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The effects of blade number and turbine baffle plates on the efficiency of free-vortex water turbines

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Abstract. This article presents the results of the study on the effect of blade number and turbine baffle plates on the efficiency of a free-vortex water turbine. The laboratory experimentation performed to determine the power generation efficiency. The 2 to 7 blade water turbines were built and tested to find the most appropriate number of blades, and the result showed the 5 blade turbine being appropriate because it yields the highest torque from receiving impact from water flow. Next, the baffle plates were designed and attached to the top and bottom of the turbine blades. Four different sizes of space from 25% to 100% of the curve area around the blades were used. Experiments were carried out at the water flow rates of 0.04 to 0.06m3/s. The finding showed the 50% proportion of the curve area being most appropriate, and the blades installed with top and bottom baffle plates had the highest efficiency of 43.83%, which was 6.59% higher than without baffle plates. It was also found that when the water flow rate increased, the system efficiency became higher.

1. Introduction

It is widely known that water is a clean energy source that does not create environmental pollution. However, there is a present constraint in hydrological power generation since it requires construction of a large dam, which has a great impact on the natural environment around the dam. Still, power generation from a river or a small water resource where water flows all year round is an alternative energy production that receives increased interest. There are now 2 methods of small-scale hydrological power generation. The first is the Bypass Method that diverts water from the main feed canal to the constructed power generation system. The second is the Open Canal Method, which involves installation of the generator across the canal without any other additional structure.

The advantage of the Bypass Method in electricity generation is that after the process is completed, the water can be discharged back to its original source and can still be used for other purposes. Nowadays, more and more researchers become interested in conducting a study of this method, for instance, power generation from free-vortex water flow or from a screw-type water turbine. The free-vortex water flow system is a system from which electricity is generated by the centrifugal flow of water through a cylindrical vortex pool that has a water outlet or hole at the bottom center. This system generates electricity at low head water, relying on the vortex flow of water, the velocity of which is accelerated by gravity at the outlet. This system was first studied by Franz Zotloterer, who built a low-head power plant based on the principle of the kinetic energy of vortex flow of water in the pool. Additional studies were later conducted on vortex water flow in the pool [1-2] and generation of power from the free vortex flow of water in a cylindrical pool [3-5]. The study showed that the outlet or discharge hole should be 0.2-0.3 times of the diameter of the pool, where free vortex occurs [6]. There are other research studies conducted on different variables affecting power generation from free-

vortex water flow based on Computational Fluid Dynamics, which demonstrated that at the highest flow, the turbine efficiency is 40% at the speed between 28 and 38 rpm [7]. A laboratory experiment showed the highest overall efficiency of 30% at the turbine speed of 40-50 rpm [8].

Additionally, there were studies of different approaches to increase the efficiency of a free-vortex water turbine such as the change of blade material, modification of the vortex pond's shape or the change of the blade design. Dhakal et al. studied the structural analysis of the pool characteristics that will create vortex flow of water and increase the propelling force of the water turbine. This study found that a conical pool was able to increase the work efficiency. The highest percentage of efficiency, when compared to a cylindrical pool, was 9.09% at the flow rate of 0.01 m³/s and the height of 0.85 m [9-10]. Other research studies were conducted on the change of material used to construct the water turbine, and new materials used resulted in increase of power generation from the free-vortex water turbine. Sritram et al. found that after changing the material of the turbine from iron to aluminium, the power generation efficiency of an aluminium turbine was on average 8.14% higher than the former turbine [11]. Suntivarakorn et al. designed a turbine with a twisted angle and the turbine size that matches the vortex flow of water. This turbine could increase the efficiency of over 15% when compared to the former turbine [12]. In addition, it has been shown that the number of blades and adjustment or installation of supplementary equipment on the blades could increase the efficiency. The study of Savonius wind turbine installed with baffle plates could increase 36% higher turbine efficiency than the old turbine [13].

The assumption in this research was that if the number of water turbine blade is higher, the system efficiency should be higher. However, the past studies have not clarified the number of blades that affect the efficiency, nor if installation of baffle plates at the water turbine blades allows the turbine to receive the impact from water and increase the turbine efficiency. Thus, this study was interested in increasing the efficiency of small-scale power generation from a free-vortex flow of water through the study of impact from the number of blades and installation of baffle plates. The study was based on laboratory experiment. The objectives were to know the effect of the number of blades and the characteristics of the baffle plates installed on the efficiency of small-scale power generation from a free-vortex flow of water.

2. Equation of Calculation

2.1. Power and torque obtained from the turbine [14-17]
Real power obtained from water current (P_m) could be calculated by:

$$P_m = \rho g Q H \tag{1}$$

Torque (T) from the turbine could be found by:

$$T = \frac{60 P_m}{2\pi N} \tag{2}$$

When ρ = water density, 1,000 kg/m³, g = acceleration by gravity, 9.81 m²/s, Q = rate of flow (m³/min), N = revolutions of the shaft (rpm), and H = water head (m).

Calculation for efficiency could be done from the proportion between the real electrical energy obtained and dynamic energy from the equations:

$$\eta = \frac{P_e}{P_m} \tag{3}$$

$$P_e = EI \tag{4}$$

When E = voltage (V), I = current (A) and P_e = electrical power (W).

3. Equipment and Experimental Method

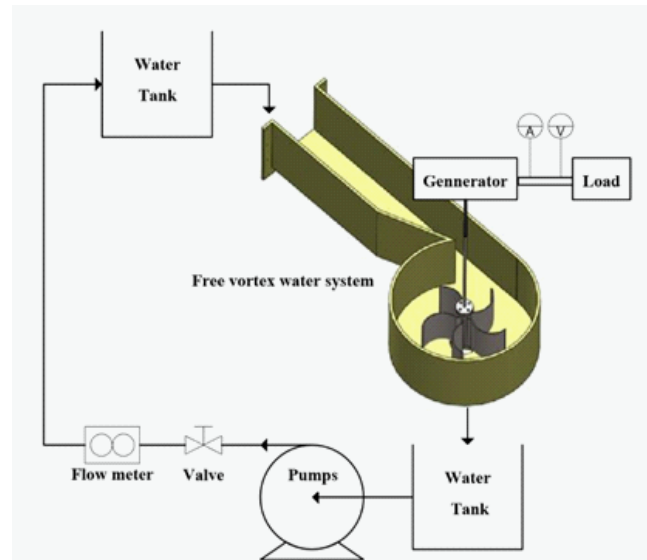### 3.1. Equipment for testing the free-vortex water system

Figure 1. Power generation from free-vortex water flow.

This study was performed on a small-scale power generation from a free-vortex water flow in the laboratory of Department of Mechanical Engineering, Khon Kaen University. The system is composed of an upper storage tank of 1.5×1.5×1.2 m connected with a gutter and a cylindrical pool 1 m in diameter and 1 m in height. There is a water outlet hole of 0.2 m diameter at the bottom of the pool and a water pump adjustable within 0.04-0.06 m^3/s. In Figure 1, the flow of water is pumped from a storage tank below through a flow rate control valve. The flow rate sonic gauge was used in order to control the rate of flow of water fed into the system. The water flows to the upper tank and then to the gutter before reaching the vortex pool. At the vortex pool, a turbine was installed with its shaft connected to the generator's shaft to generate electricity towards the load by means of the centrifugal force of the vortex in the pond. This load is exerted on the turbine. Then the water flows centrifugally to the lower water storage tank to be pumped back continuously for use in the experiment.
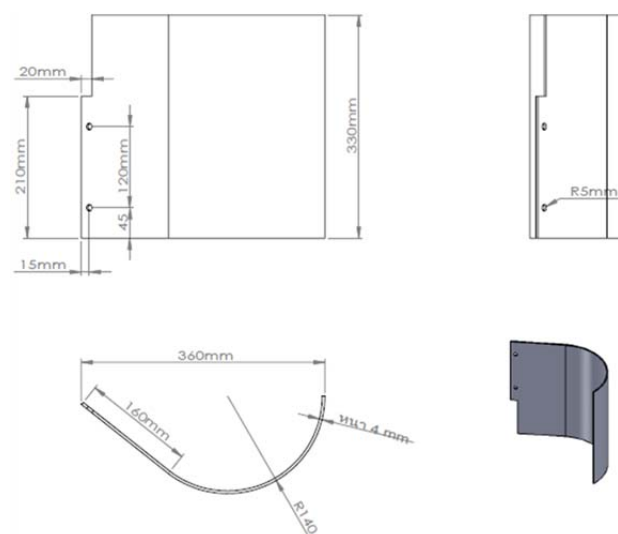

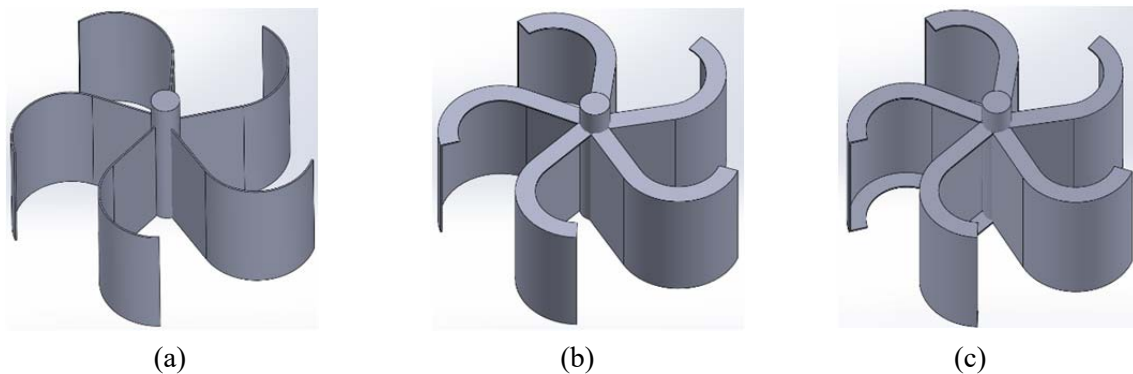**Figure 2.** The blades of the water turbine in the test.

(a)   (b)   (c)

Figure 3. (a) Turbine with no baffle plate, (b) Turbine with top baffle plates, (c) Turbine with top and bottom baffle plates

3.2. Blades

The turbine in the test has a diameter of 45 cm and a height of 32 cm. The blades were made of iron and are curved in the shape as shown in Figure 2. The blade numbers tested to find the turbine efficiency were 2 to 7 blades. After the suitable number was found, the baffle plates were installed at the blades to find the highest efficiency among the 3 cases tested: 1) blades with no baffle plate, 2) blades with top baffle plates, and 3) blades with both top and bottom baffle plates, as shown in Figure 3.

3.3. Experimental method

In the finding of the suitable number of blades for the water turbine, the efficiency of the turbine operation was tested with the turbine having from 2 to 7 blades. This was a laboratory test of power generation from a free-vortex water flow. Electrical load used consisted of four 25 W bulbs. The rate of water flow was set at 0.06 m^3/s. The load was connected with the power generation system, with the initial load of 25 W. The water head, revolution of the turbine, voltage and electric current from the generator were measured. Next, the load was increased to 50, 75, and 100 W. The experiments began on the performance of the turbine with 2 blades through to 7 blades. The results were calculated to find the torque and efficiency values, including water flow patterns in the turbine before the highest efficiency level and the most suitable number of blades determined.
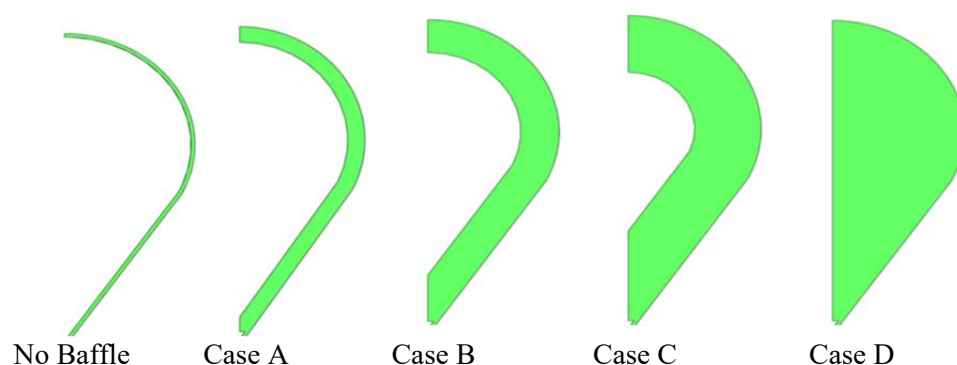

No Baffle   Case A   Case B   Case C   Case D

Figure 4. Proportion of baffles fit on 5 blades.

After knowing the suitable number of blades, the baffle plates were designed in 5 shapes. The proportions of the baffles to be attached to the blades were from 0% to 100% as shown in Figure 4.

The proportion of 100% means the surface area between both ends of the turbine was as stated in Table 1.

Wichian et al. studied the CFD program was used for the analysis of the right proportion of baffle plates on turbine blades. This study found that a water turbine Case B, with 50% proportion of baffle plate contact on the blades received impact that matched the mass distributed on the turbine [17].

Table 1. Showing correlation of space with baffle plates.

	No Baffle	Case A	Case B	Case C	Case D
Proportion of baffle fitting on blade (%)	0	25	50	75	100
Area of baffle plate (cm^2)	0	100.8	210.05	322.32	438.38

Next, the turbines were built for the experimental purpose with the number of baffle plates and proportion of fitting areas. Thus, there were 3 water turbines built for the testing: Case 1 turbine blades with no baffle plates; Case 2 turbine blades with top baffle plates; and Case 3 turbine blades with top and bottom baffle plates, as illustrated in Figure 3. In the experiment, the turbine blades with baffles were installed in the small power generation system using a small free-vortex flow of water. The efficiency of the turbine was found in the same way as in the finding of the suitable number of blades. The water flow rates in the experiments were set at 0.04, 0.05, and 0.06 m^3/s, and all of the three types of turbines were tested to find the flow force, turbine's torque, electricity and efficiency of electricity generation.

4. Results and Discussion

4.1. Effects of the number of blades on turbine's torque
The graph in Figure 5 shows the comparison of the torques obtained from the turbines with different numbers of blades (2-7 blades). The turbine with 5 blades produced the highest torque. This was consistent with the finding of Wanchat et al. who performed the test in a laboratory. In Figure 6, when the test was performed in the loads of 0-100 W, the turbine with 5 blades was still found to yield the highest torque. It can be concluded that the flow of water exerted on the turbine with different numbers of blades yields different torques. The turbine with 5 blades is the best to receive impact from water flow.
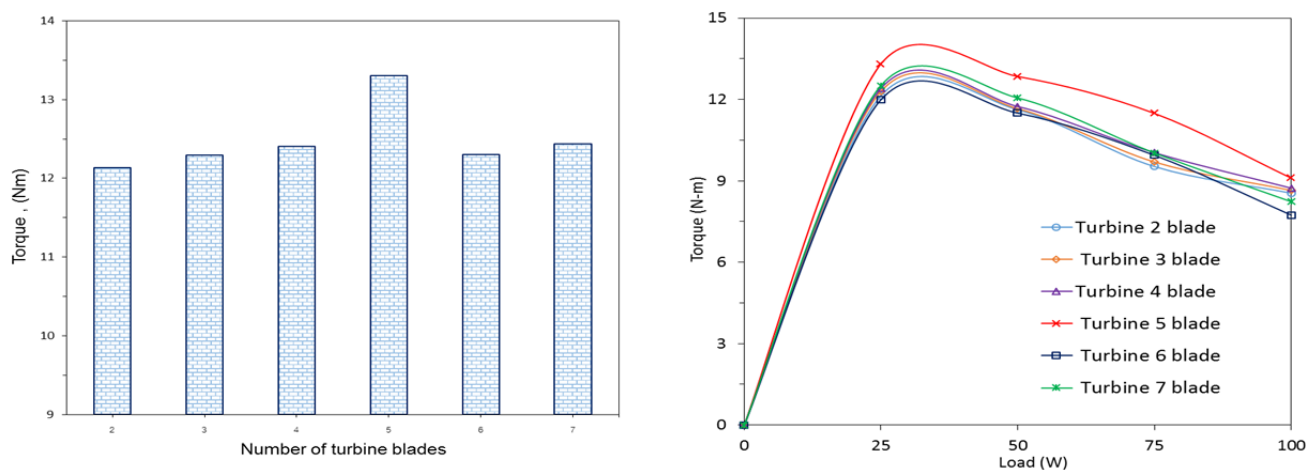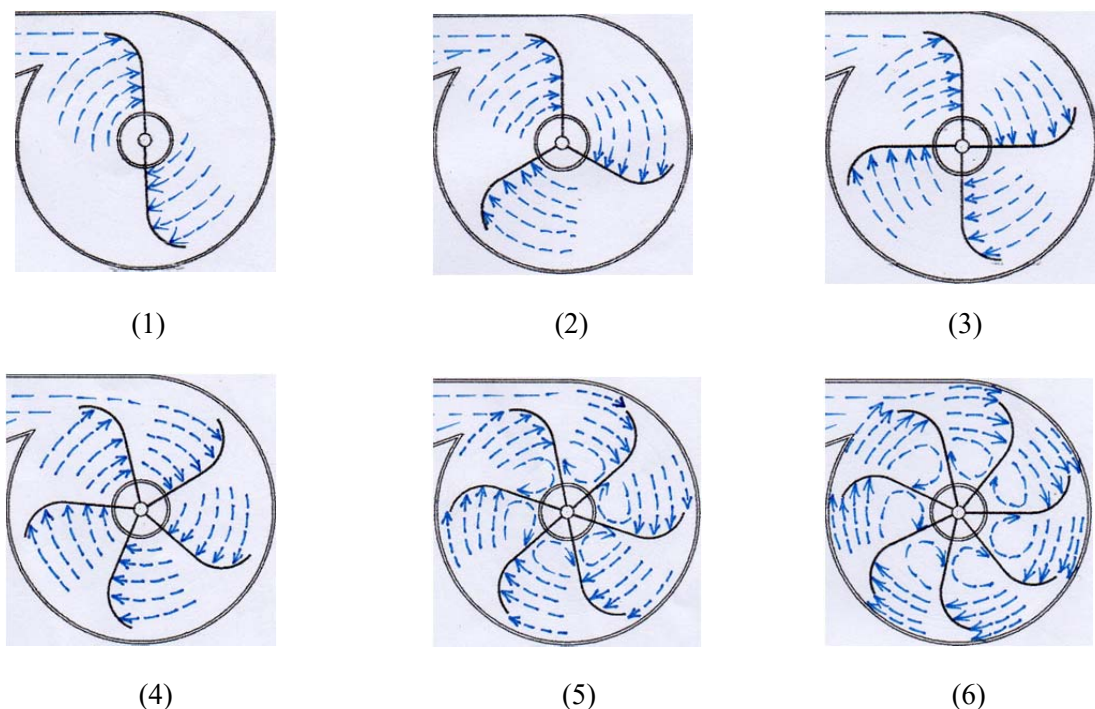
Figure 5. Torques of turbines with 2-7 blades.   **Figure 6.** Torques from turbines with 2-7 blades at the load of 0-100 W.

Observation of the channel of water flow that impacted on the blades showed that water eddy circulated around the pool and centrifugally through the hole at the bottom. The blades of the turbine then received the impact from the centrifugal flow of water. It was found that when the number of blades increased until 5 blades, the surface area contacting with water was greater, resulting in higher torque. But when there were 6 or 7 blades, the distance between blades was less, making the impact of water current on the blades decrease. Moreover, water flow through the hole developed resistance against the movement of the next blade in series, resulting in resistance of the water eddy and hence reducing the torque produced by the turbine, as illustrated in Figure 7.

(1)   (2)   (3)

(4)   (5)   (6)

Figure 7. Sketches of water direction impacting the blades of the turbines with: (1) 2 blades, (2) 3 blades, (3) 4 blades, (4) 5 blades, (5) 6 blades, (6) 7 blades

The results of the tests were extended in construction of a power generation system using a free-vortex flow of water, including a concrete pool having a diameter of 4 m and a height of 1 m. The 5 blade turbine was installed and connected to an electricity generator. It was found that at the flow rate of 0.6 m^3/s, the highest capacity of electricity generation was 1.7 kW, and the efficiency was 31.65% [18].

4.2. Effect of baffle plates on turbine efficiency

The analysis of the water turbine efficiency to compare the 3 types of turbines, namely, Case 1 no baffle plates, Case 2 with top baffle plates, and Case 3 with top and bottom baffle plates showed that at the highest flow rate of 0.6 m^3/s, the turbine Case 3 yielded higher torque than the other turbines as shown in Figure 8. In Figure 9, the turbine Case 3 yielded the greatest electricity power because the baffle plates retained more water mass impacting on the surface area of each blade, and therefore the torque was higher than other cases at all of the loads fed. Considering electricity power generated in Figure 8, it can be seen that Case 2 and Case 3 of turbines did not differ much in terms of yields. However, the blades with baffle plates were more effective than the blades without baffle plates.

From the experiment, the highest efficiency was found at the flow rate of 0.06 m^3/s and power load of L = 25 W. Case 1, Case 2 and Case 3 of turbines tested showed the efficiency of 37.24%, 42.13%, and 43.83%, respectively. It can be seen that the efficiency of turbines with baffle plates on the blades was higher than the turbine with no baffle plates. The two cases with baffle plates also showed quite a

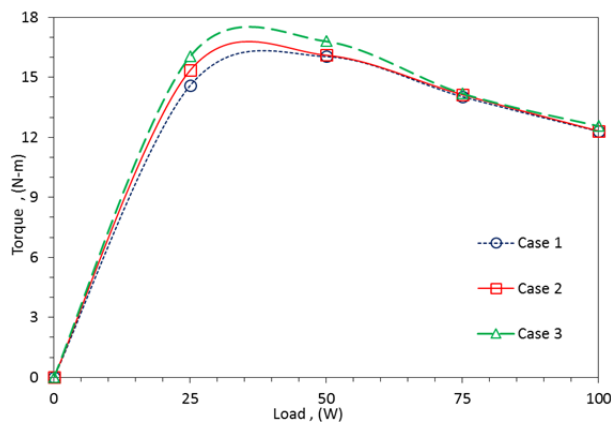similar efficiency. The tendency of the system efficiency was increased with the increase of water flow rate.

Figure 8. Turbine torques at Q = 0.06 m^3/s**.**

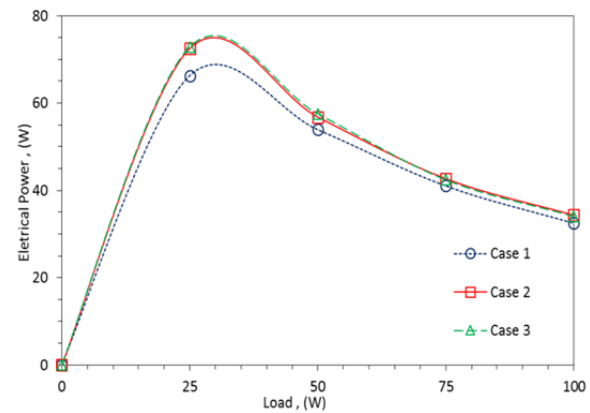**Figure 9.** Electricity power generated at Q = 0.06 m^3/s**.**

5. Conclusions
The study showed that the number of blades and baffle plates attached to the blades of the water turbine affect the efficiency of the turbine. The water turbine with 5 blades was found the most appropriate for use and it also yielded the highest torque as the distance between blades was effective for receiving the exertion of water flow on the blades. When baffle plates were attached to the blades, the efficiency of turbine increased because the baffle plates assisted in retaining the right amount of water and yielding higher torque. It was fond that the 50% proportion of the curve area being most appropriate and with the flow rate of 0.06 m^3/s and the load of 25 W, the efficiency of turbine with top and bottom baffle plates was 43.83%, and it was 6.59% higher than that without baffle plates.

6. Acknowledgements

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