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The effect of using upper shroud on the performance of a breashoot water wheel

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Abstract. The cost-effective and ecologically acceptable exploitation of hydropower machine with small scale (low head and low flow rate) is still a challenging area. Breastshoot water wheel is one mode of the small scale hydropower machine that is common to use to generate power. The effect of using upper shroud on a breastshoot water wheel was evaluated. The research was done by examining two breastshoot water wheels with the outer diameter and hub diameter of 240 mm and 160mm respectively. Furthermore, the blade width is 40 mm. The wheel consist of 2 wheel which separated by 4mm thickness rim which the diameter the same as outer diameter of the outer wheel. Each side of the wheel consists of 12 blades. The experimental was done with two variations of wheel, i.e with upper shroud and without upper shroud. The torque was measured with prony brake method. The breastshoot wheel that was tested in this research is zuppinger water wheel type. The experimental result shows that the efficiency of the breastshoot water wheel with upper shroud is higher than water wheel without upper shroud in all speed range.

1. Introduction

Hydropower is currently the most common form of renewable energy and plays an important part in global power generation, especially electricity. However, there are still many people do not have access to electricity. In 2012 the percentage of Indonesians who do not have access to electricity is around 26% [1]. One frequent cause for this problem is the large number of dispersed rural locations with challenging geographical conditions. An additional cause is the uneven distribution of population which has led to an ineffective electrical distribution infrastructure. To solve this problem, Small Hydro-Power plant could be a solution for rural areas that have natural resources such as lakes, irrigation canals, rivers or waterfalls. Small scale hydro is in most cases 'run-of-river'; in other words any dam or barrage is quite small, usually just a weir, and generally little or no water is stored [2].

Water wheel technology is one form of an energy generation machine that utilizes small scale water resources, therefore this technology is quite favourable for small scale hydropower plant. This technology also fish friendly due to the low speed and large cells, compared with the large scale hydropower technology, which most of them are turbine based technology. In addition, this technology is environmentally friendly, since it does not require large disturbance of the river flow [3]. Breastshot is one type of wheel where the water enters the wheel approximately at the level of the axis. This wheel was used for head differences of 1.5-4m, and flow rates of 0.35-0.65m^3/s per m width[4]. It is reached efficiencies of up to 80-85 %, compared to typical undershot wheels around 30%. A typical type of breast shot is Zuppinger water wheel (Zuppingerrad water wheel) which was proposed by [5], with the

water wheel design as shown in figure 1. This machine was patented by Walter Zuppinger in 1848 to fulfil the need of the head differences between 2 and 5 m. This wheel was designed to cover the gap between the low-head water wheels, and overshot water wheels (H = 2 to 5 m, Q = 0.2 to 2 m^3/s) [5]. This machine was claimed working well with efficiency in between 75-80.
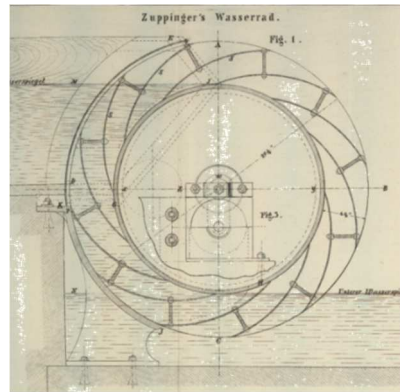

Figure 1. The turbine wheel from 1848 [5].

This machine has curve blade which make this machine dissimilar to other breastshoot machine. Furthermore this machine also accomplished with upper shroud. This curved tips on the blades would exit the water more vertically and therefore more cleanly, which reduce losses eventually. Nevertheless the existence of the upper shroud is an interesting topic that need to be investigated. In this study, the role of the upper shroud was investigated by performing two sets of experiments in which a set of machines used upper shroud, while another set was not given upper shroud.

2. Literature review

Several research results have been reported dealing with the water wheel technology. An undershot wheel was reported can be used for very small head differences, ranging from 0.5-2.5m, and flow rates in the range of 0.5-0.95m^3/s per m width [4]. This type of wheel was originally used as an impulse wheel, employing kinetic energy. The blades were typically mounted on a hub perpendicular to the circumference of the hub. When water from the mill stock flowed past the wheel, it hits the blades, and some of its momentum was transferred to the wheel. However, much of it was also reflected off the blade and lost as heat. This process was not efficient; much of the original velocity in the water remained in it, meaning that potential energy was not being captured. Typical undershot wheels were around 30% efficient [6]. This water wheel is depicted in figure 2(a).

Walter Zuppinger a Swiss hydraulic engineer designed another type of undershoot water wheel, which is believed the most efficient water wheel, He patented a waterwheel geometry, which had curved tips to the blades which would exit the water more vertically and cleanly. These machines had efficiencies up to 77% [4]. Working principle of Zuppinger water wheel is shown in figure 2(b).

A vertically mounted water wheel that is rotated by falling water striking buckets near the top of the wheel is said to be overshot. It was employed for head differences of 2.5-10m, and flow rates of 0.1-0.2 m^3/s per m width. The water collects in the buckets on that side of the wheel, making it heavier than the other "empty" side. The weight turns the wheel, and the water flows out into the tail-water when the wheel rotates enough to invert the buckets. Figure 2(c) is an example of overshoot water wheel with a sluice gate. The water can enter each cell at its natural angle of fall, by forming the cells in a certain geometry.
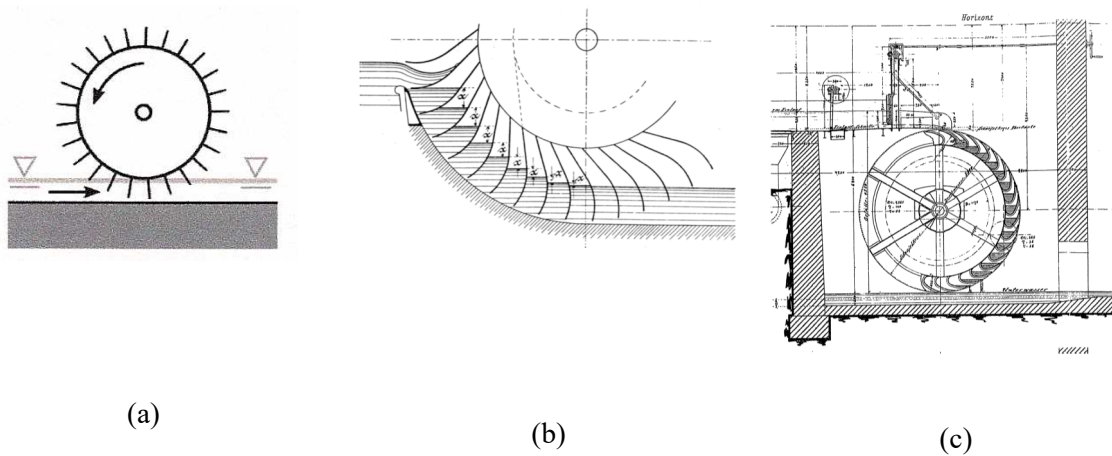
(a)

(b)

(c)

Figure 2. (a) Undershoot water wheel [7]
(b) Working principle of Zuppinger water wheel [8]
(c) A typical overshot water wheel [8]

Theoretical analysis Rotary Hydraulic Pressure Machine (RHPM) has been developed by [9] accompanied with experimental work. This machine can be applied to hydropower sources with heads up to 5m [9]. The experimental work that has been done by Senior, was shown that the efficiency of this machine can reach 80%. The graph of the Rotary Hydraulic Pressure Machine performance and the machine are shown in figure 3.
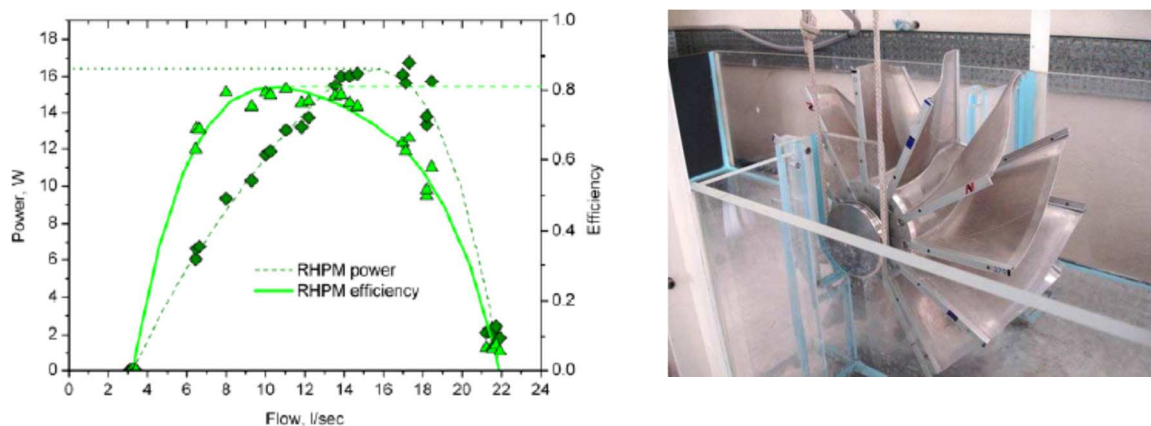

Figure 3. Rotary Hydraulic Pressure Machine performance and the machine [9]

3. Methodology

The experimental was conducted in the Hydraulics Laboratory. The model was placed in the 12m long, 30cm width and 40cm flume. Figure 4 shows a schematic diagram of the flume. The water from sump is pumped to the flume. The flow rate Q and head level H is controlled by using a control valve.
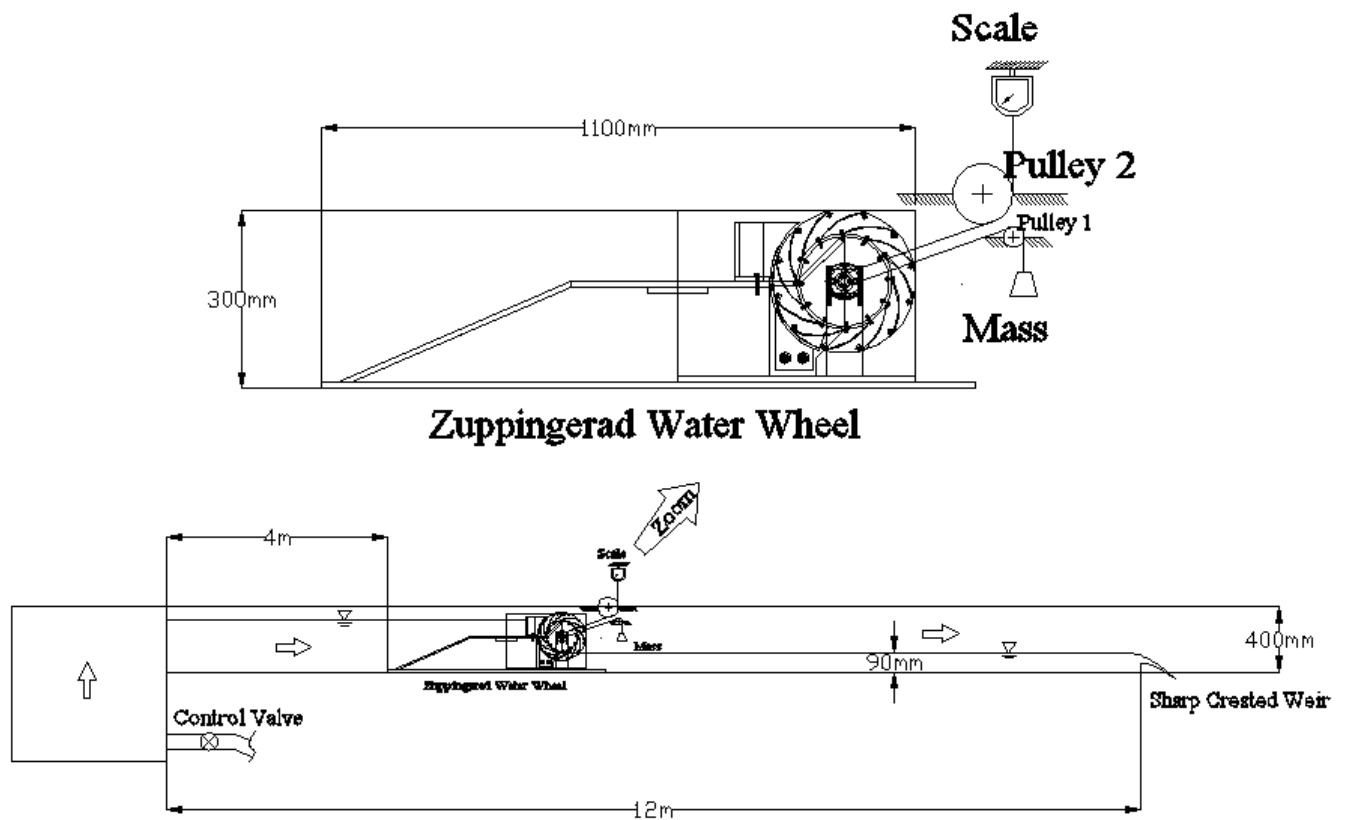
Figure 4. Schematic diagram of the flume

This Zuppingerrad water wheel was tested in two variations; with upper shroud and without upper shroud as shown in figure 5(a). A Prony was used to measure the power from the water wheel. The power is calculated by using equation 1. The friction wheel that was used is the disc which has gully as track for rope to wrap which has radius r= 26mm.

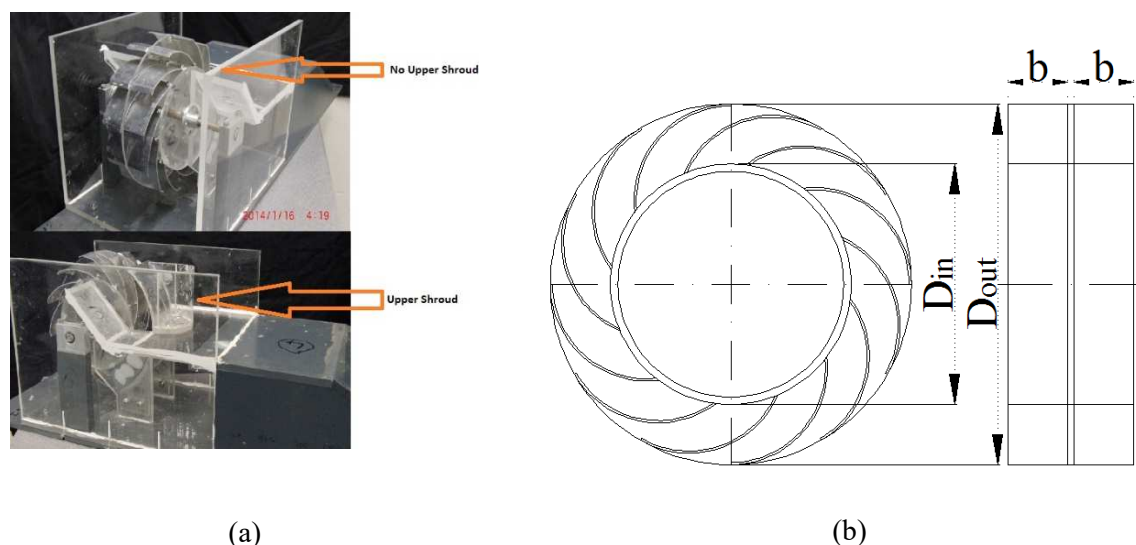(a)   (b)

Figure 5. (a) Photograph of the testing model, upper side : without shroud , lower side :with shroud (b) Wheel and the dimension

$$P_{out\ measured} = (M_{measured\ from\ scale} - m_{mass})g \cdot r \cdot 2\pi \cdot f \tag{1}$$

$$f = \frac{number\ of\ revolutions}{time(s)} \tag{2}$$

Theoretical water flow rate is the flow rate that will be used as a basis to calculate the efficiency of the machine tested in these experiments. The equation to calculate theoretical water flow rate through water wheel is based on the equation 3.

$$Q_{th} = \frac{((D_{out})^2 - (D_{in})^2 - n.l - n.t)\,\pi \cdot 2\,b \cdot f}{4} \tag{3}$$

Where D_{out} is the outer diameter of the water wheel, D_{in} is the inner diameter of the water wheel, n is number of blades, l is the length of the blade and t is the blade thickness. Whereas b and f is the blade width and rotational speed respectively. Equation 3 refers to Fig 5(b).

Hydraulic power available according to flow rate in blade of water wheel can be calculated based on the water flow rate passes through water wheel blade's P_{mi} by equation 4.

$$P_{m\,i} = \rho_{water} \cdot Q_{th} \cdot g \cdot H \tag{4}$$

The efficiency in this case is the ratio between output power $P_{out\ measured}$ and the hydraulic power available according to flow rate in blade of water wheel which is calculated based on the water flow rate passes through water wheel blade's P_{mi}. This efficiency is then called as efficiency exclude leakage η_{wl}. This efficiency η_{wl} is formulated as in equation 5.

$$\eta_{wl} = \frac{P_{out\ measured}}{P_{mi}} \tag{5}$$

Tangential velocity of the water wheel can be written as equation 6

$$v_{tan} = \frac{(D_{out} + D_{in})\,\pi \cdot f}{2} \tag{6}$$

The maximum possible velocity of the water is free fall velocity of the water on the certain distance which is the head H of the water wheel or the hub diameter.

$$v_{max} = \sqrt{2 \cdot g \cdot H} \tag{7}$$

4. Discussion and Conclusion

4.1. Measured power vs rotational speed

Fig 6 shows measured power vs rotational speed of the water wheel. Measured power is calculated as refer to equation 1, whereas the speed is the rotational speed per minute *rpm*. It reveals that the water wheel with upper shroud provides higher power in comparison with the water wheel without upper shroud. The differences in power output are more obvious in higher speed. The graph also shows that the power output is decreasing as the speed increases. More over the maximum power output for water wheel with upper shroud is 2.5 Nm/s at the speed of 67 rpm, whereas in the case of without upper shroud the maximum power is 1.7 Nm/s at the speed of 60 rpm. At speeds of more than 46 rpm, the power output from the water wheel with an upper shroud is consistently higher than the power output of the water wheel without an upper shroud. Yet at speeds lower than 46 rpm, the power output trend is not as consistent as with speeds greater than 46 rpm. The power output of both wheels seems to overlay each

other and has no pattern. This data indicates an error has occurred. This error is due to the methodology of measurement, by using the clasical prony brake which relies on the friction between the rope and the prony wheel. At low speeds (high torque), sliding occurs between the rope and the prony wheel which causes an inacurate measurement of the power output.
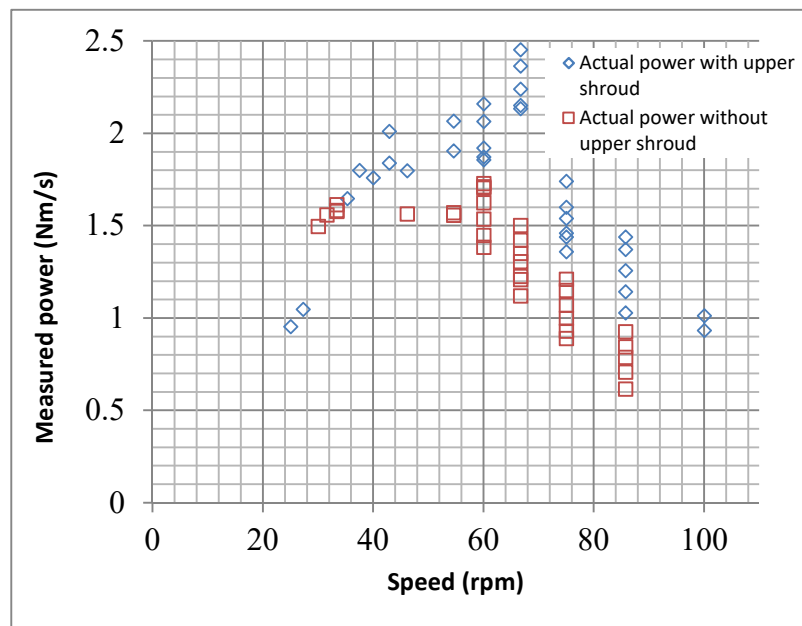

Figure 6. Power vs speed

4.2. Efficiency vs tangential velocity

Fig 7 represents the efficiency vs tangential velocity of the water wheel. The tangential velocity is non-dimensionalized by dividing it with the maximum possible velocity of the water (see equation 7). The effect of the upper shroud on the efficiency of the water wheel is being compared. The efficiency in this case is the ratio between measured powers $P_{out-measured}$ to hydraulic power available P_{mi} as stated at equation 4. Most of the data indicates that the efficiency of the turbine wheel with an upper shroud is higher than the turbine wheel without an upper shroud. For example at v_{tan}/v_{max} 0.39, the efficiency of the turbine wheel with upper shroud is in the range of 60-67%, whereas the efficiency of the turbine wheel without upper shroud is in the range of 32-42%. The difference in performance between these two turbine wheels might be related to the losses of power at the entrance of the machine. In the case of the wheel without an upper shroud, the blade hits the incoming water and creates splashing. This is what is called by [10] as 'water slamming'. Water slamming is the event where the blade hits the body of the water at the cell inlet. This situation generates additional losses especially at high rotational speed. This water slamming occurs in the case of turbine wheel without an upper shroud, whereas in the case of turbine wheel with an upper shroud this situation does not occur.
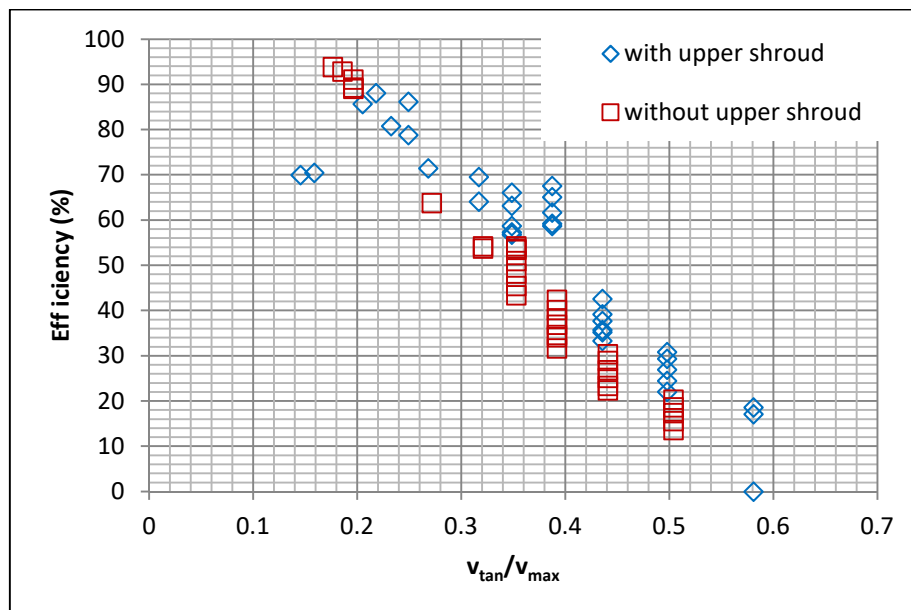
Figure 7. Efficiency vs non dimensionalized tangential velocity

5. Discussion and Conclusion

1. Water wheel with upper shroud gives higher efficiencies rather than a water wheel without an upper shroud.

2. The difference in performance between these two turbine wheels might be related to the losses of power at the entrance of the machine, which is called as water slamming.

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