INVESTIGATIONS ON PERFORMANCE OF A SAVONIUS HYDROKINETIC TURBINE

Ph.D. THESIS

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AUGUST, 2017

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A THESIS

Submitted in partial fulfilment of the requirements for the award of the degree

of

DOCTOR OF PHILOSOPHY

in

ALTERNATE HYDRO ENERGY CENTRE

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ABSTRACT

Over the last couple of decades, the energy-based economies have been drawing attention towards the development and promotion of economical, sustainable and environment-friendly energy generation. Energy crisis and greenhouse gasses (GHG) emissions are the major encouraging factors to carry out intensive research for the emerging technologies of renewable energy. In the context of the contribution in electricity generation, hydropower holds a prominent position among all the renewable energy sources worldwide. However, large-scale hydropower generation is always criticized due to negative environmental impact i.e. long gestation period, submergence of valuable land. On the other hand, Small Hydropower (SHP) is considered as environmentally friendly technologies and suitable to meet power requirement of remote and rural areas.

Almost one third of the world population are living without electricity in rural and remote areas. But, these areas do have access to flowing water with little or zero head. It is not technically possible to install the conventional hydroelectric system in flowing water such as river or canal. On the other hand, a new category of hydropower energy termed as hydrokinetic technology (HKT) can extract kinetic energy from different stream of water such as tidal, ocean, river and irrigation canals. The hydrokinetic energy converters are considered as heart of Hydrokinetic energy conversion (HKEC) system.

Based on their conversion methodology, hydrokinetic energy converters are broadly categorized in two distinct classes such as turbine type and non-turbine type. The non-turbine approaches are being investigated with keen interest and may become the innovative expectations in this new technological field. However, like wind energy conversion, turbine-type systems are considered as primary choices for hydrokinetic energy conversion. The hydrokinetic turbine is defined as ‘‘Low pressure run-off-the-river ultra-low head turbine that will operate on the equivalent or less than 0.2 m head”. The ‘hydrokinetic turbine’ is also named as Zero Head Hydro Turbine or In-stream Hydro Turbine, Ultra-low-head Hydro Turbine, Water Current Turbine, and Free Flow/Stream Turbine. The same technology is commonly known as ‘River Current Turbine (RCT)’, ‘River Current Energy Conversion System’ (RCECS), ‘River In-stream Energy Converter’ (RISEC) for rivers or artificial waterways.

Further, hydrokinetic turbines are classified as axial-flow turbines and cross-flow turbines based on the alignment of the rotor axis to water flow. The flow velocity, type of flow and desired output of turbine play an important role in the selection of hydrokinetic turbine. Due to their high-efficiency, axial flow turbines are mainly used in ocean, marine and tidal applications. Horizontal axis turbines are also expensive for small power applications.

The vertical axis turbines (VAT) are favourable for the cases of limited water flow rate or weak current conditions (like river, irrigation canal) because VAT can generate higher torque in lower tip speed ratio and lower current velocity range rather than horizontal axis turbine (HAT). Due to these leading advantages such as less expensive, independent of flow direction, easy installation and maintenance, interest in vertical axis turbine is intensified which encourages research for the design and development of improved turbine. Based on the turbine blade design, vertical axis hydrokinetic turbine can be categorized as lift -type and drag-type hydrokinetic turbine. Savonius turbine (semi-circular), Gorlov turbine (helically shaped blades), Darrieus turbine and H-shaped Darrieus (straight blades) are the popular turbines in the category of vertical axis turbines.

Savonius hydrokinetic turbine is the drag-type rotor which starts rotating at very low fluid velocity as compared to the conventional hydraulic turbine. The working principle of Savonius rotor is based on the difference of drag force between concave and convex parts of the rotor blades when they rotate around a vertical shaft. Savonius rotor is simple in construction with low cost, low noise. It has an ability to accept fluid from any direction with good starting characteristics. Due to these advantages, Savonius turbines are suitable to install in the river or canal at remote areas of developing countries. Despite such advantages, Savonius hydrokinetic turbines are still not as popular as compared to the horizontal axis turbine due to its poor performance.

In order to improve the performance of Savonius turbine, lot of studies were carried out and available in literature. In earlier studies, it was observed that unambiguity priority was granted to the design parameters and flow parameters to enhance the efficiency of Savonius rotor. Researchers also suggested that Savonius turbine can be used in water channel as a hydrokinetic turbine. Very few studies are reported on Savonius turbine in water channel (irrigation canal or river). Performance evaluation of Savonius water current turbine under various system and operating parameters is a thrust area around the world. Gravity is responsible for water flow in open channel while wind flow occurs due to pressure difference. This is the reason why the flow field developed by hydrokinetic and wind turbine is quite different. Further, presence of turbine in open channel also disturbs the contours of free surface flow. Subsequently, performance of turbine is affected. Henceforth, the effect of different geometrical parameters on the performance of Savonius hydrokinetic turbine still needs significant research. Limited studies were reported on Savonius turbine having semi-circular and conventional blade profile in water channel (irrigation canal or river). There is still need to investigate the performance of Savonius hydrokinetic turbine under several twist angles, different blade shapes or number of stages.

Keeping this in view, following objectives were proposed for the present study;

1. To develop a 3D model of a Savonius hydrokinetic turbine to simulate the model.
2. To design and fabricate the experimental set up to validate the simulations results.
3. To investigate the effect of performance parameters; twist angle, blade arc angle, blade shape factor, and number of stage on the output of Savonius hydrokinetic turbine under different flow velocity.
4. To develop correlation for coefficient of performance as function of system and working parameters.

Under the present study, an extensive numerical investigation has been carried out to study the effect of different geometrical parameters i.e. twist angle, blade arc angle, blade shape factor and number of stage on the performance of turbine under different flow velocity of water. A two blade Savonius hydrokinetic turbine with an aspect ratio of 1.58 and zero overlap has been considered to carry out Computational Fluid Dynamics (CFD) analysis in order to discuss flow properties and performance under various system and operating parameters. The turbine has been considered to be submerged completely in the water channel having water level of 0.65m. The swept area of the rotor is kept 0.04 m^2 so that the rotor presented a channel blockage of 12 %. The specification of the turbine and water channel considered for CFD analysis are as given below;

i. Number of blades : 2
ii. Aspect ratio : 1.58
iii. Overlap between blades (e) : 0

iv.	Rotor diameter (D)	: 0.160 m
v.	Rotor height (H)	: 0.253 m
vi.	Endplate diameter (D_0)	: 0.176 m
vii.	Open channel height	: 0.65 m
viii.	Open channel width	: 0.55 m
ix.	Open channel length	: 3.0 m
x.	Blockage ratio	: 12%

The numerical simulation has been performed for TSR range of 0.5 to 1.0 for each set of parameters. The velocity of water in the open channel is varied from 0.5 m/s to 2 m/s for each parameters investigated. Phase shift of 90° and 60° has been considered for double stage and three stage turbines with identical stage height. A total of 288 simulations have been performed in the present numerical investigations covering different system and operating parameters. The range of parameters investigated is as given below.

i.	Twist angle, α [degree]	: 0° - 25°
ii.	Blade arc angle, ψ [degree]	: 110° - 180°
iii.	Blade shape factor, p/q	: 0.2 - 0.6
iv.	Number of stage, S_T	: 1 - 3
v.	Flow velocity, V [m/s]	: 0.5 m/s - 2.0 m/s

A three dimensional computational model has been developed for simulating the performance of Savonius hydrokinetic turbine. The numerical simulation has been performed using the realizable k-ε turbulence model. In order to solve transport equations, commercially available ANSYS FLUENT (v 15.0) has been used as flow solver which uses finite volume method (FVM) to describe flow field by solving Reynolds averaged Navier- Stokes (RANS) equations. Moving reference frame (MRF) approach has been applied to perform transient simulations of the turbine.

In order to validate the numerical results, an experimental setup was designed and fabricated to compare the simulation results with experimental results for different values of TSR at flow velocity of 0.5 m/s. The experimental set up comprised with a model of conventional Savonius hydrokinetic turbine with supporting structure, an open channel, axial pumps and instrumentations (digital weighing scale, RPM indicator, current meter with data logger). To validate qualitatively flow patterns obtained numerically have also been compared with flow distribution reported under earlier studies. It has been found that the similar trend of velocity contours and pressure contours around the turbine blades was obtained under present numerical investigations. The value of power coefficient, predicted numerically under different value of TSR has also been compared with the experimental results obtained under flow velocity of 0.5 m/s.

After qualitative and quantitative validations of numerical results obtained, the numerical investigation on the performance of Savonius hydrokinetic turbine has been carried out to investigate the effect of (i) Twist angle, (ii) Blade arc angle, (iii) Blade shape factor, (iv) Number of stage, (v) Flow velocity. The parameters investigated are velocity and pressure distribution, performance characteristics.

In order to study the flow field, the velocity contours and pressure contours are observed and discussed under the present investigation. The pattern of velocity at the inlet is found to be similar for the given boundary condition. High-speed zone has been found at the tip of the blade. Due to rotation of the turbine, low-speed zone (wake zone) has also been observed behind the rotor blades. It can also be observed that flow velocity is decreased sharply in wake zone. Flow regains its velocity after marching ahead of wake zone. At upper and lower side of wake zone, the flow velocity is again increased periodically. High randomness is also found in the flow behind the rotor which causes turbulence in the flow. The turbulence is found to be increased with the flow velocity from 0.5 to 2.0 m/s.

Pressure drop has also been occurred across the rotor from upstream to downstream side. At the inlet of the channel, pressure is found uniform, whereas higher pressure values are found in upstream side i.e. the concave side of advancing blade and convex side of returning blade. Lower pressure region is developed in downstream side (the convex side of advancing blade and the concave side of returning blade). Thus, two pressure regions i.e. higher and lower are found near the blades within the flow domain which creates a pressure drop. Turbine blades start rotating due to this pressure drop across the rotor which causes power extraction by the Savonius hydrokinetic turbine from the flowing water in the channel. Again, the pressure starts to increase after passing the Savonius rotor and flow experiences an adverse pressure gradient. Due to the adverse pressure gradient, the flow separates from the surface and creates a highly turbulent region behind the rotor. Due to flow separation and recirculating flow, wake zone appears in the flow domain behind rotating Savonius rotor. The pressure inside the wake region remains low as the flow separates, and a net pressure force (pressure drag) is produced.

Further, to determine the performance of turbine, coefficient of power is computed using the expression $C_P = C_m \times \lambda$ where C_m and λ are the coefficient of moment obtained numerically and tip speed ratio (TSR) of turbine respectively. The coefficient of power of turbine has been estimated based on the simulations results obtained for each set of system and operating parameters considered in the present study.

It has been found that coefficient of power is a strong function of geometrical and flow parameters. The coefficient of power increases with an increase in TSR (λ) and attains maximum value corresponding to TSR value of 0.9 in the range of parameters investigated. Beyond this value of TSR, coefficient of power value declines. The coefficient of power has been found to attain maximum values when values of twists angle (α) and blade arc angle (ψ) are 12.5° and 150° respectively. The coefficient of power increases with an increase in the value of blade shape factor (p/q) and flow velocity (V). It has also been found that the coefficient of power attain maximum values for double stage rotor. With further increase in number of stage, power coefficient is found to decrease. In the entire range of all geometrical parameters investigated, coefficient of power has been found to increase monotonically with increase in Reynolds number.

Finally, based on the results obtained during numerical investigation, correlation for coefficient of power (C_P) has been developed as function of the system and operating parameters (λ, α, ψ, p/q, S_T, Re) of Savonius hydrokinetic turbine.

The values of coefficient of power predicted by correlation under different system and operating parameters are compared with those obtained by simulation. A good agreement has been found between the numerical and predicted values of coefficient of power.

Summarizing, based on the numerical investigation carried out under the present investigation, it is concluded that the maximum power coefficient value is obtained for twist angle of 12.5°, blade arc angle of 150° , blade shape factor of 0.6 and double stage turbine corresponding to TSR value of 0.9 at flow velocity of 2 m/s. The numerical results obtained under the present investigation may be useful to predict the velocity and pressure variation across the turbine blade for future studies. The developed correlation may be useful for turbine design engineers to predict the performance of turbine for given range of parameters.