Experimental Study on Performance of Undershot Water Wheel in Snow Drainageway at Shiramine District by Field Test

Yoshitaka KIKUCHI¹, Takahiro KIWATA², Shinya WATADA¹ and Takaaki KONO²

¹Graduate School of Natural Science and Technology, Kanazawa University, Kanazawa 920-1192, Japan
²Research Center for Sustainable Energy and Technology, Kanazawa University, Kanazawa 920-1192, Japan

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Abstract: The performance of an undershot micro water wheel for the power generation in a snow drainageway was investigated by the field test. The power coefficient of water wheel with arc blades is better than that with the straight blades. The peak value of maximum power coefficient $C_{p_{\text{max}}}$ depends on the submerged blade height $h_c/D$, and it is found that the power coefficient of the water wheel with arc blades of $\beta = 30^\circ$ is larger than the other inlet angle.

Keywords: Water wheel, Hydroelectric power generation, Snow drainageway, Field test, Arc blade, Straight blades

1. Introduction

Hydropower provides about 42 percent of all renewable energy in Japan [1]. Both small and large hydroelectric power is one of the most promising renewable energy resources to avoid the global warming caused by greenhouse gases. Various types of hydroelectric power generator [2] have been developed, e.g. Pelton turbine, Francis turbine, propeller turbine, Savonius turbine and cross-flow turbine. Micro-scale hydroelectric power generation is expected to provide an independent and dispersed power supply for harnessing hydro-energy of small-sized rivers and agricultural waterways. The micro-scale hydroelectric power generation with the undershot water wheel by the water current can be constructed at lower cost. There is a lot of candidate sites for construction in Japan [3].

The snow drainageway is developed in a region with heavy snowfalls in Northern Japan. Figure 1 shows the scene of winter at Shiramine district near Mt. Hakusan in Ishikawa Prefecture. This area is one of the heaviest snowfall areas in Japan. As shown in Fig.2, the snow drainageway, which has a shallow and fast flow, is utilized to remove the snow surrounding houses and on roads in winter [4]. Sapporo City has also the snow drainageway. The flow of drainageway in Shiramine and Sapporo is the supercritical flow. Therefore, the snow drainageway is suited for a micro hydroelectric generation. The electric power by micro hydroelectric generation is expected for the power supply of the snow melting system (Fig. 3), and the emergency electric battery and so on. The hydroelectric power generation with the undershot micro water wheel can be set up on the waterway without a large-scale improvement work. In addition, the snow chunk can throw into the waterway while the water wheel rotates, so we adopted the undershot waterwheel. Katayama et al. [3] carried out an experimental investigation of the effect of the number and the thickness of blades, and the flow conditions on the performance of an undershot open cross-flow turbine. (Maximum power coefficient is 0.40). They found that the power coefficient changed drastically with varying impinging flow thickness and runner installation height. Nishi et al. [5]-[7] studied numerically and experimentally to develop an undershot cross-flow turbine with a very low head suitable for application to open channels (Maximum power coefficient is 0.38). They suggested that the output power of the straight blades runner was greater than that of the curved blades runner regardless of the rotational speed.

The objective of the present study is to optimize the shape of the blade of a micro undershot water wheel that can be generated electricity in the snow drainageway. The effects of the shape of blades and the inlet angle $\beta$ of arc blades on the power of the undershot water wheel were investigated by the field test in the snow drainageway. The effect of submerged height of blade $h_c$ was also investigated to reach the stage of practical use.

2. Experimental Apparatus and Method

Figures 4 and 5 show the overview of micro-scale hydroelectric power generation, and the dimensions of the undershot water wheel and the snow drainageway, respectively. The snow drainageway is made of the reinforced concrete, which has been used since 40 years ago.

Fig. 1 Main Street of Shiramine district in winter
Fig. 2 Snow drainageway with a rectangular holes and ultrasonic displacement sensor
Fig. 3 Snow melting system by circulation warm water and kerosene fuel for a roof

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The snow drainageway has rectangular holes with length of 900 mm and width of 600 mm to throw snow. The water wheel had a diameter of $D = 600$ mm and a width of $W = 410$ mm. The testing water wheel is composed of the blades with two circular end plates. Figures 6 show the cross section of two kind’s shape of blades, i.e. straight and arc blades. The straight blades were made of the aluminum. The number of straight blades $n$ was changed from $n = 6$ to $16$, and the blade height $d$ was changed from $d = 100$ mm to 200mm. The arc blades were made of the vinyl chloride resin. The chord length of arc blade was 100 mm, and the radius of curvature of arc blade was 77.7mm. The arc blade inlet angle $\beta$ was changed from $\beta = 0^\circ$ to $36^\circ$. The number of arc blades was $n = 12$.

Figure 7 shows a schematic diagram of experimental apparatus. The torque of the water wheel was transmitted to the power generator (Sky electronics, SKY-R250: Rated output 200 W) via a chain and sprockets with a speed ratio of 7 to 1. The power of water wheel $P = VI$, which was calculated from the output voltage $V$ and the output current $I$ of the generator, was measured in each case in order to calculate the power coefficient $C_p = P/(0.5\rho AA^3)$, $\rho$: water density, $A$: water receiving area ($= hW$), $h_c$: submerged blade height, $A$: depth-averaged velocity). The tip speed ratio of the water wheel $= \lambda = \pi DN/60U$, $N$: rotational speed of water wheel) was varied by the adjustable load-resistor ($R = 7 \Omega$ to 180 $\Omega$). The water level $H$ was measured using an ultrasonic displacement sensor (Keyence, UD-320) and a measuring rule. The water velocity $u$ was measured using an electromagnetic flow meter (NKS, PVM-3i).

3. Result and Discussion
3.1 Flow characteristic of the snow drainageway

Figure 8 shows the vertical distributions of velocity in the snow drainageway without the water wheel. The mean velocity increases gradually from bottom of the waterway to surface of water. The turbulence intensity $u'_{max}/U$ is smaller at $y/H < 0.5$ than that near the water surface. The depth-average velocity for $H = 99$ mm is $U = 2.51$ m/s, which was calculated by integrating the mean velocity distribution in the center of a waterway. The depth-average velocity computed from three-point method is $U = 2.55$ m/s. The value of depth-average velocity by three-point method is almost the same as that by the integral value of velocity distribution. Therefore, the relation of the depth-average velocity $U$ to the water depth $H$ can be gotten by three-point method. Figure 9 shows the depth-average velocity $U$ represented as a function of the water depth $H$. The solid line was determined from least-squares method. The depth-averaged velocity $U$ was calculated from the water depth $H$ for the experiment of the performance of the undershot water wheel. In the snow drainageway of Shiramine, the Froude number is $F = U/(gh)^{0.5} \approx 2.6$. This flow becomes the supercritical flow owing to $Fr > 1$.

Figure 10 shows the frequency distribution of water level during 5th months from July to November in 2014. The water level $H$ varies in the range from 100 mm to 250 mm. The water level $H$ is most often 220 to 230 mm, accounting for about 25% of the total. The hydro-energy of the water current in the snow drainageway at $H = 230$ mm is approximately 4 kW. Figure 11 shows the variations of water level on sunny and rainy days. The fluctuation of the water level on the sunny day is within a 5 mm. On the other hand, when rain started, the water level increased approximately 2.5 times. So we have to pay attention to the weather in the experiment.
3.2 Effects of number and height of blades

In order to investigate the influence of the number of blades \( n \) on the power performance, the experiment was carried out with the straight blade height \( d = 100 \text{ mm} \) and the submerged blade height \( h_c/D = 0.12 \). Figure 12 shows the power coefficient \( C_P \) and the torque coefficient \( C_T \) for the tip speed ratio \( \lambda \). Figure 13 shows the variations of maximum power coefficient \( C_{P\text{max}} \) and the tip speed ratio at maximum power coefficient \( \lambda_{C_{P\text{max}}} \) with the number of blades \( n \) (\( d = 100 \text{ mm}, h_c/D = 0.12 \)).

The tip speed ratio \( \lambda \) at the maximum power coefficient is approximately 0.4. The water wheel with 8 and 12 blades has high power coefficient in the wide range of the tip speed ratio. The maximum power coefficient \( C_{P\text{max}} \) is approximately 0.19. As the tip speed ratio \( \lambda \) increases, the torque coefficient \( C_T \) tends to be decreasing. The maximum torque coefficient is 0.57 at the number of blades \( n = 12 \) for \( \lambda = 0.27 \). Figure 14 shows the quarter part of water wheel and the equation of the fluid force for the water wheel with \( \theta = 90^\circ \) is obstructed by the front blade before it receives maximum fluid force. On the other hand, the power for the water wheel with \( n = 8 \) decreases as the number of blades decreases, since the front blade does not obstruct the flow to the rear blade before it receives maximum fluid force.
about 110 N. Figure 16 shows the integration of the fluid force in the range of the submerged blade height. The integration of the fluid force for the water wheel with \( n = 8 \) is larger than the other number of blade. The power for the water wheel with \( n > 8 \) decreases as the number of blades increases, since the front blade obstructs the flow to the rear blade before it receives maximum fluid force. On one hand, the power for the water wheel with \( n < 6 \) decreases as the number of blades decreases, since the front blade receives the fluid force after the rear blade receives maximum fluid force. Thus, the water wheel has an optimum number of blade.

Next, the influence of the blade height \( d \) on the power performance was evaluated. The experiment was conducted by varying the blade height \( d = 100 \) mm, 150 mm and 200 mm. Number of blades was \( n = 8 \) and the submerged blade height was \( h_c/D = 0.15 - 0.16 \). Figure 17 shows the power coefficient \( C_p \) and the torque coefficient \( C_T \) for the blade height \( d \). Figure 18 shows the variations of maximum power coefficient \( C_{p\text{max}} \) and the tip speed ratio at maximum power coefficient \( \lambda_{C_{p\text{max}}} \) with the blade height \( d \). The power coefficient \( C_p \) decreases with a decrease in blade height \( d \). The tip speed ratio \( \lambda \) at the maximum power coefficient is approximately 0.4. The power coefficient of the blade height \( d = 100 \text{ mm} \) has larger than the other height of blades. The torque coefficient \( C_T \) also had a similar trend. Especially, the power coefficient at \( d = 200 \text{ mm} \) was lower than the other one.

Figure 19 shows the effects of the submerged height of blades \( h_c/D \) on the power coefficient \( C_p \) and the torque coefficient \( C_T \) at the number of blades \( n = 12 \) and the blade height \( d = 100 \text{ mm} \). Figure 20 shows the variations of maximum power coefficient \( C_{p\text{max}} \) and the tip speed ratio at maximum power coefficient \( \lambda_{C_{p\text{max}}} \) with the submerged height \( h_c/D \). The power coefficient of the submerged height \( h_c/D = 0.117 \) becomes larger than the other submerged height of blade. The tip speed ratio that indicates the peak of the power coefficient is decreased. The maximum power coefficient of the water wheel is 0.18 at \( h_c/D = 0.117 \). As shown in Figs. 14, 15 and 16, the power of water wheel is related to the submerged water height of blades. The power coefficient for the water wheel increases as the submerged water height decreases, since the front blade does not obstruct the flow to the rear blade before it receives maximum fluid force.

We also observed the effect of snow on the rotating water wheel. The snow chunk was thrown into the snow waterway...
at 20 m upstream from the water wheel with 16 blades. The volume of snow chunk is about 0.012 m³. The power output is shown in Fig.21. Although the power output falls instantaneously due to the collision of snow at $T = 58, 75, 110, 129, 151, 177$ and $189$ s, the operation of the water wheel does not stop, and the power output recovers quickly. Thus, there was no problem in operation of water wheel when snow was thrown into the snow drainageway.

### 3.3 Effect of the shape of blades
To compare the performance of water wheel with the straight and the arc blades, the variation of power coefficient $C_P$ with tip speed ratio $\lambda$ is shown in Figure 22. Although the blade inlet angles $\beta$ of the straight and the arc blades is different, i.e. $\beta = 90^\circ$ and $\beta = 36^\circ$, the angle between a chord line of arc blade and tangent line to circle of water wheel is close to a right angle as shown in appended figure. For the all tip speed ratio, the power coefficient $C_P$ with the arc blades is higher than that with straight blades. The maximum power coefficient $C_{P\text{max}}$ with straight blades is 0.18 at $\lambda = 0.39$, and the $C_{P\text{max}}$ with arc blades is 0.25 at $\lambda = 0.47$. Therefore, the performance of water wheel with arc blades becomes better than that with the straight blades. This result is different from Nishi’s results. It is inferred that this difference is caused by the flow condition, i.e. the subcritical flow or the supercritical flow.

### 3.4 Effect of the inlet arc angle $\beta$
The influence of the blade inlet angle $\beta$ on the power
When snow was thrown into the snow drainageway, the wheel does not stop, and the power output recovers quickly. As shown in Figure 21, the operation of the water wheel is instantaneous due to the collision of snow at inlet angles of 90°, 75°, 61°, 58°, 53°, 43°, 36°, 30°, and 6°. Although the power output falls with the arc blade inlet angle of β = 30°, the angle between a chord line of arc blade height hc/D = 0.102 to 0.201 at the tip speed ratio λ = 0.4. The power coefficient CPmax on the power coefficient CPmax with the arc blade inlet angle β = 30° and 36°, the performance of water wheel with arc blades is better than that with the straight blades. This result is different from the field test of power of the undershot micro water wheel carried out in the snow drainageway at Shiramine district. The effects of the shape of blades, the inlet angle of arc blade β and the submerged blade height of blade h/D on the performance of water wheel were investigated. The experimental results of the water wheel are applied to the supercritical flow with Fr > 1. The following conclusions can be drawn:

1. The power coefficient of water wheel with arc blades is better than that with the straight blades.
2. The peak value of maximum power coefficient CPmax depends on the submerged blade height h/D, and the power coefficient of the water wheel with β = 18° - 36° is larger than that with β = 6°.

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References

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**Fig. 27 Appearance of the rotating water wheel in the snow drainageway (Arc blade, h/D = 0.201)**

**Fig. 28 Variations of maximum power coefficient CPmax with submerged height h/D (Arc blade)**

