Experimental study to the influences of rotational speed and blade shape on water vortex turbine performance

T C Kueh\textsuperscript{1,5}, S L Beh\textsuperscript{2}, Y S Ooi\textsuperscript{1,3} and D G Rilling\textsuperscript{4}

\textsuperscript{1}Centre for Advanced Materials and Green Technology, Multimedia University, 75450 Melaka, Malaysia
\textsuperscript{2}University of Southampton Malaysia Campus, No. 3, Persiaran Canselor 1, Kota Ilmu Educity @ Iskandar, 79200 Nusajaya, Johor.S
\textsuperscript{3}Faculty of Engineering and Technology, Multimedia University, 75450 Melaka, Malaysia
\textsuperscript{4}Studiendekan School of Engineering & Technology Management, Akad University, 70469 Stuttgart, Germany
\textsuperscript{5}Author to whom any correspondence should be addressed.

E-mail: kuehtzecheng@hotmail.com

Abstract. Water vortex turbine utilizes the natural behaviour of water to form free surface vortex for energy extraction. This allows simple construction and ease of management on the whole water vortex power plant system. To our findings, the literature study specifically on water vortex turbine is inadequate and low efficiency was reported. Influences of operating speed and blade shape on turbine performance are the two parameters investigated in this study. Euler Turbomachinery Equation and velocity triangle are used in the improvement analysis. Two turbines with flat blades and curved blades are tested and compared. Both turbines show similar rotational speed at no load condition. This suggested that the circulation force of the water vortex has more dominant effect on the turbine rotational speed, compared to the turbine’s geometry. Flat-blades turbine showed maximum efficiency of 21.63\% at 3.27 rad/s whereas curved-blades turbine showed 22.24\% at 3.56 rad/s. When operating load is applied, the backward-leaning curve helps the turbine blades to reduce the disturbance on the water vortex, and hence provide a better performance.

1. Introduction

1.1. Water vortex power plant

Water vortex power plant (WVPP) is a hydropower system that generates electricity by utilizing the natural feature of water to form free surface vortex. Water vortex creates swirl flow which is beneficial to the rotation of the turbine system for electricity generation purpose. Figure 1 shows an illustration of WVPP.

WVPP can operate under low head condition. It does not need a water dam to operate. Hence, its construction and management can be simple. Not only reduction on financial cost, this can also decrease the damage on the environment. The large cross-section area of flowing water and low runner speed are also doing less harm to under-water creatures that pass through the system. On the other hand, the absence of high head drop causes the efficiency of the system to be low compared to other
typical turbine systems. However, WVPP still has its own application especially to act as a
decentralized small scale hydropower system in remote area.

![Figure 1. Water vortex power plant.](image)

The number of studies focused on WVPP is quite limited. Yaakob et al. [1] reviewed the studies of
free surface vortex and different types of current existing turbine as the early stage of WVPP study.
Wanchat et al. [2] studied the WVPP by varying the outlet diameter of the basin and reported an
optimum efficiency of 30%. The inadequate of the literatures encourages more studies to be taken into
this field to improve the performance of WVPP. With a better efficiency, the application of WVPP can
be much widened.

1.2. Turbine optimization
There are a lot of factors that can influence the performance of a turbine. Researchers have been
studying turbines’ performance from different aspects. Singh and Nestmann [3] [4] compared the
influences of the angle, height and number of the runner blades on the axial turbine efficiency. Free
vortex theory and velocity triangle were used for the analysis purpose in their studies. Angle at the
blades’ exit and height of the blades were reported to have a more dominant effect.

Alexander et al. [5] proposed the idea to remove all possible angular momentum in an axial turbine
design as the improvement steps. Date et al. [6] studied the efficiency of simple reaction turbine under
different operating loads. They suggested that in an ideal case, where assumption of no friction loss is
made, the optimum efficiency of the turbine will be obtained when the operating load is half of the
maximum shaft torque.

Although water vortex turbine is also classified as a reaction turbine, but its operating concept is
different than the typical reaction turbines. Therefore, application of these optimization approaches on
water vortex turbine becomes an issue to be investigated in this study.

There are two main objectives to be carried out by this study. First, to investigate the performance
of water vortex turbine at different operating speeds, and second, to investigate the performance of
water vortex turbine with two different blades’ shapes.

2. Methodology

2.1. Theoretical analysis
The output power of the turbine system is defined by equation (1), where T and ω represent the
operating load and operating speed of the turbine respectively. The operating load is obtained from the
Euler Turbomachinery Equation as shown in equation (2). The term \( m \) is mass flow rate, r is radius,
and \( V_\theta \) is water velocity in tangential direction. Subscripts 1 and 2 are indicating the location of inlet
and outlet.

\[
P = T \omega 
\]

\[
T = m(r_1 V_{\theta 1} - r_2 V_{\theta 2}) 
\]
of water vortex is in a swirl direction, velocity triangles at the inlet and outlet have to be constructed in different views.

From the constructions of velocity triangle at the blade inlet and outlet, $V_\theta$ in equation (2) can be rewritten in the function of operating angular speed ($\omega$). By substituting this into equation (1), the output power of turbine can be described as a function of operating speed. If a simple shape is used for the turbine blade and assumption of no friction loss is made, the relation between $V_\theta$ and $\omega$ can be simplified. In this case, the optimum power can be determined by differentiating the equation of power in the function of operating speed.

![Velocity triangle constructed on water vortex turbine's blade.](image)

**Figure 2.** Velocity triangle constructed on water vortex turbine’s blade.

However, in real cases, that assumption cannot be true when the turbine blades are often in a more complicated shape. Therefore, a practical way is to observe the output power of the turbine by varying its operating speed, which is one of the objectives in this study.

Besides that, figure 2(c) shows that increment of exit blade angle can reduce the magnitude of $V_{B2}$. Smaller $V_{B2}$ can deliver higher turbine output power as shown in equation (1) and (2). This is another subject of research in the experiment study.

### 2.2. Experiment setup

An experiment setup system which includes basin and turbine components was built to study the water vortex turbine. Water is circulating within the system by a pump as shown in figure 3. Two turbines are tested in this study. One of them is made of four flat blades while the other one contains four curved blades. Their geometry and dimensions are shown in Figure 4.

![Schematic diagram of experiment setup.](image)

**Figure 3.** Schematic diagram of experiment setup.
The basin is two meters in diameter with 0.8 m depth. The water inlet is flowing into the basin at 0.5 meter from the bottom of the basin. Hence, 0.5 m is selected as the head drop of the system. Water reservoir is placed to be filled up before the water enters the basin. This can remove the initial water velocity which is imposed by the water pump. By doing this, the input power is only contributed by the water potential energy but not its kinetics energy, therefore equation (3) can be fulfilled.

Input power is shown in equation (3). Gravity acceleration and head drop is known. Mass flow rate of the water is obtained by the portable ultrasonic flow meter. The portable ultrasonic flow meter contains two transducers which are attached at the upstream and downstream of a pipe. The transducers send and receive ultrasound within the pipe. Flowing water as the transmission medium will cause a difference between the times taken for the ultrasound to travel from upstream to downstream and the opposite way. Portable ultrasonic flow meter collects the times difference and obtains the speed of water by a proper calculation.

To measure the output power at different operating speeds, a braking system is designed and located at the turbine shaft. It is shown in figure 5. The braking system is tighten at different strengths to apply different friction torques on the turbine. The friction torque is simulating the operating load of the turbine, and hence relevant operating speed is obtained. Load-cells are connected at the two end of the braking belt to measure the tension force difference. This difference is used to calculate the friction torque.

\[ P_{\text{input}} = mgH \]  

(3)

Figure 4. Dimensions of turbines.

Figure 5. Braking system.
Several friction torques were applied to obtained different operating speeds. Water flow rate, operating torque, and operating speed in these cases were collected and recorded to calculate the input power, output power and efficiency of the turbine. Then the turbine was replaced by another one and the experiment was repeated.

3. Results and discussion

3.1. Results

When the pump was started, water vortex formed inside the basin and the turbine was rotating. Figure 6 shows the illustration of the water vortex turbine system during its operation. Certain strengths of friction torque were applied on the turbine shaft and the turbine was still able to rotate. The values of the friction torques, responding angular speeds and water flow rates were obtained and recorded. From these values, input power, output power and efficiency were calculated and recorded in table 1 and table 2 for flat turbine and curve turbine respectively.

![Figure 6. Operation of water vortex turbine setup.](image)

| Experiment | Flow rate, kg/s | Operating Load, Nm | Operating Speed, rad/s | Input Power, W | Output Power, W | Efficiency, % |
|------------|----------------|--------------------|------------------------|----------------|----------------|---------------|
| 1          | 11.19          | 0.00               | 4.08                   | 54.84          | 0.00           | 0.00          |
| 2          | 11.98          | 1.40               | 3.87                   | 58.76          | 5.42           | 9.22          |
| 3          | 12.98          | 3.21               | 3.72                   | 63.66          | 11.94          | 18.76         |
| 4          | 14.68          | 4.38               | 3.43                   | 71.98          | 15.02          | 20.87         |
| 5          | 15.47          | 5.02               | 3.27                   | 75.90          | 16.42          | 21.63         |

Table 1. Result for flat turbine

| Experiment | Flow rate, kg/s | Operating Load, Nm | Operating Speed, rad/s | Input Power, W | Output Power, W | Efficiency, % |
|------------|----------------|--------------------|------------------------|----------------|----------------|---------------|
| 1          | 10.68          | 0.00               | 4.08                   | 52.39          | 0.00           | 0.00          |
| 2          | 11.78          | 1.44               | 3.93                   | 57.78          | 5.66           | 9.79          |
| 3          | 12.08          | 2.64               | 3.84                   | 59.25          | 10.14          | 17.11         |
| 4          | 12.48          | 3.23               | 3.80                   | 61.21          | 12.27          | 20.05         |
| 5          | 13.48          | 4.13               | 3.56                   | 66.10          | 14.17          | 22.24         |

Table 2. Result for curve turbine.

The maximum efficiency that can be obtained from the flat turbine is 21.63% at 3.27 rad/s of operating speed whereas the curve turbine showed 22.24% of maximum efficiency at 3.56 rad/s. The graph of efficiency versus operating speed for both turbines are plotted in figure 7.
3.2. Discussion and analysis

For both turbines, generally the efficiency increases when the speed is decreased. The efficiency is expected to drop when the speed is reduced to a certain value. However, those range of experiment cannot be carried out in this study due to equipment limitation. To perform the experiment at such low speed, it requires large friction torque, which is not able to be provided by current braking belt system and load-cells components.

The input flow rate is influenced by the pump capacity and the total water volume in the water tanks. At different turbine speed, the ratio of water volume contained in basin and water tanks is different. This reason causes the input power varies at different operating speeds. Therefore, instead of output power, efficiency as a dimensionless term is taken as the outcome reference of this study.

Figure 7 shows the trend of efficiency changes with respect to the operating speed. The complete graph which is expected in parabolic shape cannot be obtained due to the mentioned reason, and the optimum efficiency is not reached. However the comparison between the performances of two graph is still obviously shown. At any operating speed, the efficiency of curve turbine appears to be higher than the flat turbine’s.

From the results, the operating speeds of both turbines are same when no operating load is applied. This shows that initially the speed of the turbine is mostly influenced by the circulation of water vortex only. When operating load is applied, the circulation strength of water vortex is weaken. Therefore, water tends to flow in more axial direction. In these moments, the curves at the turbine’s blades can extract the angular momentum better, thus the curve turbine produced a better efficiency.

4. Conclusion

Water vortex forms in the basin to rotate the turbine. With only 5 meters of head drop and flow rate around 15kg/s, the system is able to produce 16.42W of output power. This is an open surface system without a dam involved. Therefore, water vortex power plant is suitable to be used in the remote areas which are off-gridded from the electricity network.

The efficiency was varied at different speeds, but the optimum efficiency of water vortex turbine was failed to be determined in this study. The maximum efficiency obtained is low, at the value of 22.24%. In run-of-the-river type of turbine system, where no water dam is used to control the required flow rate, low efficiency is expected. However, further optimization to increase the efficiency is possible.

Improvement is reported in this study when curves are added to the exit of the turbine blades. Further study can be carried out to find the optimum speed of the turbines where they produce optimum efficiency. The relation between the optimum speed and the blades’ angle can also be studied.
in a more detailed way. The results can be used to adjust the blades’ angle to fit different speed requirements of the turbine in different conditions.

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