Development and Computational Validation of an Improved Analytic Performance Model of the Hydroelectric Paddle Wheel

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ABSTRACT

This article presents an innovative analytical model to correctly evaluate the performance of a paddle wheel in generating electricity from moving fluid (water). The deficiencies of current analytical model in evaluating such performance are pointed out and overcome by the developed analytical algorithm. Important factors that affect the performance of paddle wheel, such as the drag force, relative velocity, efficiency curve of generator, are considered in the developed method. Next, computer simulations are performed. The computer simulation results agreed very well with the analytical results calculated following the presented approach. The presented analytical method and computational techniques can be extended to estimate the performance of other hydroelectricity devices in the early design stage.

Nomenclature

A	Wetted area of vertical paddle, m^2
A_i	Wetted Area of slanted paddle, m^2
C_D	Drag coefficient
C_L	Lift coefficient
D	Radius of each paddle, m
d	Wetted depth of vertical paddle, m
E	Efficiency factor
F	Force, N
L	Length of paddles, m
P	Power, W

q	Flow rate, m^3/s
r	Torque handle (distance between centroid of paddle to axis of rotation), m
T	Torque, N·m
T_d	Drive torque, N·m
T_r	Resistance torque, N·m
v	Water velocity, m/s
v_r	Relative velocity, m/s
α	Angle between each paddle and vertical plane, radian
ρ	Density of water, 1000 kg/m^3
ω	Rotational speed, rad/s

Keyword: CFD, paddle wheel, power generation, analytical analysis, performance curve

INTRODUCTION

Hydroelectricity refers to electricity generated by hydropower, which is derived from the force and energy of moving water. Hydroelectricity is the most widely used form of renewable energy [1]. In comparison to traditional energy sources such as fossil fuel, hydroelectricity has a lower environmentally impact by producing much lower carbon emissions and creating less pollution. Because of that merit, approximately 20% of the world electricity and about 88% of electricity from renewable sources comes from hydroelectric power plants, and more hydroelectric projects are planned. Therefore, it is important for designers and engineers to roughly estimate the electric generation performance of a proposed hydroelectric complex before it is put into construction to avoid unnecessary investments and wastes. In modern hydroelectricity devices, paddle wheel is a crucial mechanism used to generate the hydroelectricity, whose capacity in generating electric power has to be properly modeled and calculated. Unfortunately, existing analytical methods have evident deficiencies and cannot correctly calculate that capacity. The objective of this article is to provide an improved analytical model to correctly calculate the electric generation performance of a paddle wheel and validate it through computer modeling and simulations. The analytical and computational methods presented in this article can be applied to evaluate the performance of an entire hydroelectricity complex and other similar devices.

LITERATURE REVIEW

Because of its important role in generating electric power, the paddle wheel has been extensively employed in a variety of power plants to provide renewable and sustainable power generation. For example, paddle wheels will be used in a series of large concrete hydroelectric stations being constructed in the Belle Isle Strait, Canada [2]. Paddle wheel can also be found from the Rance River tidal power plant to generate electricity out of ocean energy [3]. In a microalgal biomass production station, paddle wheel is even mixing of ponds to achieve a required water velocity (20-25 cm/s) [4].

Unfortunately, compared to the numerous applications of paddle wheel in modern power plants, only a few analytical and numerical methods were developed to predict the electric generation capacity of the paddle wheel. Jiang [5] presented a method to determine the optimal driving surface angle of the paddle and derive theoretical calculation formula for design of the folding plane paddle. The theoretical results were then verified through comparing to experimental data. Chen et al. [6] presented an optimal design of paddle-wheel with improved efficiency and reduced cost. A mathematical model was built taking the efficiency as the optimization objective and the obtained optimal design increased the efficiency by 20%. The optimal results obtained using MATLAB were also verified through finite element analysis and computer simulations.

Based on reviewing previous work in evaluating the performance of the paddle wheel, it was confirmed that a novel approach that combines analytical and computational techniques to correctly predict the paddle wheel power generation capacity has to be developed, which is the motivation of this study.

CURRENT ANALYTICAL METHOD AND DEFICIENCIES, ONE PADDLE

We start by calculating the power generation performance of a single paddle wheel. Based on the current analytical method [7], when water impacts a paddle at a velocity v, the generated power P (W) from the paddle and its rotational speed ω (rpm) is calculated as:

$$\omega = \frac{60v}{2\pi d} \tag{1}$$

$$P = T \times \omega = Fr\omega \tag{2}$$

Equations (1) and (2) are simple and straightforward, however, a number of factors that critically affect the rotating paddle are not considered. Such assumptions oversimplified the problem and led to incorrect estimation. Important factors missing in the current analytical method are listed as follows.

It was assumed that the paddle rotates with the same speed as the water passes through, which is not correct. Even worse, slip condition was ignored.

The power was calculated based on force and torque, and the force was calculated from momentum equation by using absolute velocity of the water. Obviously, in this situation, the relative velocity between the water and the paddle instead of the absolute velocity of water should be used. Also, in order to acquire a correct evaluation, the force should be calculated as the drag force of the water that applies on the paddle with drag coefficient of flat object instead of using the momentum equation.

Friction of the moving parts and resistance of generator were ignored in calculating the angular velocity of the paddle.

Due to above deficiencies, the current analytical model cannot correctly predict the power generation capacity of the paddle wheel and an enhanced method has to be developed to overcome those deficiencies.

IMPROVED ANALYTICAL MODEL TO CALCULATE GENERATED POWER BY A SINGLE PADDLE

In this section, an improved analytical method is presented, which eliminates the aforementioned deficiencies of the current method by computing the generated torque based on drag force. In the new method, the paddle force and torque are calculated separately.

Paddle Force

Initially, the equations for a single rectangular paddle with a height of "D," negligible thickness, which extends perpendicular to the flow direction, are developed to relate the paddle to its angle to the vertical plane (α), drag coefficient (C_D), and lift coefficient (C_L), as depicted in Figure 1. With geometrical consideration, one can have

$$x = D\cos\alpha - (D - d) \tag{3}$$

$$y = x/\cos\alpha = [D\cos\alpha - (D - d)]/\cos\alpha \tag{4}$$

$$A = yL = L[D\cos\alpha - (D - d)]/\cos\alpha \tag{5}$$

where L is the length of paddle, d the wetted depth of vertical paddle, and A the wetted area (or effective area) of the paddle.

The paddle force is then calculated as

$$F = (C_D + C_L)\frac{\rho v^2 A}{2} = (C_D + C_L)\frac{\rho v^2}{2} L[D\cos\alpha - (D - d] \tag{6}$$

where ρ is density of the water and v is its speed. The angle α of a paddle in the paddle wheel can be determined based on the angle between two neighboring paddles, which is a constant.

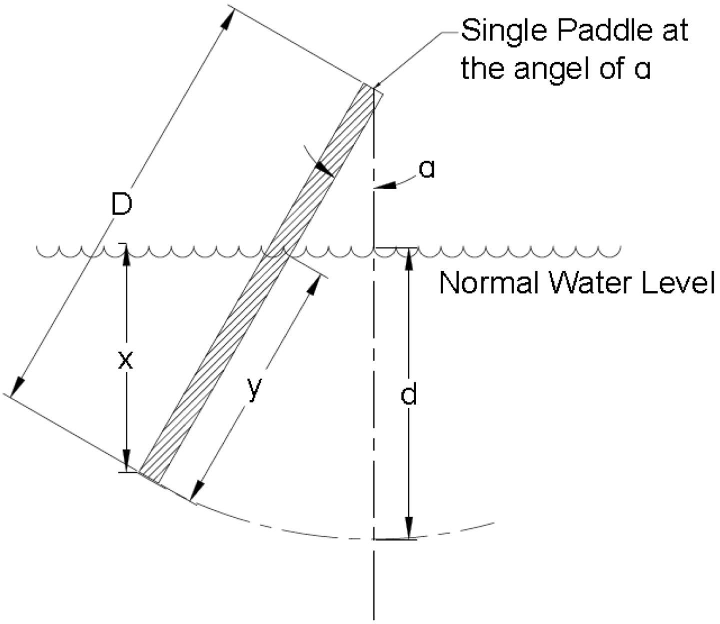


Figure 1. Schematic of a single paddle

Paddle Torque

Paddle torque can be calculated based on its definition T = F × r, where the r is the arm of the paddle force F and can be calculated based on the geometrical shape of the paddle as

$$r = [D\cos\alpha + (D - d)]/(2\cos\alpha) \tag{7}$$

Substituting Eqns. (6) and (7) into the torque definition one can obtain

$$T = \frac{\rho v^2}{4\cos\alpha}(C_D \cos\alpha + C_L \sin\alpha)L\left[D^2\cos^2\alpha - (D - d)^2\right] \tag{8}$$

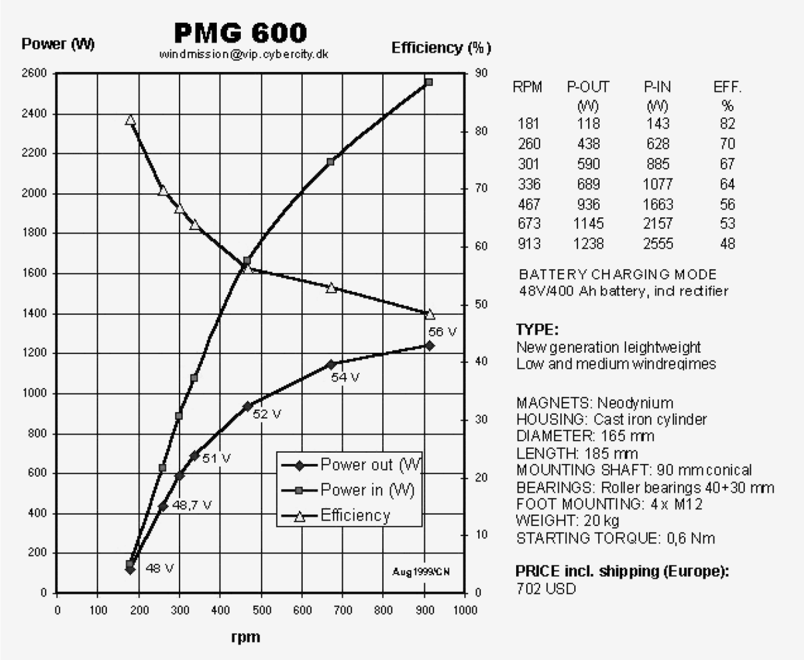
Eqns. (6) and (8) explain how to calculate the force and torque caused by a single paddle. Obviously, the total torque generated from the paddle wheel and transferred to shaft equals to the algebraic summation of each paddle torque. Even better, if the shape of paddle is symmetric about the vertical plane, the lift force can be neglected so that $C_L = 0$. Also, for an inclined paddle, its C_D can be calculated from the drag force coefficient of a vertical paddle (C_{Dv}) as $C_D = C_{Dv}\cos\alpha$. A good assumption for a long flat plate vertically placed along the flow direction is $C_{Dv} = 1.2$ [7].

Angular Velocity

The angular velocity of the paddle depends not only on the speed of the water and design of the paddle, but also on the resistance of generator and its gear ratio. In the current analytical model, the influences of generator and gear box were neglected. Here, a typical efficiency curve for a PMG 600 generator (Figure 2) is used for calculating the angular velocity. Thus to correctly predict the paddle wheel performance, the efficiency curve of the particular generator connected to the paddle is needed. Figure 3 displays the flow chart of calculating the angular velocity, where the relative velocity (v_r) between the water and the paddle is calculated as

$$v_r = v - \omega \times r \tag{9}$$

Finally, the power generated from a paddle can be calculated based on the enhanced torque and angular velocity equations as P = T × ω.



RPM	P-OUT (W)	P-IN (W)	EFF. %
181	118	143	82
260	438	628	70
301	590	885	67
336	689	1077	64
467	936	1663	56
673	1145	2157	53
913	1238	2555	48

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Figure 2. Efficiency curve for PMG 600

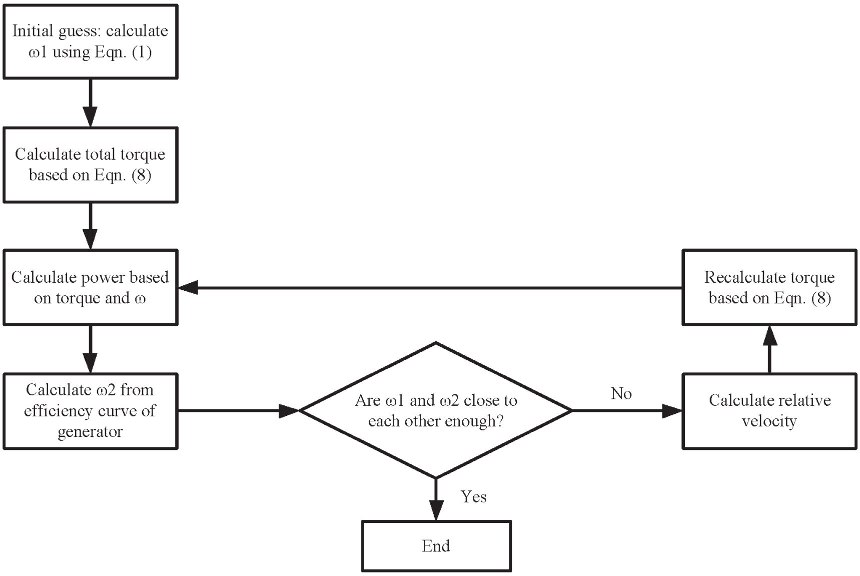


Figure 3. Algorithm of calculating angular velocity

Validation and Discussion

In order to validate the developed analytical model, a computer simulation for the vertical paddle is created and computational fluid dynamics (CFD) approach is used to numerically solve the flow problem. Different water velocities from 1.8 m/s (4 mph) to 4.5 m/s (10 mph) are used for that simulation and the simulation results are compared to the analytical results calculated from the developed analytical methods (Eqns. (3) to (9)) to demonstrate the accuracy of the presented method. In this validation, a vertical 12.2 m (40 ft) × 6.1 m (20 ft) rectangular paddle is assumed, which is submerged 2.44 m (8 ft) into the water. The power generated from a single paddle is calculated separately using different methods. The computational results and two sets of analytical results are displayed and compared in Table 1 and Figure 4. Figure 5 shows the distributions of velocity and pressure in the region around the vertical paddle. Detailed information of computer modeling and simulation techniques will be introduced latter.

Table 1. Comparisons of computational and analytical solutions of the generated power

Water velocity	Analytical results (old)	Analytical results (new)	Computer results	Difference
1.8 m/s	84.9 kW	51 kW	45.9 kW	11.24%
2.2 m/s	165.8 kW	99.6 kW	89.6 kW	11.24%
2.7 m/s	286.5 kW	172.2 kW	154.8 kW	11.23%
3.6 m/s	679 kW	408.1 kW	366.9 kW	11.22%
4.5 m/s	1326.3 kW	797 kW	716.6 kW	11.21%

From the displayed results, we see that the computational results agreed very well with the results calculated from the new analytical method. It is clear the old analytical method overestimates the generated power with respect to water velocity. Note the new analytical method and the CFD computer simulation better agree at predicting generated power. Therefore, the accuracy of the developed analytical method in evaluating the power generated from a single paddle is verified. In coming sections, the developed method will be used for calculating the generated hydroelectric power from an entire, rotating paddle wheel.

COMPUTER SIMULATION OF A PADDLE WHEEL

In this section, the power generation capacity of an entire paddle wheel is first calculated through the computer simulation. To find the

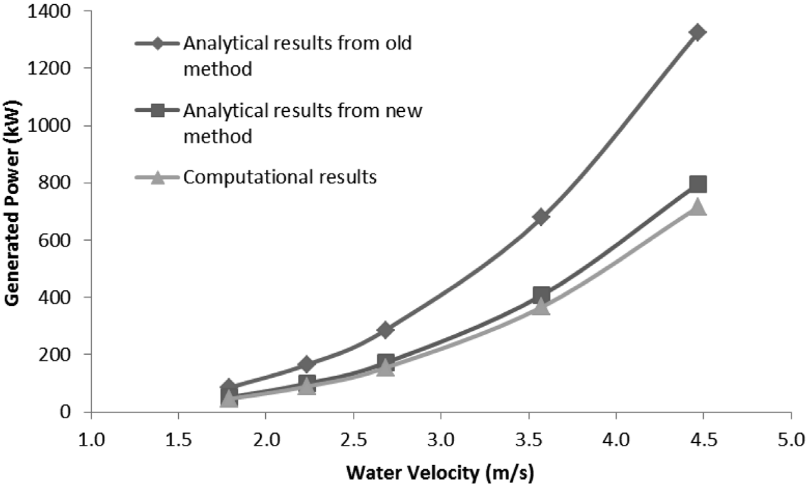
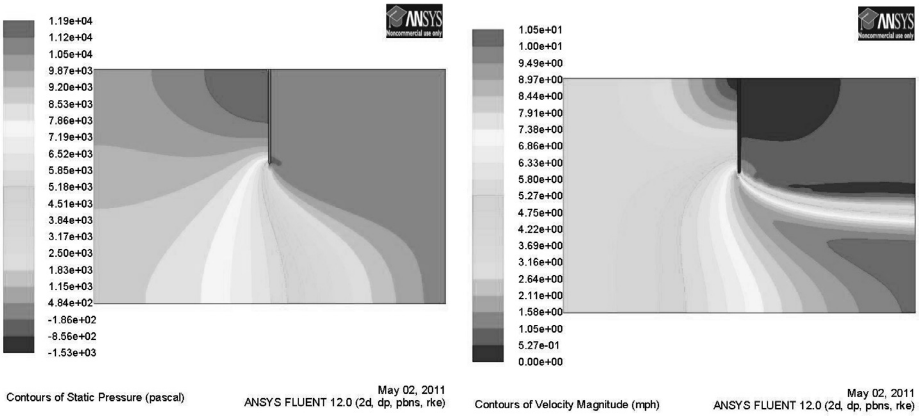


Figure 4. Comparison of computational and analytical results



(a) Contours of pressure (Pa)

(b) Contour of velocity (m/s)

Figure 5. Contour of pressure and velocity around a vertical paddle (v = 1.8 m/s)

performance of a regular paddle wheel, the computer simulation will always be the first choice because it is easy to be implemented and can generate visual simulation results to vividly animate the interaction between the paddle wheels and the moving water. Software package ANSYS FLUENT [8] is used for modeling, analysis and simulation. The paddle wheel consists of 16 paddles and only 7 paddles are submerged into water at the same time.

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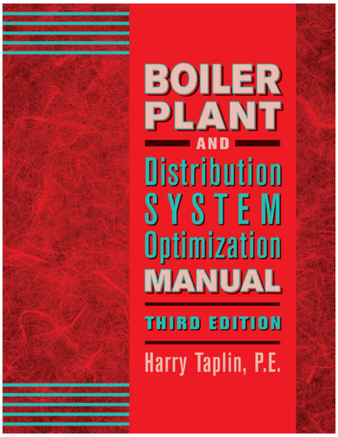

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Computer Models

2D Computer-aided design (CAD) models for the paddle wheel and the moving water are first created, as shown in Figure 6. In the generated computational environment, the physical domain is considered to be only the fluid part and the heat transfer between the paddle wheel and water is neglected. The model consists of stationary and rotational reference frame, which are separated by circular boundary around the paddles.

The CAD model is then meshed and cells are generated in the entire domain to create the CFD model. As shown in Figure 7, in the meshed CFD model, the essential fluid flows are described through these cells, which will be solved numerically so that the discrete values of the flow properties such as the velocity, pressure, temperature, and other transport parameters of interest can be determined [9].

CFD Analysis

As shown in Table 1, five water velocities (1.8, 2.2, 2.7, 3.6, 4.5 m/s) are defined in this CFD model separately and used for CFD analysis to find the hydropower electricity generation capacity of the paddle wheel. Under each water velocity, six equally-increased angular velocities from 0 to maximum value are applied on the paddle wheel and used for simulation. The maximum angular velocity is calculated with respect to that the net generated torque on the wheel shaft becomes zero. In another word, when the wheel is rotating by maximum angular velocity, the torque exerting on the paddles is zero. Following this manner, overall 30 simulations are performed. Table 2 illustrates important algorithms, approximations, and other settings.

Simulation Results

Figures 8 and 9 display the distribution of the pressure and water velocity around a stationary paddle wheel at water speed of 1.8 m/s, respectively. From those figures it can be seen that the majority of the force is applied on the left four paddles through the flow while other paddles were indispensible in making a continuous rotation. It is also obvious that the left four paddles created most power because of the high pressure and high velocity around them.

The output torque and generated power are calculated from the thirty simulations and listed in Tables 3 to 7. From those results, the performance curves of the paddle wheel under different water velocities

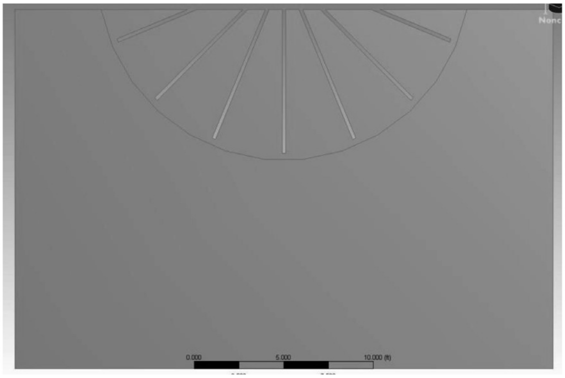

Figure 6. CAD model of a paddle wheel under water

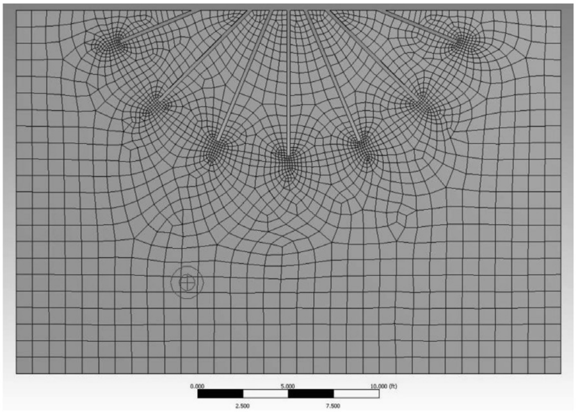

Figure 7. CFD model with meshes and cells

Table 2. Important CFD analysis settings

Solver Type	Pressure based, double precision, steady state, 2D
Viscose Model	k-ε realizable with standard wall function
Fluid	Water with density of 998 kg/m^3
Rotation	Multiple reference frame model
Pressure-Velocity coupling	Coupled
Gradient discretization	Least square cell based
Pressure discretization	Standard
Momentum discretization	Second order upwind
Turbulent kinetic energy discretization	Second order upwind
Turbulent dissipation energy discretization	Second order upwind
Convergence Criteria	1×10^{-4}
Boundary condition	Velocity inlet (1.8, 2.2, 2.7, 3.6, 4.5 m/s) and ambient pressure outlet

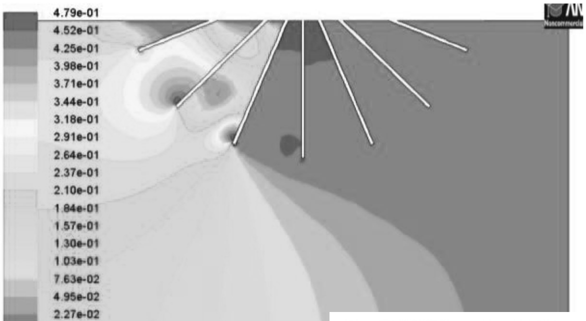

Figure 8. Pressure distribution at water velocity of 1.8 m/s for stationary paddles

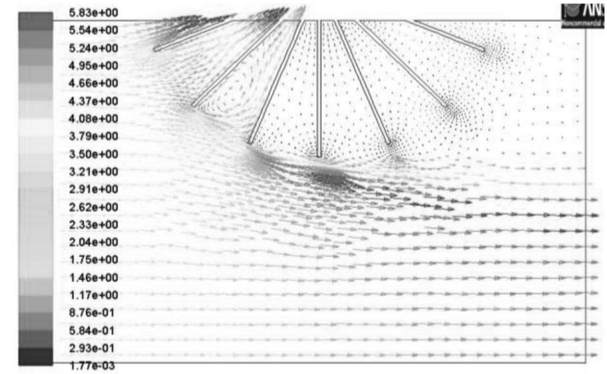

Figure 9. Velocity distribution at water velocity of 1.8 m/s for stationary paddles

can be obtained, which are plotted in Figures 10 and 11. From those figures, it is obvious that the relationship between the torque and the angular velocity can be fitted with second order polynomials. Finally, the relationships of generated torque and power to the angular velocity of the paddle wheel are investigated.

Discussions

Based on the computational results, it can be found that the left four paddles produced the majority of hydropower. Therefore, the analytical model must be established based on those paddles to correctly predict the power generation capacity of the whole paddle wheel. It is also found that when the angular velocity increases, the paddle force decreases. In current analytical model, the generated power is calculated by multiplying the maximum torque and the peak angular velocity, which will unavoidably overestimate the performance of the paddle wheel. This is because the maximum torque and angular velocity cannot appear at the same time. A critical point at which the product of the torque and angular velocity is maximum should be located in order to find the maximum output power. Actually, the performance curves displayed in Figures 10 and 11 can be used to determine the maximum power generated from a paddle wheel.

Table 3.
CFD results at water velocity 1.8 m/s

ω (rpm)	Torque (N·m)	Power (kW)
0	76627	0.0
0.5	66544	3.5
1	52316	5.5
1.5	33943	5.3
2	11217	2.3
2.205	0	0.0

Table 4. CFD results
at water velocity 2.2 m/s

ω (rpm)	Torque (N·m)	Power (kW)
0	119750	0.0
0.75	100060	7.9
1.5	71213	11.2
2.1	41343	9.1
2.5	17825	4.7
2.7799	0	0.0

Table 5.
CFD results at water velocity 2.7 m/s

ω (rpm)	Torque (N·m)	Power (kW)
0	172444	0.0
0.9	144036	13.6
1.8	102754	19.4
2.7	47573	13.5
3.1	18703	6.1
3.34	0	0.0

Table 6. CFD results
at water velocity 3.6 m/s

ω (rpm)	Torque (N·m)	Power (kW)
0	306592	0.0
1	265981	27.9
2	210202	44.0
3	137453	43.2
4	47915	20.1
4.47	0	0.0

Table 7.
CFD results at water velocity 4.5 m/s

ω (rpm)	Torque (N·m)	Power (kW)
0	39292	0.0
1.25	34090	54.4
2.5	26980	86.1
3.75	17681	84.7
5	6262	40.0
5.61	0	0.0

Furthermore, if those performance curves are employed with the performance curve of the electric power generator, the natural point (intersection of the paddle wheel performance curve and the generator performance curve) and the generated hydroelectric power can be easily determined by drawing the performance curves of the paddle wheel and the generator together.

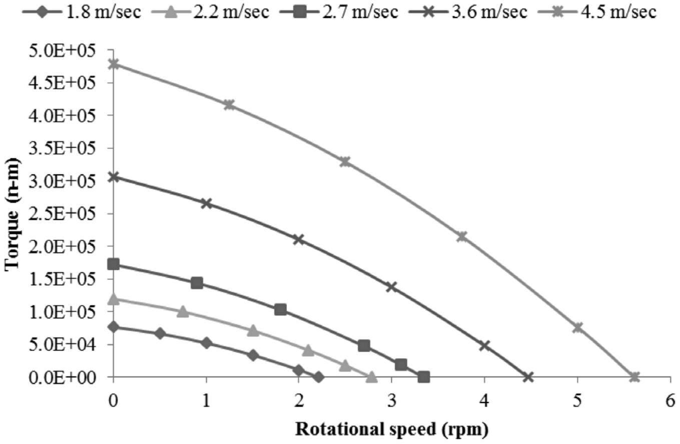

Figure 10. Relationships between torque and angular velocity

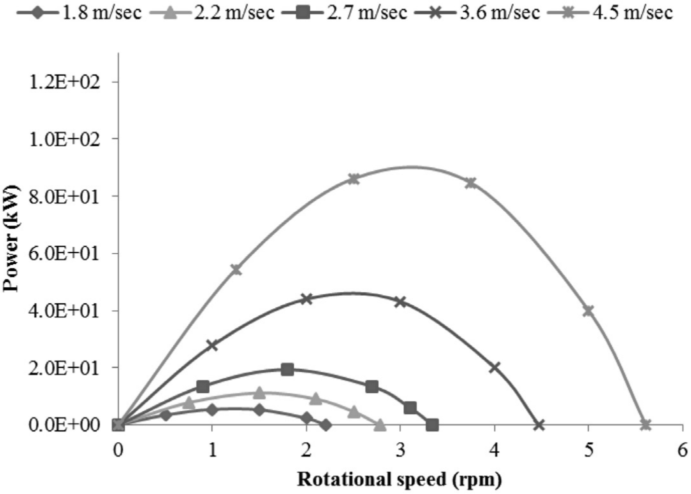

Figure 11. Relationships between power and angular velocity

DEVELOPMENT OF PADDLE WHEEL ANALYTICAL MODEL

An analytical model of the paddle wheel (with several paddles) is developed based on the previous analytical model for a single paddle. In order to correctly estimate the capacity of the paddle wheel in generating power, the force exerting on a single paddle is divided into two forces: driving force and resistance force. The driving force is caused by the force that water exerts on front of the paddles and the resistance force is due to confrontation of water which is against rotation of the paddles. Drag coefficients are considered for both types of forces.

Driving Force

As illustrated in simulation results (section 5), the left four paddles generated most force to rotate the wheel and produced majority of hydropower. Therefore, the driving force is only calculated as the summation of the forces that exerted on the four paddles (Figure 17). The effective area for each paddle can be estimated using Eqn. (5) as

$$A_{e1} = \frac{L[D\cos\alpha_1 - (D-d)]}{\cos\alpha_1} \text{ and } A_{ei} = \frac{DL[\cos\alpha_i - \cos\alpha_{i-1}]}{\cos\alpha_i}, \text{ (i = 2, 3, 4)} \tag{10}$$

It is appropriate to assume that the driving force is exerted on the midpoint of the effective area, then the torque handle can be calculated as

$$\text{and } r_1 = \frac{D\cos\alpha_1 + (D-d)}{2\cos\alpha_1} \text{ and } r_i = \frac{D[\cos\alpha_i + \cos\alpha_{i-1}]}{2\cos\alpha_i}, \text{ (i = 2, 3, 4)} \tag{11}$$

Eqn. (9) can be modified to calculate the relative velocity of paddles (v_{ri}) based on the rotational speed of the wheel and the water velocity (v) as

$$v_{ri} = v - \omega r_i \cos\alpha_i \tag{12}$$

Finally, the resultant driving force and torque that are applied on the front surface of the left three paddles can be computed using Eqns. (13) to (15) (refer to Eqns. (6) to (8) by neglecting lift force).

$$F_i = C_D \cos \mathrm{a}_i \frac{\mathrm{r}\, v_{\dot{r}}^{\,2} A_{\dot{e}}}{2g_c} \frac{v_{\dot{r}}}{|v_{\dot{r}}|}, \text{ (i = 1, 2, 3, 4)} \tag{13}$$

$$T_i = r_i F_i \cos\alpha_i \tag{14}$$

$$T_d = \sum_{i=1}^{3} T_i \tag{15}$$

Resistance Force

The resistance force is caused by the friction force of water on back of all paddles. The resistance force is divided in two parts: shear and normal forces. The shear force is caused by tangential viscous forces between the water and the paddles while the normal force is generated by normal impact of the water on the paddles. The shear force can be neglected in comparison with the normal force because of its small magnitude. In order to simplify the model, the resistance force is approximated as the normal drag force exerting on back surface of each paddle, and is uniformly distributed through entire area. In determining the resistance force, the effective area is considered to be entire wetted surface of paddles, as described in Eqn. (16). The existence of water behind all of the submerged paddles leads to the resistance forces that affect on all paddles that submerged into the water (7 paddles total). Thus, different from the driving force, all paddles have to be considered in calculating the resistance force. By taking the same assumption as calculating the driving force, the distance of each paddle to its axis of rotation is determined using Eqn. (17). In calculating the resistance force, the velocity that water hits on the back of each paddle is only related to the angular velocity of the paddle wheel, which is $v_i = r_i\omega$. Thus, the resistance force and its corresponding torque which are applied on the back surface of each paddle is computed as

$$A_i = \frac{L[D\cos\alpha_i - (D-d)]}{\cos\alpha_i} \tag{16}$$

$$r_i = \frac{D\cos\alpha_i + (D-d)}{2\cos\alpha_i} \tag{17}$$

$$F_i = C_D \frac{\rho v_i^2 A_{ei}}{2}, \text{ (i = 1, 2, 3)} \tag{18}$$

$$T_i = -r_i F_i \tag{19}$$

$$T_r = \sum_{i=1}^{3} T_i \tag{20}$$

The total torque which is caused by the driving force and the resistance force then can be determined as

$$T = T_d + T_r \tag{21}$$

As mentioned in section 4, the drag coefficient C_D is assumed as 1.2, which will be verified through analytical calculations and computational simulations. A free body diagram of the analytical model is plotted in Figure 12.

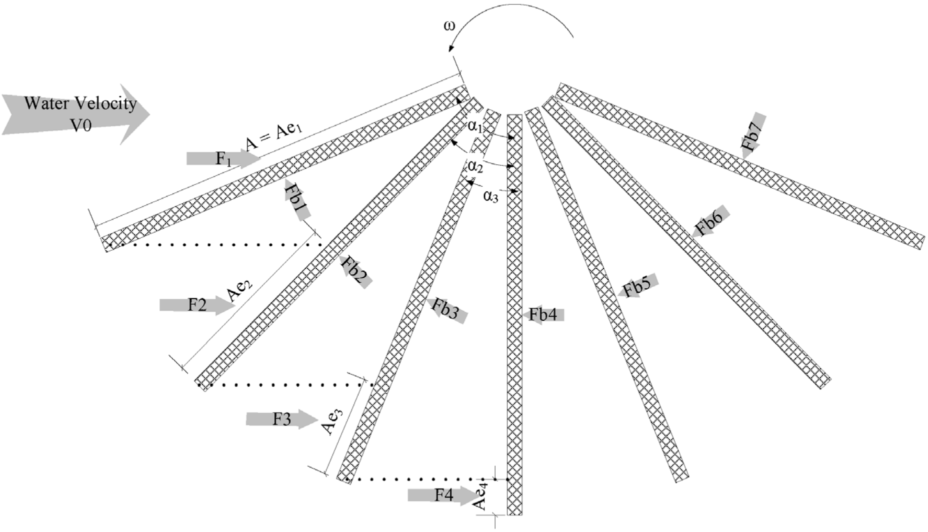

Figure 12. Schematic of the analytical model

VALIDATION

After developing the analytical model, it is used to compute the power generated by a paddle wheel which has 16 paddles at different water velocities. The analytical results are then validated by comparing to the computational results, as shown in Figures (13) to (17). From those figures it can be found that the analytical model correctly predicted the generated power when the paddle wheel rotated at low angular velocities (< optimum angular velocity) while it slightly overestimated the generated power under high angular velocities (> optimum angular velocity). This is because that at high angular velocities, the flow pattern changes from turbulent flow to laminar flow and the drag coefficient dramatically drops, which directly causes the decrease in driving force. It is evident that in order to improve the accuracy of the present analytical model, a precise drag coefficient for the laminar flow has to be determined.

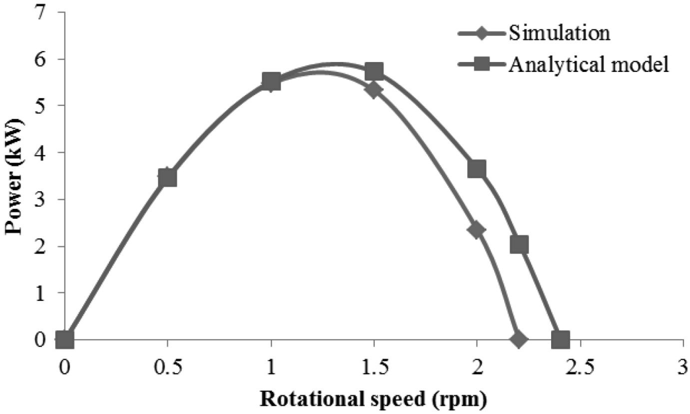

Figure 13. Comparison of performance curves at water velocity 1.8 m/s

CONCLUSIONS

This article presents an analytical model to correctly predict the hydropower generation capacity of a paddle wheel. Compare to current method, the developed analytical model considers the effects of drag force and the resistance force which is caused by the friction between the paddles and the moving water. Relative velocity between the water and the paddles are used instead of the absolute velocity of water. Even better, the efficiency curve of generator is applied in the new model to determine the angular velocity of the paddles. Performance curves of the paddle wheel are plotted with respect to different water velocities to display the output power calculated based on different torques and angular velocities. The analytical model is then validated through computer simulations. It is found that the analytical results agreed with the simulation results very well, especially when the paddle wheel rotated at low angular velocities. However, the analytical model overestimates the capacity of the paddle wheel when it rotated at high angular velocities, which is because of dependency of drag coefficient to the relative velocity at higher angular velocities.

Despite the good results obtained from the analytical and computational analyses, the analytical and CFD results still need to be validated by comparing to experimental results. It is expected that the analytical and computer results might overestimate the performance of the paddle wheel. This is because that neither the simplified, ideal

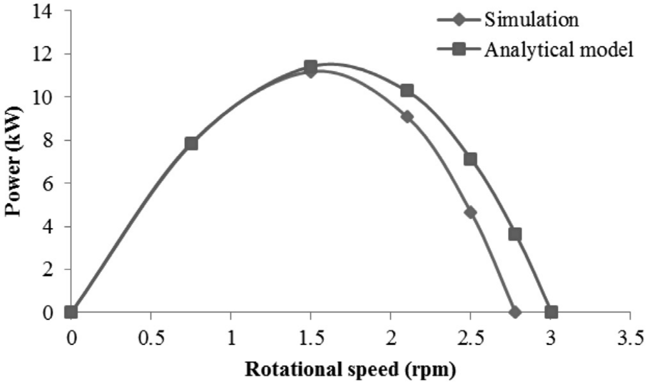

Figure 14. Comparison of performance curves at water velocity 2.2 m/s

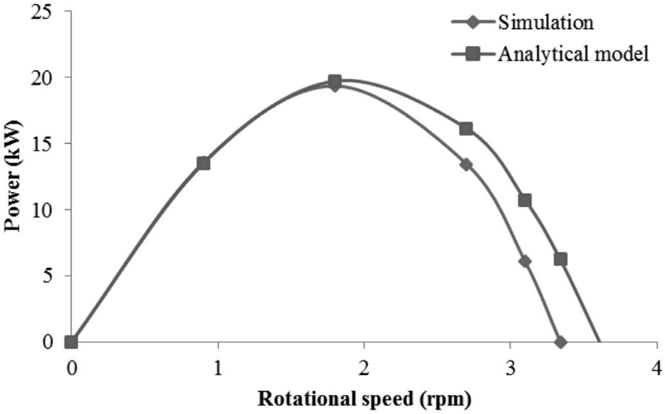

Figure 15. Comparison of performance curves at water velocity 2.7 m/s

analytical model nor the computational model and environment can exactly represent every detail in real condition. At first, in the present study, the efficiency of equipments and loss due to friction were not considered. The displayed results were generated at the paddle where, before turning into electricity, it has to be transferred from the paddle wheel to the generator, then the inverter, and then the gear box. If we assume each equipment has an efficiency of 90%, the total transferred power will then be 90% × 90% × 90% ≈ 73%. In another word, about 27% power will be lost during this process. Moreover, considering other loss during the transferring such as heat loss, etc., the percentage of the lost power will be even higher than 27%. Secondly, in our

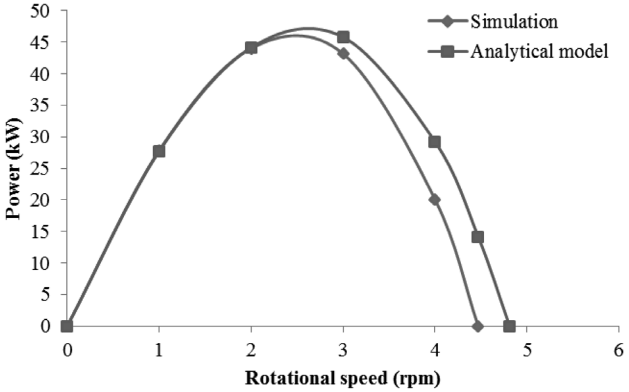

Figure 16. Comparison of performance curves at water velocity 3.6 m/s

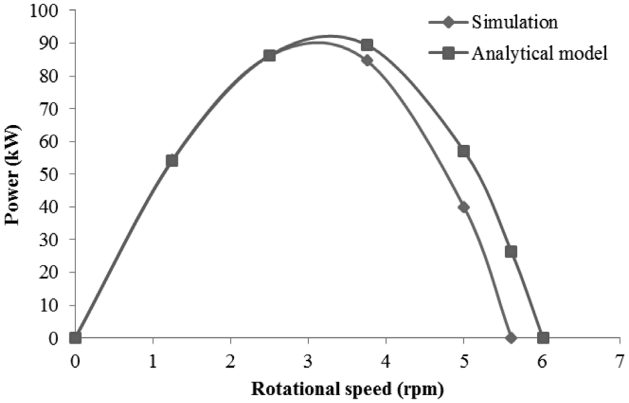

Figure 17. Comparison of performance curves at water velocity 4.5 m/s

study, it was assumed that the water hits the paddle wheel at a constant velocity, which is not true in reality, nevertheless. In practice, the water speed at different depth of a river is not the same, the deeper the water is, the lower its speed would be. Thus, the assumption of constant water speed in the present analytical and computational analyses may cause another overestimate in the generated power. In the future, a scaled paddle wheel prototype will be modeled and its capacity in generating hydroelectricity will be tested through experiments and the experimental data will be compared with the analytical and computational results to further validate the presented approach.

In summary, this article provides two techniques, analytical method and computational method, to correctly evaluate the power generation capacity of a single paddle and an entire paddle wheel in moving water. The presented methods can be extensively used in early design stage to estimate the performance of the planned power plant. With specified electric power generators and appropriate gear ratios, the presented methods can be used to evaluate the output electricity generated by other hydroelectricity devices. In the future, this work can be extended along several directions. (1) Develop an experimental approach to validate the present analytical and computational results. (2) New method needs to be developed to correctly evaluate the drag coefficient under the laminar flow. (3) For a certain hydroelectricity device which may include an array of paddle wheels, optimum design needs to be performed on each paddle to find its best generator and gear ratio so as to maximize the output hydroelectric power of the entire device.

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