Improvement of compact Darrieus-type hydraulic turbine for extra low head by changing inlet shape

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Abstract. Hydraulic power generation has a potential as an environmental friendly energy, which is not discharging a carbon dioxide gas during operation. Currently, high and middle water head turbine has been fully developed in practical use. However, extra low head hydraulic turbine has not been developed yet as a commercial utilization. Compact Darrieus-type hydraulic turbine has been focused on for small waterway. The purpose of this study is to improve the performance of the compact Darrieus-type hydraulic turbine, by changing inlet shape. In our previous study, the blade shape, the number of blades, the water wheel diameter ratio of chord length and pitch circle radius are optimized. The purpose of the present study is to further improve the performance of the compact Darrieus-type water turbine based on former results. In this study, the inlet shapes were changed to increase inflow velocity and to contribute improvement of efficiency. As a result, the efficiency of the turbine with using only half side counterpart nozzle was increased compared to the other settings.

1. Introduction

In recent years, our world faces a lot of energy problems such as nuclear power safety, increased energy demand and global warming and so on. Renewable energy is the one of the way to solve these problems. In renewable energies, hydroelectric power generation has a high potential since no carbon dioxide discharging during operation. Hydropower has a relatively high energy density, if efficient power generation method will establish, it will help to solve the energy problem. In utilizing hydraulic power, obtained output is as large as the water head. Currently, the hydroelectric power generation for high and middle water head has been developed as a commercial utilization. On the other hand, low head hydraulic and hydrokinetic power is not enough developed as a commercial utilization. If the effective turbine for low head will developed, it will be possible to generate power in any place with water flow. Low head hydraulic and hydrokinetic power can be greatly expected as a new local energy.

C. M. Niebuhr, et al. [1] summarized a review of hydrokinetic turbines and enhancement techniques for canal installations. I. Loots, et al. [2] provides a review of available low head hydropower technologies and applications in a South African context. B. Kirke [3] examined the cost per kW actually
delivered in real rivers, identified a source of confusion and erroneous power prediction, suggests measures to address them a simple ultra-low head turbines. This paper describes a simple low-cost horizontal axis cross flow turbine with much greater swept area and able to generate more power than an axial flow turbine of similar diameter. Vertical axis tidal turbines (VATTs) are perceived to be an alternative to their horizontal axis counterparts in tidal streams due to their omni-directionality. There are many papers in numerical simulations for VATTs [4-8]. Lots of experimental investigations for vertical axis straight blade turbine (Darrieus-type turbine) are also carried out [9-12].

Among various kinds of water turbines, the Darrieus-type water turbine is one of the best options which can be used as a hydrokinetic turbine due to its high efficiency. In addition, since the Darrieus-type water turbine is small and simple structure, it is considered to be advantages for cost performance. Furukawa et al. [13] developed ducted Darrieus turbine for low head hydropower utilization. Their research group [14-18] obtained result for optimal design and conditions in their experimental setup. In our previous study [19-21], the optimal setup was obtained for the water wheel diameter, ratio of chord length and pitch circle radius. In this study, these conditions were fixed. The purpose of the present study is to further improve the performance of the compact Darrieus-type water turbine based on former results. In this study, the inlet shapes were changed to increase inflow velocity and to contribute improvement of efficiency.

2. Experimental setup

2.1. Theory of operation

Figure 1 shows theory of operation of a Darrieus-type turbine. Rotation starts by the lift force $F_l$ generated in the blade installed in the water flow with inlet velocity $V$. When the runner is rotating in the tip speed $U$, a larger lift force $F_l$ works on the blade due to the relative flow velocity $W$ with the water flow into the blade. When the circumferential component of lift works positive with respect to the direction of rotation, the runner is further accelerated. Although higher efficiency can be obtained if the rotational speed increases, it becomes steady state at a balanced rotational speed with the drag force affecting on the blade.

2.2. Experimental facility

Figure 2 shows experimental turbine. The blade shape is NACA0018, the number of blades is five. The water wheel diameter is 150 mm, which is 1/2 of the waterway width. The ratio of chord length $l$ and pitch circle radius $R$ was 0.5. Figure 3 shows experimental apparatus. The water of the waterway was pumped up from the water pool by underwater pump, the water flowing through the waterway was recycled back to the pool. The maximum flow rate $Q$ of the pumps is about 0.5 m$^3$ per minutes. This experiment was carried out in the maximum flow rate.

As for the experimental waterway, length $L$ is 3000 mm, width $t$ is 300 mm, height $H$ is 500 mm, which is simulated an agricultural waterway. The side wall of the waterway was made of a clear acrylic plate to observe the interaction between turbine and water flow.

2.3. Method of experiment

The performance test of the water turbine was carried out in the following procedure. Beginning with no-load operation, loads were sequentially increased. For each load condition, the rotation speed $n$, the torque $T$, the upstream water level $h_u$, and the downstream water level $h_d$ were measured. The water levels $h_u$ and $h_d$ were measured visually by using a ruler. In order to compare the performance in different sized water turbines, the torque, the output power, and the water wheel rotation speed is normalized. The torque coefficient $C_T$, the output power coefficient $C_P$, and the tip speed ratio $\lambda$ are obtained by the following equations (1) to (3).
**Figure 1.** Theory of operation of Darrieus turbine

**Figure 2.** Experimental turbine

**Figure 3.** Experimental Waterway

**Figure 4.** Darrieus turbine set up with inflow guide

**Figure 5.** Inflow guide angle
\[ C_T = \frac{T}{\rho V^2 BD} \quad (1) \]
\[ C_P = \frac{P}{\sqrt{2} \rho V^3 BD} \quad (2) \]
\[ \lambda = \frac{U}{V} \quad (3) \]

Where, \( \rho \) is the water density, \( R \) is the radius of pitch circle of the turbine, \( B \) is the blade span, \( D \) is the diameter of Darrieus runner pitch circle, and \( V \) is the inlet water velocity to the turbine. The torque coefficient \( C_T \) is obtained by dividing the water turbine shaft torque \( T \) by the axial thrust. The output coefficient \( C_P \) is obtained by dividing the water turbine shaft power \( P \) by the kinetic energy of water. The tip speed ratio \( \lambda \) is obtained by dividing the tip speed \( U \) of the water wheel by the water turbine inlet velocity \( V \). The efficiency \( \eta \) of the water turbine is obtained by the following equation (4).

\[ \eta = \frac{T \omega}{\rho g Q H_t} \]

Where, \( H_t \) is the total water head, which is obtained by the following equation (5) in consideration of the dynamic pressure.

\[ H_t = (h_u - h_d) + \left( \frac{V_u^2}{2g} - \frac{V_d^2}{2g} \right) \]

Where, \( h_u \) is the upstream water head, \( h_d \) is the downstream water head, \( V_u \) is the upstream flow velocity, and \( V_d \) is the downstream flow velocity.

3. Results and discussions

3.1. Inflow guide effect

The performance test was conducted with a water inflow guide installed upstream of the Darrieus-type turbine inlet as shown in figure 4. The experiment was tested under four conditions, (1) without inflow guide which called base condition, (2) with only following side for turbine rotational direction where the water flow comes same turbine blade moving direction, (3) with only heading side for turbine rotational direction where the water flow comes opposite turbine blade moving direction, (4) with both side inflow guide which was V-shape inlet nozzle. The inflow guide was used 300mm flat plate. The angle of the inflow guide plate was about 85 degrees for the vertex of triangle as shown in figure 5.

Figures 6, 7 and 8 show the results of performance test with inflow guide. Figure 6 shows output power \( P \) and tip speed ratio \( \lambda \) comparing with four conditions. As shown in figure 6, maximum output power was obtained when a flow guide was installed on the heading flow side. On the other hand, output power was reduced when a flow guide was installed in the following flow side and both side.

Figure 7 shows torque coefficient \( C_T \) and tip speed ratio \( \lambda \) comparing with four conditions. As shown in figure 7, torque coefficient divided into two patterns. One of them is the base condition and heading side inflow guide installed condition. These torque coefficients obtained higher than the other conditions which is both side and following side conditions. From these results, it is considered that the flow direction is important for obtaining a large torque. In order to obtain large torque, it is considered that the optimal attack angle required for the turbine blade lift force.

Figure 8 shows efficiency \( \eta \) and tip speed ratio \( \lambda \). As shown in figure 8, the trend of the curve is similar to the output power. Because the efficiency is the ratio of the obtained power to the theoretical power. The maximum efficiency is just only about 15 % when a flow guide was installed on the heading flow side. Despite low efficiency, the advantage of the Darrieus-type turbine is its simple structure and low cost.
Figure 6. Output power with inflow guide

Figure 7. Torque coefficient with inflow guide

Figure 8. Efficiency with inflow guide

Figure 9. Output power comparing guide angle

Figure 10. Torque coefficient comparing guide angle

Figure 11. Efficiency comparing guide angle
As our expected before experiment, maximum output power would be obtained when a both side inflow guide was installed. Because, it was expected the water flow velocity would be increased due to the water way width narrowing. However, from the observation for the water flow in the experiment, the water flow was stagnant when the water way narrows. In open flow, it became clear that the effect of increasing the water flow velocity cannot be expected by narrowing the water way width. Preferably, inflow guide should be installed on the heading side where the water flow comes opposite turbine blade moving direction. It is important for the water flow at the optimal angle of attack in order to increase the lift force of the turbine blade.

3.2. Optimum inflow guide setting

In the previous section, since the higher performance obtained when the inflow guide installed on the heading side, the optimum inflow guide setting was tested. The experiment was tested under four conditions, (1) without inflow guide which called base condition, (2) the angle of the inflow guide plate was 80 degrees, (3) 75 degrees and (4) 70 degrees for the vertex of triangle.

Figures 9, 10 and 11 show the results of performance test with changing guide blade setting angle. Figure 9 shows output power $P$ and tip speed ratio $\lambda$. When the inflow guide was installed, the higher output power was obtained compared to base condition. It seems to be no big difference, when the angle of the inflow guide plate was 75 degrees, the maximum power was obtained.

Figure 10 shows torque coefficient $C_t$ and tip speed ratio $\lambda$. It seems almost the same curve was obtained when the tip speed ratio was lower than two. When the tip speed ratio was upper than two, the torque was different for each conditions, the maximum torque was obtained 75 degrees condition.

Figure 11 shows efficiency $\eta$ and tip speed ratio $\lambda$. As shown in figure 11, the trend of the curve is similar to the output power. The maximum efficiency is about 15.5 % when a flow guide was installed on the heading flow side. Although the efficiency is relatively low, if the water turbine operate continuously in small water way, by increasing the number of unit, total obtained energy might be relatively large.

From the above results, it was concluded that the optimum setting was 75 degrees of the angle for the inflow guide plate. It seems to be optimum attack angle to increase the lift force of the turbine blade.

4. Conclusions

The purpose of this study is to investigate for performance improvement of compact Darrieus-type hydraulic turbine for extra low head hydropower applications in a small waterway by experiment. In this study, the inlet shapes were changed to increase inflow velocity and to contribute improvement of efficiency. The obtained conclusion is as follows.

- As a results of the performance test with a water inflow guide installed upstream of the Darrieus-type turbine inlet, the maximum power and efficiency was obtained when a flow guide was installed on the heading flow side. On the other hand, output power was reduced when a flow guide was installed on the following flow side and both side.

- In a result of the torque coefficient, when the condition without inflow guide and with installed inflow guide in the heading side, the torque coefficient was obtained higher than the other conditions. It is considered that the flow direction would be important which depends on the attack angle for the turbine blade lift force.

- As for the V-shape inlet nozzle which the both side inflow guide was installed condition, our expecting was higher than the other conditions. However, the performance of the V-shape inlet nozzle was not high, since the water flow was stagnant when the water way narrows. In open flow, the effect on increasing the water flow velocity cannot be expected by narrowing the water way width.

- As a results of the experiment with changing the angle of the inflow guide plate, the optimum setting could be obtained in 75 degrees. It is important to be optimum attack angle to increase the lift force of the turbine blade.
In the next step, further performance improvement will be needed for practical use. Not only the inlet conditions but also the other conditions such as outlet nozzle, rectifier blade, drain pipe and so on would be investigated.

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