NEW WATERWHEEL BLADES FOR POWER GENERATION IN KUROSHIO

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Kuroshio, one of ocean currents in the Pacific, passing through the eastern Taiwan provides a kind of clean ocean energy. For collecting Kuroshio power, we need to build high performance turbine generators suitable for flow speed less than 1.5 m/s. Conventional blades of waterwheel turbine are usually fixed to the rotating disk, and this leads to retard the rotation of the rotating disk due to the counteraction of the thrust. In this study, we present a new waterwheel blade, solar-planetary type blades, to upgrade energy conversion efficiency. A preliminary experiment was conducted at Gia-nan irrigation ditch located on the downstream of Wushantou dam in Taiwan. Experimental results indicate that waterwheel apparatus with solar-planetary type blades can raise the output power from 3.3 kW to 13.8 kW when the flow speed varied from 0.5 m/s to 1.2 m/s. The power coefficient is 1.22 and power output reaches 7.51 kW at 1.0 m/s water velocity. Compared with fixed type blades, the proposed rotatable blades can improve the power generation efficiency and enhance energy conversion efficiency.

Keywords: Solar-planetary, Blade, Current turbine, Kuroshio, Energy conversion efficiency.

1. Introduction

Due to excessive use of fossil fuels causing the environmental problems and exhausted energetic resources, the exploitation of clean and renewable energy becomes urgent all over the world. As an unfledged member of the renewable energy family, ocean energy having the higher density compared with wind energy is more potential and effective for power generating. Nowadays, four ocean energies including ocean current power, thermal power, tidal power and wave power are usually chosen to exploit electric energy. Among them, ocean current energy is converted into kinetic form when the water mass moves along a given route, such as Kuroshio, with stable flow velocity.

Kuroshio is the maximum ocean current in the north Pacific, passing through the east of Taiwan, with a band of 120 km ~170 km in width. As Kuroshio flows between the eastern coast of Taiwan and Green Island, the flow speed is pretty stable with 1.0~1.5 m/s and the flow capacity is about 20.7~22.1 Sv (Johns *et al.*, 2001), where Green Island is a small volcanic island in Pacific ocean, about 33 km off the eastern coast of Taiwan. Estimated reserves of Kuroshio power near the coast of Green Island are at least 30 GW (Hsu *et al.*, 1999; Chen, 2010; Tang, 2010).

Previously, it was difficult to exploit ocean energy from the sea technically because of the difficulties in constructing equipment in such a harsh environment. Recently, some water turbine generators have been operated to generate power (Anderson, 2006; Khan, 2008; Kuo, 2008; Sornes, 2010) but the flow speed of water needs to greater than 2.0 m/s in general. Commercially, up to now, no waterwheel turbine generators can capture Kuroshio energy to generate electricity due to low flow speed (less than 1.5 m/s). In order to extract higher power output from the fluid flow, we had better construct a suitable system to increase the flow velocity. From the experiment of wind turbines, current turbine combined with augmentation channels (ducted or diffuser-augmented current turbines) have some potential advantages of increasing power output and reducing turbine and gearbox size for a given power output. (Ponta and Dutt, 2000; Setoguchi,

2004; Kirke, 2005; Ponta and Jacovkis, 2008).

Here, we concentrate on an improvement of waterwheel blades in ducted current turbine suitable for Kuroshio near Green Island with flow speed of 0.9 m/s~1.5 m/s. We first present a new blade type of water turbine, and calculate the power output by using Fluent software (computational fluid dynamics, CFD) at 1.0 m/s flow. A prototype waterwheel turbine was placed in on-site irrigation ditch with 19.2 m in width and 4 m in depth. Finally, we compare the numerical results with the experiments by discussing energy conversion efficiency of power output.

2. New Waterwheel Blades in Kuroshio

To overcome climate effect and capture stably ocean current flow, the waterwheel apparatus needs to be put in seawater at about 20 m to 60 m deep when applied for Kuroshio power generation in Taiwan. While a conventional waterwheel apparatus is applied to underwater shown in Figure 1, the blades in the lower part directly face the water flow, and bear the maximum thrust. However, as they are fixed to the rotating disk, the back surface of the blades in the upper part that faces the water flow, so the thrust borne by the blades in the upper part and the thrust borne by the blades in the lower part are in opposite directions, which hinders the
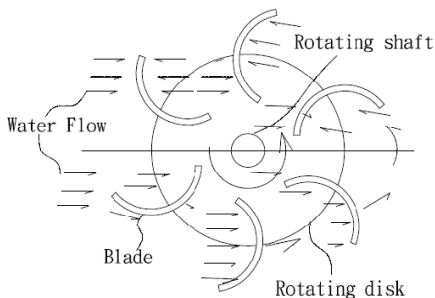

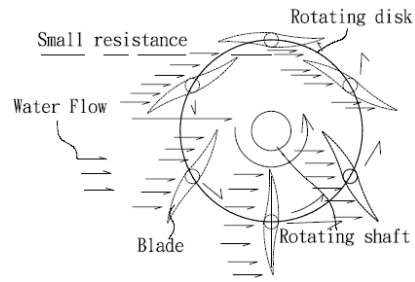Fig. 1. Conventional waterwheel apparatus submerged in water.

Fig. 2. Waterwheel with solar-planetary type blades submerged in water.

rotation of the rotating disk. As a result, the efficiency of the waterwheel apparatus is compromised. Here, a waterwheel apparatus with solar-planetary type blades is proposed to solve the above problems.

A new waterwheel apparatus includes a frame, at least one solar-planetary type blade assembly, and a power unit. The solar-planetary type blade assembly is fixed to the frame shown in Figure 2.

In Figure 2, the solar-planetary type blade assembly includes a rotating disk, a central fixed portion, a plurality of blades, and a transmission mechanism. The rotating disk is capable of rotating relative to the central fixed portion. The blades are pivoted to the rotating disk, and capable of rotating relative to the rotating disk. The transmission mechanism is located between the rotating disk and the central fixed portion for transmitting power between the rotating disk and the central fixed portion, so that the blades can spin and also revolve around the central fixed portion. The power unit has an axle center, and the axle center rotates together with the rotating disk. The waterwheel is designed to work on Kuroshio, and, to speed the flow velocity, the current turbine is surrounded by diffuser (or duct).

After a water flow enters the duct, the blade of waterwheel not only revolves around the rotating disk, but also spins itself to change the angle in contact with the water flow. Therefore, the blade on the top is horizontally disposed with only one end facing the water flow. At this point, the

blade bears a rather small tangential thrust, and almost does not hinder the rotation of the rotating disk. Afterward, the blade gradually moves to the bottom with the rotation of the rotating disk and returns to the perpendicular state, the tangential thrust borne thereby is also increased accordingly. Because the blade does not bear any tangential thrust at the top position, but bears a tangential thrust at any position below the top position. When the new waterwheel apparatus is used to generate power, the solar-planetary type blade assembly achieves higher power generation efficiency than the conventional waterwheel apparatus does shown in Figure 1.

Further, the horizontal solar-planetary blade on the top of waterwheel will reduce the volume space of the diffuser, and this apparatus has a smaller impact on the velocity of the ocean currents, thereby reducing the damage caused by the ocean currents to the natural environment.

3. Calculation of Energy Output

Ducted water current turbine shown in Figure 3 consists of two waterwheels, and each waterwheel has 9 blades with equiangular distribution along the edge of rotating disk. The chord line length and span width of blade are 334 mm and 4000 mm,
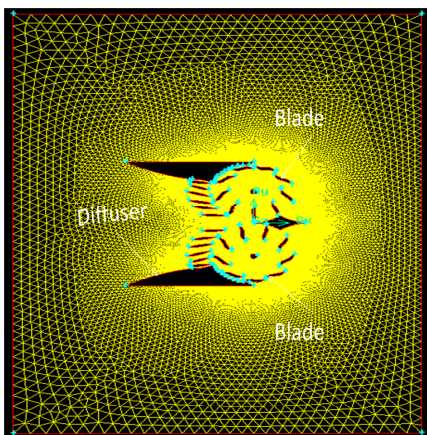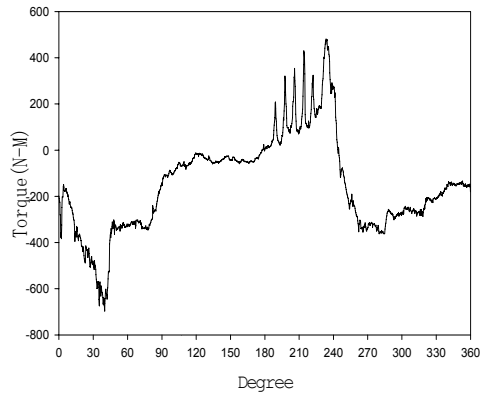
Fig. 4.   Output torque of single blade.

respectively. The chord line length of inlet is 2580 mm and rotation diameter of blade is 999 mm. Two-dimensional (2-D) unstructured mesh grids have been used to divide the computational domain (8.1×6.7 m^2) into small control elements with total 1.7×10^5 nodes.

We use Fluent to simulate the thrust of the blade and the energy output of ducted water current turbine at the inlet velocity of 1.0 m/s. At this moment, revolution speed of turbine is 15 rpm. Figure 4 indicates the output torque of single blade with rotation from 0 to 360 degrees. The negative value of torque means a positive work done by the blade. Obviously, the rotated angle of blade at about 40-degree measured from vertical position provides the maximum torque to the turbine. Revolution speed of turbine with 15 rpm represents 4 seconds to rotate one period of waterwheel. Figure 5 shows average output torque of 9 blades in one period, and average output torque T is 2689.47 N-m. As input rotation speed $N = 15$ rpm to the power formula $P = TN/9551$, we calculate the total output power of ducted water current turbine to be 4.22 kW. We need to check this power output accompanying with theoretical value and experimental output.

Theoretically, the energy flux of the water stream is dependent on the density, cross-sectional area and velocity cubed
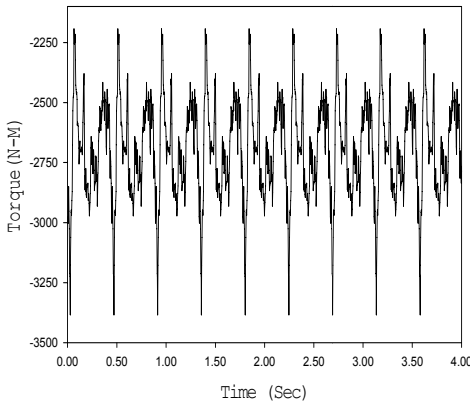
Fig. 3.   Ducted waterwheel apparatus meshed by two-dimensional unstructured elements.

Fig. 5.   Average output torque of nine blades.

(Khan *et al.*, 2009), with the form as follows.

$$P = \frac{1}{2} \ \rho A \ (f_C V)^3 \qquad (1)$$

where P = power, ρ = water density, f_c = power coefficient, A = turbine area, and V = velocity of water. Here, ducted turbines are not subject to the so-called Betz limit, which defines an upper limit of 59.3% of the incident kinetic energy that can be converted to shaft power by a single actuator disk turbine in open flow (Kirke, 2005).

Pressure diagram of ducted water current turbine is shown in Figure 6, with the unit of Pa. In Figure 6, the flow pressure
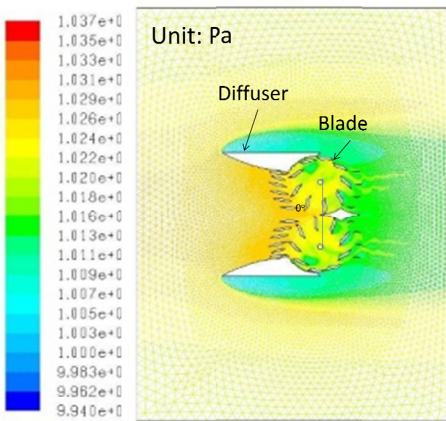

Fig. 6.   Pressure ducted waterwheel turbine at 1.0 m/s flow speed.

around duct inlet (orange color) is greater than that (green color) duct outlet. Rotation speed of turbine is fast if pressure difference between inlet and outlet becomes large. It seems that this ducted current turbine does not have much turbulent nearby.

4. Experiments

A preliminary on-site test was conducted at Gia-nan irrigation ditch located on the downstream of Wushantou dam in Taiwan. This irrigation ditch is 19.2 meters in width and 4 meters in depth, shown in Figure 7. In Figure 7, water depth kept 3.15 m and four flow speeds of duct inlet were assigned to test the turbine: 0.5 m/s, 0.7 m/s, 1.1 m/s and 1.2 m/s, respectively, with measured position under the water of 1.0 m. Inlet section for water turbine is 4.6×2.58 m^2. Figure 8 shows a prototype of diffuser-augmented water current turbine before submerged in the water. The main components of water current turbine were completely submerged in the ditch except the accelerator and generator.

A generator of 15 kW/125 rpm connected to the ducted water turbine was chosen to measure voltage and electric current. From power formula, P (kW) = $1.732 \times V(Volt) \times I$ (Amp), we calculate power output. By adjusting the frequency of the generator and the rotational velocity of turbine to obtain an optimum operation, power output of the generator at different flow
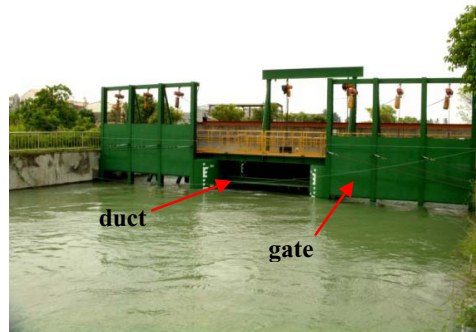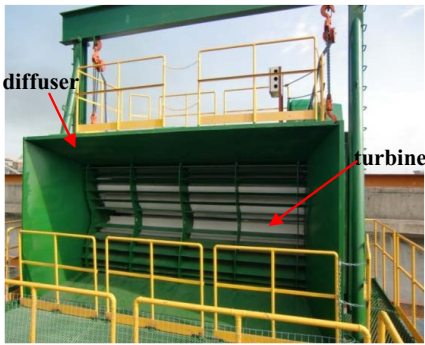

Fig. 7.   Test site assembly.

Fig. 8.   Ducted water current turbine.

Fig. 9.   Power output and rotational speed.

Table 1.   Power output of generator.

(at 0.5 m/s Flow)			(at 0.7 m/s Flow)		
Freq.	rpm	kW	Freq.	rpm	kW
18	45.0	1.7	23	57.5	2.7
25	62.5	2.0	28	70.0	3.5
31	77.5	2.9	42	105.0	4.5
38	95.0	**3.3**	55	137.5	**5.6**
48	120.0	2.3	61	152.5	5.2
65	162.5	1.8	71	177.5	3.8

(at 1.1 m/s Flow)			(at 1.2 m/s Flow)		
Freq.	rpm	kW	Freq.	rpm	kW
36	90.0	6.5	45	112.5	9.2
45	112.5	7.5	60.5	151.25	12.2
61	152.5	9.2	76	190.0	**13.8**
68	170.0	**10.0**	95	237.5	11.5
82	205.0	8.7			

speeds is shown in Table 1 and Figure 9. Figure 9 shows how we conducted the performance experiment in the ditch. While the flow speed varied from 0.5 m/s to 1.2 m/s, the output power raised from 3.3 kW to 13.8 kW as well. Though the power is not proportional to the cubic of flow velocity, this deviation could be resulted from the flow meter. Maximum power output at 1.1 m/s flow shown in Table 1 is 10 kW.

5. Results and Discussion

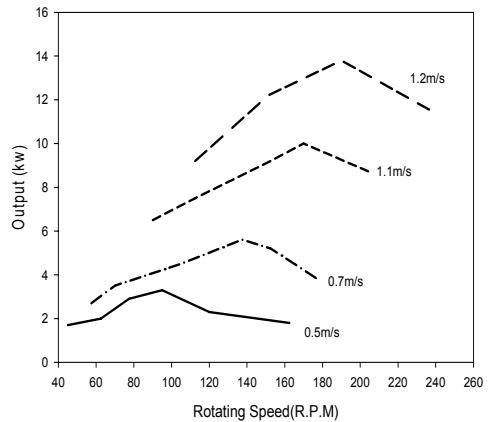Let power coefficient $f_c = 1$ in Eq. (1), and the parameters $A = 10.32$ m², $\rho = 1025$ kg/m³, $V = 1.0$ m/s, the theoretical output power is 5.29 kW. From the numerical result of CFD, the output power of ducted water current turbine is 4.22 kW. Meanwhile, we can get the output at flow speed 1.0 m/s by converting the output 10 kW at flow speed 1.1 m/s in Table 1, and the result at 1.0 m/s is 7.51 kW.

Comparisons of power output at flow speed 1.0 m/s, the experimental power output is $7.51/4.22 = 1.78$ and $7.51/5.29 = 1.42$ of the numerical and theoretic output, respectively. A power coefficient reaches 1.22 and is exceeding the Betz limit of 0.59 due to the use of diffuser device. Compared with Ponta (2000) and Khan *et al*. (2006), where a maximum velocity increase factor of 1.67 was reported, the velocity increase factor of 1.22 in ducted waterwheel current turbine with solar-planetary type blades is acceptable.

6. Conclusions

A new ducted waterwheel current turbine with solar-planetary type blades is developed, and its power coefficient reaches 1.22 at flow velocity 1.0 m/s. The power output is 7.51 kW. This water current turbine is suitable for power generation in Kuroshio, or in low velocity of water.

Acknowledgments

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