Betz limit could be surpassed by eight times [12].

3. CLASSIFICATION OF HYDROKINETIC TURBINES

Based on the alignment of the rotor axis with respect to water flow, two generic classes could be formed, namely, the axial and cross flow turbines. The axial turbines have axes parallel to the fluid flow and employ propeller type rotors. On the other hand, the cross flow types encounter water flow orthogonal to the rotor axis and mostly appear as cylindrical rotating structures [13]. Performance analysis was conducted by various investigators and available in the literature [14–16]. Classifications of hydrokinetic turbines are shown by a schematic in Fig. 1.

![Fig. 1: classification of hydrokinetic turbines](image)

4. SAVONIUS HYDROKINETIC TURBINES

Savonius rotor, a vertical axis turbine is basically a drag type rotor which is proposed by Finnish Engineer Savonius [31]. The basic shape of this rotor is an ‘S’ type, having a small overlap between two semi-circular blades. Savonius rotor is simple construction with low cost, low noise. It has an ability to accept fluid from any direction with good starting characteristics. It has low aerodynamic efficiency compared with Darrieus type turbine. The working principle of Savonius rotor is based on the difference of the drag force between the concave
and the convex parts of the rotor blades when they rotate around a vertical shaft. The drag coefficient for concave surface is more than that of convex surface. So advancing blade with concave side facing the water flow would experience more drag force than returning blade [30].

The conventional single stage Savonius rotor has a large static torque variation with the rotor angle. The rotor also develops a negative static torque at certain angular positions. The torque variation and the negative torque have an adverse impact on the use of Savonius rotor for different applications [30]. Many researchers proposed that the savonius turbine can run at low speed because it has low starting torque as it is simple in construction and low cost recommends to use savonius turbine for power generation also very easy to couple with generator make it easy in maintenance. A typical two bladed Savonius rotor is shown in Fig 2.

![Fig. 2: (a) A typical two bladed Savonius rotor (b) drag forces acting on this rotor [6]](image)

5. EFFICIENCY REPRESENTATION AND PARAMETERS AFFECTING EFFICIENCY

5.1 Efficiency

Efficiency of hydrokinetic turbine can be defined as ratio of output shaft power of turbine to the inlet kinetic energy of water per unit time or the total amount of hydro kinetic energy that can be converted into mechanical energy by turbine is known as efficiency of the hydro kinetic turbine.

\[
\eta = \frac{P}{(1/2) \rho A \times V^3} 
\]  (4)
5.2 Parameters

i. Tip speed ratio

As discussed above, tip speed ratio ($\lambda$), is the ratio of the speed of the blade, at its tip, to the speed of the flowing water and is considered one of the important parameter. It can be written as:

$$\lambda = \frac{\omega R}{2V}$$  \hspace{1cm} (5)

Where, $\omega$ is Angular velocity of Turbine blade, $R$ is Radius of the blade, $V$ is Water flowing speed. The maximum value of $\lambda = 3.027$ at which performance coefficient ($C_p = 0.215$) is maximum [26].

ii. Blade arc angle

Blade arc angle ($\psi$) is the angle between blade profiles. As results, the modified Savonius rotor without overlap ratio, with blade arc angle of $124^\circ$ and with an aspect ratio of 0.7 has a maximum power coefficient of 0.21 at Reynolds number of 150,000 [34]. The blade arc angle is shown in Fig.3.

![Fig 3: Modified blade shape of Savonius rotor [18]](image)

iii. Blockage ratio

Blockage ratio ($B$) is defined as the ratio of the frontal swept area of the turbine to the frontal swept area of the channel. It can be written as:

$$B = \frac{HD}{H_W W}$$  \hspace{1cm} (6)

Where, $H$ is Height of the turbine, $D$ is Diameter of turbine rotor, $H_W$ is Height of the water in channel, $W$ is Width of the channel. According to the research work carried out by Alexander and Holownia, the blockage ratio above 30% essentially needs correction. As the free stream
velocity essentially varies with respect to different water depth, the velocity of the water current is measured at different layers from the bed level [27].

iv. **Blockage ratio**

Overlap ratio (β), bucket overlap create effect on the efficiency of the turbine so it is also very important parameter. The blockage ratio is shown in Fig. 4.

\[
\beta = \frac{e}{d}
\]

From the present investigation, it is observed that with the increase of overlap, the power coefficients decreased. The maximum power coefficient of 51% was obtained at no overlap condition. Study revealed that there is a definite improvement in the power coefficient for the combined Savonius–Darrieus rotor [28].

v. **Aspect ratio**

Aspect ratio (α) is the ratio of height of the rotor (H) divided by its diameter (D). This is very important criterion for the evaluation of the hydro kinetic turbine. Aspect ratio at 0.7 has maximum efficiency of hydro kinetic turbine [29]. Aspect ratio is shown in Fig. 5.

\[
\alpha = \frac{H}{D}
\]
vi. Number of stages

Number of stages, The coefficient of power, coefficient of torque and no load tip speed ratio increase with increase in the Reynolds number (water velocities) for one, two and three stage hydro kinetic rotor rotors. The number of stages of savonius turbine is shown in Fig.6.

![Fig. 6: Simple savonius rotor with single, two and three stage](image)

vii. Rotor design and other parameter described in table form which is essential for turbine to maintain high efficiency:

Table 1: Summary of experimental investigation carried out by researchers on Savonius turbines with water as working medium

<table>
<thead>
<tr>
<th>Author</th>
<th>Turbine aspect ratio</th>
<th>Reynolds no. $\times 10^6$</th>
<th>Free stream velocity</th>
<th>Water tunnel dimension</th>
<th>Orientation of the axis</th>
<th>Turbine tested</th>
<th>Parameter measured</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Khan et al.[23]</td>
<td>1.82</td>
<td>0.98, 1.52, 1.96</td>
<td>1</td>
<td>5 $\times$ 3</td>
<td>Vertical</td>
<td>Single-stage, two-stage, three-stage conventional Savonius turbines with an overlap ratio of 0.207</td>
<td>$C_p$, $C_t$</td>
<td>$C_p$ max of 0.038, 0.049, and 0.04 for single-, two-, and three-stage Savonius turbines</td>
</tr>
<tr>
<td>Nakajima et al.[24]</td>
<td>1.48</td>
<td>1.1</td>
<td>0.8</td>
<td>0.6 $\times$ 0.5</td>
<td>Horizontal</td>
<td>Single-stage conventional Savonius turbine</td>
<td>$C_p$, flow visualisation</td>
<td>$C_p$ max of 0.25 for single-stage Savonius</td>
</tr>
</tbody>
</table>
### EFFICIENCY MEASUREMENT TECHNIQUES

Based on literature review following techniques used under various studies are discussed

- Experimental test of Hydrokinetic Turbine using open channel flow Type 1.
- Experimental test of Hydrokinetic Turbine using open channel flow Type 2.
- Experimental test of Hydrokinetic Turbine using open channel flow Type 3.
- Computational modeling
6.1 Experimental Test Of Hydro Kinetic Turbine Using Open Channel Flow Type 1

Assume simple three bladed Savonius turbine is considered for the experimentation process and is represented in the figure. An aspect ratio of “X” of Savonius blades, highest power coefficient of the turbine is obtained [19].

![Figure 7: A three blade Savonius turbine](image_url)

6.1.1 Steps to Find Out Efficiency

- The velocity of the water current is measured with the help of an Acoustic Doppler Velocity meter (ADV). The incident flow with a free stream velocity (V) carries the energy of the flow that can be expressed as:

\[ P_{\text{max}} = \frac{1}{2} \rho AV^3 \]  

(i)

- The torque generated can be expressed in terms of the velocities at the upstream and the downstream of the turbine as:

\[ T = \frac{1}{2} \rho AR (V_1^2 - V_2^2) \]  

(ii)

- The power extracted by the Savonius turbine from the incident flow can be evaluated as:

\[ P_{\text{rot}} = T \omega \]  

(iii)
Fig. 8: Measurement of velocity at (a) upstream of the turbine and (b) downstream of the turbine [19]

- One of the prime factors, which relate the velocity of the free stream and the velocity of the tip of the blades, is the tip speed ratio (TSR) given by:

\[
\lambda = \frac{\omega R}{2V} \tag{iv}
\]

- The coefficient of power determines the fraction of power that is extracted by the turbine, and is represented by:

\[
C_p = \frac{P_{rot}}{P_{max}} \tag{v}
\]

- Blockage ratio (B) is given by:

\[
B = \frac{HD}{H_W W} \tag{vi}
\]

Fig. 9: Open water channel schematic diagram of the experimental setup [19]
6.2 Laboratory Test Of Hydro Kinetic Turbine Using Open Channel Flow Type 2

- Figure shows schematic the water channel used for study, and figure shows the experimental setup for conducted test on rotating Savonius rotor. The setup consists of a structure housing the modified Savonius rotor [18].

![Diagram of test setup for Savonius rotor](image)

**Fig. 10: Schematic diagram of the test setup for Savonius rotor [17]**

(1) Pulley (2) Nylon string 1 mm diameter (3) Weighing pan (4) Shaft (5) Supporting structure (6) Savonius rotor (7) Spring balance

6.2.1 Steps To Find Out The Efficiency

- Discharge in the channel is measured by venture meter having a coefficient of discharge of 0.99 and area ratio of 0.6 or flow meter. Differential pressure transducer is used for pressure drop measurement across venture meter.

\[
Q = AV \quad (i)
\]

- Reynolds number based on the rotor diameter is given by:

\[
Re = \frac{\rho AV}{\mu} \quad (ii)
\]

Where \( Re \) is Reynolds number, \( \rho \) is the density of water, \( U \) is the free stream velocity, \( D \) is the rotor diameter, and \( \mu \) is the absolute viscosity of water.

- Tip speed ratio is given by:

\[
\lambda = \frac{\omega R}{2V} \quad (iii)
\]
Where $\omega$ is the angular velocity.

- Torque is calculated from the measured load, and spring balance load is given by:

$$T = (M-S)(r_{\text{shaft}} + d_i)g/1000[N-M] \quad (iv)$$

Where $M$ is the load, $S$ is spring balance load, $r_{\text{shaft}}$ is the radius of the shaft, $d_i$ is the diameter of the nylon string.

- Coefficient of torque ($C_t$), and coefficients of power ($C_p$) are given by:

$$C_t = 4T/(\rho U^2D^2H) \quad (v)$$

$$C_p = TSR \times C_t \quad (vi)$$

- Blockage ratio ($B$) is given by:

$$B = HD/H_wW \quad (vii)$$

Where $H_w$ is the height of the water channel. $W$ and $H$ are the width and height of the water channel.

### 6.3 Laboratory Test of Hydro Kinetic Turbine Using Open Channel Flow Type 3

Experiments can be carried out in the open channel or canal according to the required size of turbine rotor. It will equip with a towing carriage with a power coefficient of the single stage rotor as a function of tip speed ratio. Finds out the single stage rotor at water speed of $X$ m/s, the peak power $Y$ W at a rotor speed of $Z$ rev/min. At a speed of $X_1$ m/s, the double stage gave $Y_1$ W at $Z_1$ rev/min, while the three stages gave $Y_3$W at $Z_3$ rev/min. These differences can be calculated. The torque variation of all three prototypes will be drawn in the excel sheet, for one torque setting and one flow speed. Torque variation and the frequency of all type (single or multistage) could be found out. Analysis would show the reason for torque variation. What would be the reason for variations like rotor geometry, flow induced vibration of the box frame on that rotors held could be predicted. In future work, corrections may be made to analyze the performance and for improvement of turbine. The flow analysis requires further investigation using either computational fluid dynamics analysis or flow visualization experiments can be done. MATLAB will be used to analyze the tests’ data and plot characteristics of the turbines. All the prototypes will be tested individually in the channel [32].
6.4 Computational Modeling

- First of all, a small model of the turbine will be considered that has a blade chord length of $X$ m, height of $H$ m connected with a shaft of diameter $D$ m. The blade with thickness $t$ m according to the requirement of the experiment.

- The entire geometry of the turbine is designed computationally in Ansys Design Modeler in such a way that the turbine lies within a computational domain resembling an open channel. The computational domain is segmented into two parts separating the outer fluid zone and the inner fluid zone as shown in Fig. 12.

i. After the creation of the geometry, it is exported to ANSYS Mesh so that it can be meshed with a suitable grid.

  - The tetrahedron mesh is chosen since it is capable of meshing complex geometries.
• Sweep mesh is used for the cylindrical bodies with better quality and accuracy.
• The generated mesh on the geometry is exported to the computational solver ANSYS Fluent. Where in the case is defined and solved with necessary conditions.
• The process of simulation is repeated with different refinement levels of the mesh. The refinement is carried on undertaking different mesh size and is extended up to a limit after which there is no significant quantitative change in the result.
• This limit of the refinement is called the grid independent limit (GIL) and the mesh is said to have attained the limit of grid independence.
• In this experiment, the upstream and the downstream velocities will be find at x m and y m away from the turbine, and at each distance the velocity has been computed for different water layers.
• The variation of Cp with tip speed ratio and the variation of power extracted by the turbine with the rotational speed of turbine when operated in different velocity conditions as well as we can calculate the torque and power coefficient [19].

The variation of performance and torque coefficient with respect to velocity is obtained as shown in Fig.13.

![Fig. 13: Variation of (a) torque and (b) power extracted with velocity][19]

7. PROPOSED STEPS TO DETERMINE THE EFFICIENCY EXPERIMENTALLY OF HYDRO KINETIC TURBINE

Step1. A water channel will be designed and constructed. The experimental device will be used to investigate the conditions experienced by a hydro kinetic turbine placed in the water flow. For this case water channel with an open test section facility has to be developed.

Step2. Torque measurement: - To measure the dynamic torque on the rotor shaft, a DC generator will be used, which transforms the torque on its axis to an electrical current. It should couple the generator to the electric motor that would display the speed and the torque.
The electric motor is used to provide mechanical power to the generator which delivers an electric current in a resistive load.

Step 3. It will allow to tracing the calibration curve that connects the electric current supplied by the generator to the dynamic torque. This calibration curve will be used to determine the dynamic torque by referring to the value of the electric current supplied by the generator.

\[ \text{Fig 14: Calibration curve Current and Torque [33]} \]

Step 4. Determine the power coefficient \( C_p \) of a Hydrokinetic turbine which is defined by:

\[
C_p = \frac{P_{\text{max}}}{(1/2) \rho AV^3} \tag{i}
\]

Step 5. Determine the coefficient of torque \( C_m \) which is given by:

\[
C_m = \frac{4T}{(\rho V^2D^2H)} \tag{ii}
\]

Where, \( A \) is cross sectional area of channel, \( V \) is velocity of water, \( D \) is diameter of rotor, \( H \) is height of rotor, \( \rho \) is density of water. For measuring the velocity of water hand current meter or water logging current meter can be used. For more accuracy acoustic Doppler velocity measurement instrument is better. Flow chart given below which makes clear to prepare a setup and calculate the discharge: The steps discussed above is represented by a flow chart given in
8. CONCLUSION

In order to tap the hydro potential available in velocity of flowing streams, hydrokinetic turbines are considered the suitable turbines. However, the technology for such turbines is not established so far. These turbines basically work on wind turbine concept and most of the hydro kinetic turbines developed so far are design on this basis. The measurement of the efficiency of the developed turbines is the main concern for optimal designs. Under this paper, a literature review is carried and presented basically on efficiency measurement aspect. It has been found that a very few experimental studies are carried out and available in the literature. An attempt is also made to work out a suitable efficiency measurement technique for Savonius type hydro kinetic turbine.

REFERENCES


[19] N.K. Sarma, A. Biswas “Experimental and computational evaluation of Savonius hydrokinetic turbine for low velocity condition with comparison to Savonius wind turbine at the same input power” Deptt. of Mechanical Engg, NIT Silchar, Silchar, Assam 788 010, India.

[20] Shujie Wang, Chao Xu “Hydrodynamic optimization of channeling device for hydro turbine based on lattice Boltzmann method” Mechanical Engineering, Ocean
University of China, Qingdao 266100, PR China. (Grant No. 50906075 and No. 50979101)


[33] A. Damak, Z. Driss and M.S. Abid “Experimental investigation of helical Savonius rotor with a twist of 180°”. National Engineering School of Sfax (ENIS), Laboratory of Electro-Mechanic Systems (LASEM), University of Sfax, B.P. 1173, km 3.5 Soukra, 3038 Sfax, Tunisia.