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Experimental Study on 3D Vortex Gravitational Turbine Runner

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Abstract. Vortex turbine is one of the solutions to utilize the low head hydro energy resources. In recent studies, researchers employ four main runner types, namely: flat radial, paddle, centrifugal, and modified form. The turbine performance can be increased by improving the turbine runner from these types into three dimensions (3D) type. In this present work, the performance of a 3D type runner was designed and examined experimentally. The experiment showed that the maximum efficiency was around 24%, at rotational speeds about 90 to 120 rpm. The maximum efficiency was reached at the design condition. The turbine has demonstrated its capability to run from low rotational speed around 40 rpm to relatively high rotational speed 194 rpm. Compared with the previous runner profile, the 3D runner profile can produce a higher rotational speed and showed its stability to run in a wider range of rotational speed. At low rotational speed, power and efficiency decrease because water leaves the runner blade too fast before transferring its energy to the blade. Whereas at high rotational speed the water tends to be pushed out. The turbine performance and efficiency still can be increased by improving the runner profile.

INTRODUCTION

The technology of utilizing hydro energy head medium and high can be said to be already established, but ultra low head hydro energy utilization technology still needs to be developed. Several types of turbines have been studied to extract the low hydro head energy, such as open flume Francis turbine, Kaplan turbine, propeller turbine, tabular turbine, cross-flow turbine, Archimedes turbine, and hydro-kinetic turbine[1], A horizontal spiral turbine and water wheel has also been studied [2]. Researchers have studied these turbines, but most of them are not ready to use. A kind of turbine that is easily constructed and gives satisfactory performance, to utilize the ultra low head hydro energy resources such as tidal energy, ocean wave, irrigation, wastewater generation, tailrace from hydropower, is still needed. It seems that gravitational vortex turbines or vortex turbines are expected to meet these demands. The vortex turbine is environmentally friendly. The turbine provides a wider surface area of water, better aeration, smaller disturbance to aquatic organisms, and improves oxygen solubility[3]. Vortex turbine generation capacity ranges from 0.2 - 40 kW, but can be increased up to 1 MW, even more [4]. Since patented in 2004, gravitational vortex turbine has received much attention as a solution to utilizing low head flow, as low as 0.7 m[5].

The important parts in the vortex turbine are open channel water passage, vortex pool, and runner. The vortex pool is a generally cylindrical shape, with a circular hole at the center. A vortex flow is formed above the hole, and the water flows downward. The runner, which is installed above the hole, rotates due to vortex flow. To increase the intensity of the vortex flow, water flows into the pool in a tangential.

LITERATURE REVIEW

From the literature study, there are four main types of runners, namely: flat radial[6], paddle type[7, 8], centrifugal form[9], and modified types, as shown in Figure 1. The first three types do not have vertical components in their blade. They can only extract the horizontal component of the water stream. To be able to extract the vertical component of hydraulic power, vertical sections must be added to the blade which is carried out in the case of a

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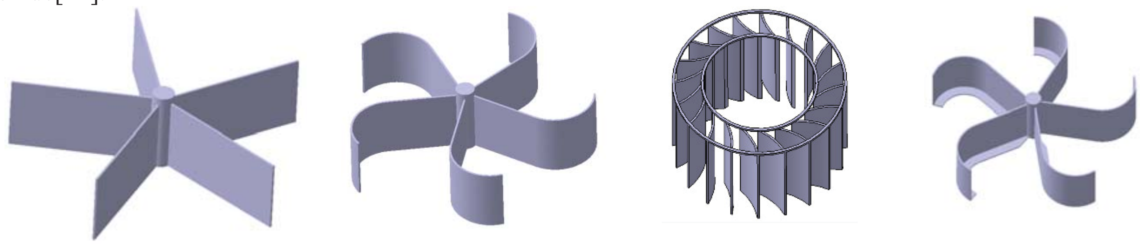
modified runner. So far there have been two modifications made, adding baffles[10], and curves at the bottom end of the blade[11].



(a) (b) (c) (d)

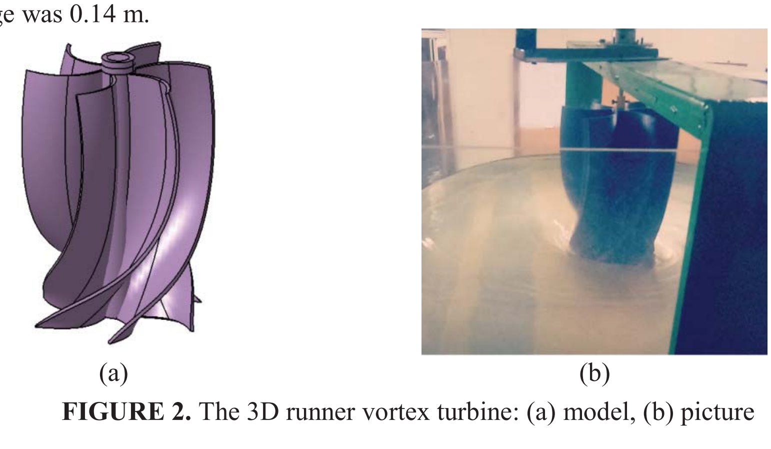
FIGURE 1. Types of runners: (a) flat radial, (b) paddle, (c) centrifugal, (d) modified

Rahman et al.[3] study confirmed that the vertical position of the runner affects efficiency, and that maximum efficiency is obtained if the turbine is placed close to the outlet. A centrifugal-form runner study has been carried out by Nishi and Inagaki[9] booth experimentally and numerically. The results of numerical calculations were in accordance with the results of the experiment, provided that idling power included in shaft power. Shabara et al.[12], conducted a vortex turbine study, with 8 blade runners, validated with CFD, ANSYS Fluent. In the study, the head was chosen between 0.7 - 3 meters. The CFD calculation is validated with a high-speed camera. The results of this study showed that the turbine rotated between 30-40 rpm, with an efficiency of 40%.

Sitram and Suntivarakorn[7] have conducted studies on the number of blade effects on the performance of paddle type turbines. The researchers concluded that the optimum blade number of paddle-type vortex turbine is 5. This configuration gives the highest torque as the distance between blades is effective for receiving the exertion of water flow on the blades. Wichian and Suntivarakorn[10] works concluded that paddle-type runner with baffles gives a better efficiency. Runners with 50% baffles produce the highest torque. Kueh at al.[11] also studies additional effects similar to baffles on the bottom of the blade runner, which are called curves. The study also concluded that adding a curve to the runner also improved the performance of the vortex turbine. These studies lead us to develop a more streamlined runner.

METHODOLOGY

In this study, a vortex turbine experiment with a 3D profile will be carried out, as seen in Figure 2 below. The helix angle is 60º at the bottom, and 300 mm height, 200 mm diameter, and the inlet angle is 30º from radial direction, which was determined with velocity the triangle according to Bajracharya[13]. The blade number was 5 as recommended by Sritram and Suntivarakorn[7]. The runner is vertically twisted, to utilize the potential energy of water. The runner height was designed higher than the water surface to maximize the absorption of available hydraulic power. The vortex pool diameter was 0.8 m, and the vortex hole diameter was 0.14 m, The width of the open channel passage was 0.14 m.



(a) (b)

FIGURE 2. The 3D runner vortex turbine: (a) model, (b) picture

The hydraulic power was calculated with Equation 1, where P_h is the input hydraulic power, ρ is water density, g is gravitational acceleration, H is input water head, and Q is flow rate. The input head was measured from the height difference of the inlet waterway and an outlet channel.

$$P_h = \rho.g.H.Q \tag{1}$$

Before the measurements were made, the system was waited until steady. The water flow rate was measured by an orifice at the inlet pipe. The turbine brake power obtained from Equation 2, where P_s is shaft power, n is rotational speed and T is torque,

$$P_s = 2.\pi.n.T / 60 \tag{2}$$

Figure 3 shows the experiment setup schematic diagram. The main parts of the experimental device are vortex pool to produce vortex (3), runner (2), inlet waterway (5) in the form of open channel, plenum (7), outlet channel (4), reservoir (9), circulation pump (10)). Water discharge was regulated using a valve (6). While the measuring instruments used are: torque meter (1), orifice (8).

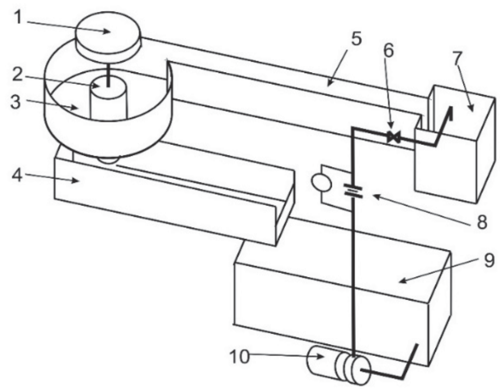


FIGURE 3. Experiment setup schematic diagram

RESULT AND DISCUSSIONS

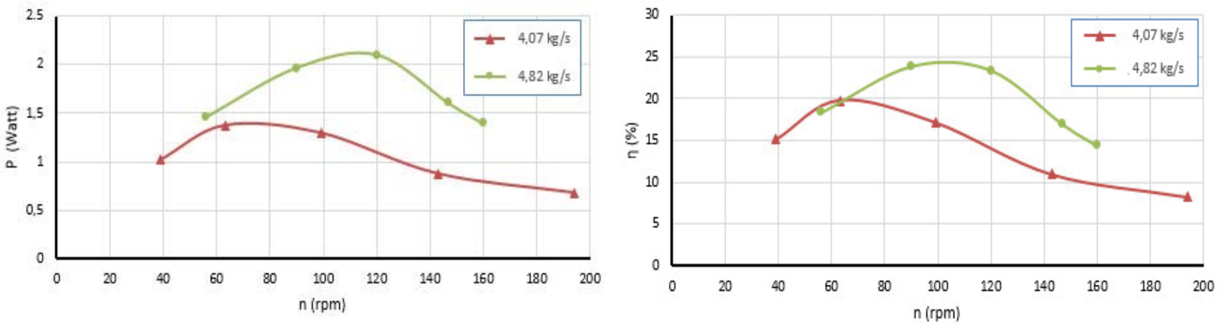
From the experiments that have been carried out obtained data, and processed. Data and processing results are shown in Table 1 and presented in Figure 3.

TABLE 1. Experimental data and calculation result

Mass Flow rate kg/s	Pool Level (m)	Rotational Speed (rpm)	Head (m)	Torque (Nm)	Hydraulic Power (Watt)	Shaft Power (Watt)	Efficiency (%)
4.07	0.17	39	0.120	0.24	6.59	1.00	15.1
4.07	0.17	63	0.120	0.20	6.79	1.34	19.7
4.07	0.19	99	0.135	0.12	7.39	1.26	17.1
4.07	0.20	143	0.145	0.06	7.79	0.85	10.9
4.07	0.20	194	0.150	0.03	7.99	0.66	8.3
4.82	0.17	56	0.120	0.24	7.80	1.43	18.3
4.82	0.17	90	0.120	0.20	8.04	1.92	23.8
4.82	0.19	120	0.135	0.16	8.75	2.04	23.4
4.82	0.20	147	0.145	0.10	9.22	1.56	17.0
4.82	0.20	160	0.150	0.08	9.46	1.36	14.4

Efficiency

From Figure 3 it can be seen that the power and efficiency reach the maximum at certain rotational speeds. The maximum efficiency reached 23.8% at the design mass flow rate of 4.82 kg/s, and rotational speed of 90 rpm, while at 120 rpm the efficiency was slightly reduced, 23.4%. For a lower flow rate, the maximum efficiency decreased to 19.7%, at a lower rotational speed of 63 rpm. This is caused by a torque decrease due to the tangential velocity decrease, and changes in the angles in the velocity triangle, so that the relative entry angle is not the same with the entering angle of the runner.



(a) (b)

FIGURE 4. (a) Power against rotational speed (b) Turbine efficiency against rotational speed

From Kueh et al. [11] vortex turbine experiment with flat and curved runners, the maximum efficiency is 21.26% for the flat runner and 22.24% for the curved runner. This efficiency is still below the 3D runner. The maximum rotating speed for both flat runner and curved runners is 40 rpm at zero torque, while their rotating speed at the maximum efficiency for the flat runner are 31 rpm and 34 rpm respectively. The curved runner has slightly better efficiency and rotating speed. The minimum rotating speed for the 3D runner was 39 rpm at 15.1% efficiency, and the maximum rotating speed was 194 rpm. This comparison shows that the 3D has better performance than the flat and curved runner.

Some numerical studies showed higher efficiencies. CFD study on the paddle-type runner by Shabara at al. [12] resulted a maximum efficiency of about 42%. A study on radial type runner by Nishi and Inagaki [9] found that the maximum efficiency was 35.4%. The turbine efficiency from the CFD study included idling power as mechanical shaft power, therefore they obtained higher figures.

However, the runner design method did not provide any details on the 3D profile. The turbine efficiency can still be increased by improving the profile.

Rotational Speed

This experiment showed that the turbine has demonstrated its capability to run from low rotational speed around 40 rpm to relatively high rotational speed 194 rpm. At that rotational speed range, the lowest efficiency was 8.3%. Kueh experiment [11] showed that the rotational speed for flat and curved type runner was around 30 – 40 rpm, while the lowest efficiency was zero at about 40 rpm. Nishi and Inagaki [9] study on radial runner found that the runner rotational speed was from about 40 to 160 rpm. Compared with previous studies, it can be concluded that this runner profile can produce a higher rotational speed at 194 rpm, showed its ability run from low speed, and showed its stability to run in a wider range of rotational speed.

Inlet Water Level

Figure 4 shows that the inlet reservoir waterway level against rotational speed. The inlet water level tends to increase toward the rotational speed. Figure 5 shows the velocity triangle at the inlet and outlet position of the blade. The blade velocity, the water velocities were represented by u, v, and w respectively, while α and β are absolute and relative flow angles. At the inlet side, for design condition (120 rpm, 4.8 kg/s), the relative flow angle, β_1, is the same as the blade profile. The water flows smoothly towards the blade. Therefore, the efficiency reaches the maximum value. Any deviation from design conditions, such as decreasing flow rate, increasing or decreasing rotational speed will decrease the turbine shaft power and efficiency, which can be seen in Figure 5a.

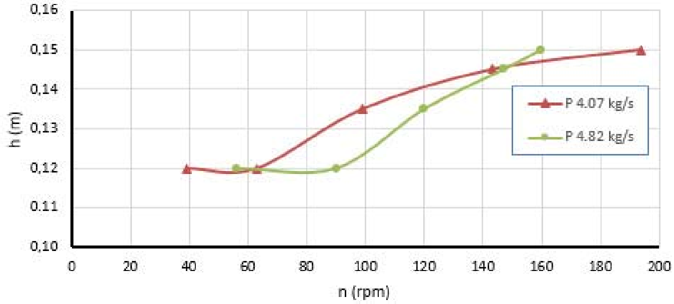


FIGURE 5. Inlet water level against rotational speed

FIGURE 6. The velocity triangle: (a) at inlet side (b) at outlet blade side

At the outlet side, the water assumed move downward vertically, with constant velocity. The velocity is equal to the water flow rate divided by the area of the hole. The relative angle decrease because of increasing rotational flow. To compensate the decreasing relative angle, therefore the water level increase to make water absolute velocity, *v*, constant, as shown in Figure 5b. At low rotational speed, power and efficiency decrease because water leaves the runner blade too fast before transferring its energy to the blade. Whereas at high rotation the water tends to be pushed out, thus raising the surface of the water in the reservoir. This is evidenced by the increase in water level in the upper reservoir due to an increase in turbine rotation.

CONCLUSIONS AND RECOMMENDATION

From the previous discussion, it is concluded:

1. There is an optimum rotational speed that provides the highest efficiency, at about 90 to 120 rpm. The maximum efficiency reaches 23.8 % at 4.07 kg/s mass flow rate. This figure was slightly higher than of flat and curved runner.
2. The turbine has demonstrated its capability to run from low rotational speed around 40 rpm to relatively high rotational speed 194 rpm. Compared with the previous runner profile, the 3D runner profile can produce a higher rotational speed and showed its stability to run in a wider range of rotational speed.
3. At the design condition, the relative flow angle was relatively the same as the blade profile. Therefore, the efficiency reaches the maximum value. Any alteration from design conditions, such as decreasing flow rate, increasing or decreasing rotational speed will decrease the turbine shaft power and efficiency.
4. The relative angle at the outlet side of the blade, decreases because of increasing rotational flow. To compensate the decreasing relative angle, therefore the water level increase to make water absolute velocity is constant.

Furthermore, efforts should be made to increase performance and efficiency by improving the runner profile

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