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Development of the Dethridge Wheel Blade Shape for Hydropower Generation in Irrigation Canals in Indonesia

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ABSTRACT

Consumption of electrical energy continues to increase along with population growth. As a result, various sources of electrical energy are utilised to meet these needs, especially in areas that have not been reached by the national electricity network. In countries with hilly geography and irrigation canals, pico hydro energy is often considered an alternative. One of the tools used to convert water flow energy into electrical energy is the Dethridge wheel. The Dethridge wheel is a simple waterwheel that is easy to manufacture and suitable for irrigation canals with very low water head heights. This study aims to increase the performance of the Dethridge wheel by changing the shape of the wheel blades and examine the effect of the variation of water flow rate in the channel. Experimental and numerical methods were used to investigate the potential of the developed wheel. The Dethridge wheel and its development were tested using an artificial irrigation canal with flow rates of 20, 30, 60, 90 and 120 m³/h. Furthermore, a three-dimensional numerical model of the Dethridge wheel was simulated using Ansys Fluent 18.2 software. The highest efficiency of the experimental Dethridge wheel, 55.6%, was achieved when the flow rate was 30 m³/h. The developed Dethridge wheel efficiency increased to 71.72%. These results are also in agreement with the simulated model.

1. Introduction

The global use of electrical energy continues to increase due to general population growth. In 2012, electricity consumption increased by 1.8% from the previous year, and in 2018, it jumped by 4% from 2017 [1]. Until now, the largest source of electrical energy has come from fossil fuels, at 57.1% of electricity generation, followed by nuclear at 18%, and then hydropower at 13.2%, although its utilization is the largest compared to other renewable energy sources [2]. In Indonesia, the target of renewable energy application is 23% by 2025 especially in off-grid areas [3]. In areas with limited access to the national electricity grid, electrical energy generated from micro hydro helps the development of local areas, contributes to improving community welfare and bolsters environmental conservation [4,5]. Furthermore, the availability of power would enhance the growth of industries

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and activities in the service sector and increase its competitiveness [6,7]. However, the utilisation of renewable energy from water energy is not simple, as it is dependent on the weather and geographical conditions [8,9].

If they can be utilised, irrigation canals are a potential source of renewable energy that can provide up to 1.5–2 kW/Ha [10,11]. However, hydropower plants must be able to operate efficiently and not obstruct the environment [12]. An efficient, reliable and cost-effective option is pico hydro, which is produce less than 5 kW of power and can be operated at locations with low water head heights [13,14]. Pico hydro may be more effective to generate power than diesel engines, wind generators and solar cells [15]. The application of pico hydro is suitable for off-grid electricity in Indonesian rural areas even when utilising low heads [16].

For heads less than 5 m, an axial pump can be employed as a generator with a flow rate of 50 to 1000 L/s [17]. Meanwhile, for lower heads, waterwheels are a cost-effective choice as long as the ratio between the radius of the wheel and the submerged radius is at least 0.5 [18]. The Zuppinger mill has an efficiency of up to 75% [19] for a 1 m head, which is reduced to 60% for a 0.5 m head [20]. Even at heads between 0.2 and 1 m, hydrostatic pressure mills can still be used [21]. Meanwhile, Paudel has used the Dethridge mill to generate electrical energy from irrigation flow and has also investigated the optimal wheel size–canal geometry ratio [22,23].

The Dethridge wheel is a waterwheel that is simple and easy to make; it can be made with simple equipment and materials. These mills are suitable for driving generators in irrigation canals with very low heads, although they were initially used as water flow meters. Furthermore, studies have shown that the Dethridge wheel has a weakness due to the shape of the blades, because the force of the water decreases when the blade starts to spin up [24]. However, few improvements have been proposed for the Dethridge wheel blade shape to increase its efficiency. Therefore, this study aims to develop the Dethridge wheel by changing the shape of the blades.

2. Methodology

2.1 Experimental Setup

This study used an irrigation canal made of transparent plastic with a length of 20 m in accordance with the standard of quaternary irrigation canals in Indonesia [25]. The waterwheel was placed 10 m from the inlet to allow the water flow to become subcritical. To focus the water impulse, the width of the canal was reduced such that the distance between the canal wall and the wheel was only 7 mm on each side, as shown in Figure 1.

Fig. 1. Dethridge wheel experimental rig installation

The tools used in this study are listed in Table 1.

Table 1
Measuring tools used

Measuring Instrument	Type
Rotameter	0–150 [m^3/h]
Tachometer	KW06-563
Torque meter	Lutron TQ-8800
Flow Velocity meter	Flowatch FL-03

This research compares two systems: the Dethridge wheel (DW) adapted from Paudel and Saenger [22] and a developed Dethridge wheel (dDW) with a different blade shape. The two waterwheels used the same blade material: steel plates with a thickness of 1.8 mm. The two wheels have hub radii of 300 mm and widths of 250 mm. The hub covers are made using wood materials. The dimensions of the DW and dDW can be seen in Figure 2 and Figure 3, respectively.

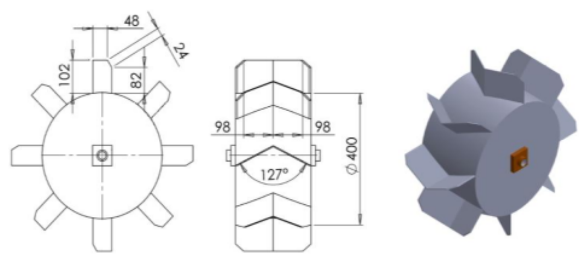


Fig. 2. Dethridge wheel geometry

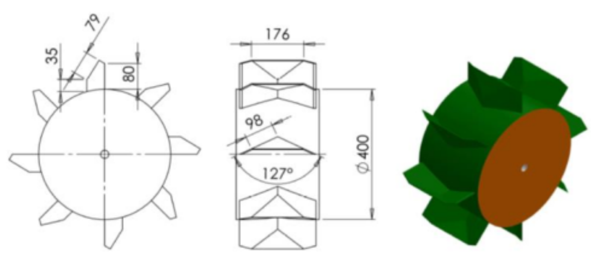


Fig. 3. Developed Dethridge wheel geometry

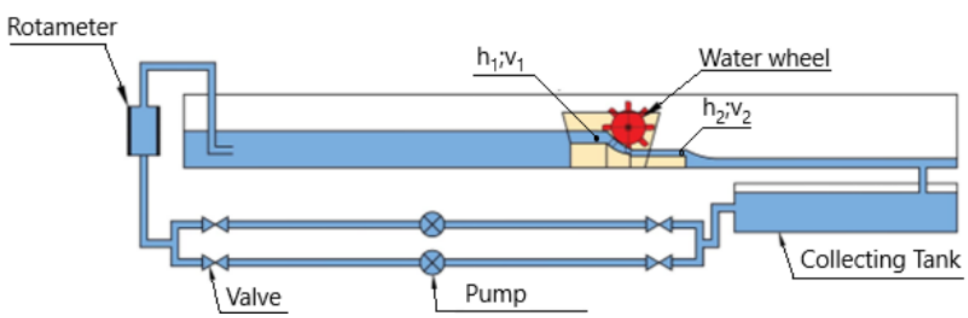


Fig. 4. Experimental setup

Two water pumps were used to pump water from the collecting tank to the canal by first passing the water through the rotameter, as shown in Figure 4. The water discharge was regulated by changing the pump rotation. The water that enters the canal flows towards the wheel, and afterward, it enters the collecting tank. Waterpower is obtained by multiplying the pressure due to the head difference with the flow of water (Q). The total head is obtained based on the difference in pressure and speed at the entrance and exit of the wheel, where h_1 and v_1 are the height and velocity of the water entering the wheel, respectively, while h_2 and v_2 are the height and velocity of the water leaving the wheel, respectively [19]

$$H = \left(h_1 + \frac{v_1^2}{2g}\right) - \left(h_2 + \frac{v_2^2}{2g}\right)$$

$$P_i = \rho \; x \; Q \; x \; g \; x \; H$$

The power produced by the wheel is calculated by multiplying the torque (T) and angular velocity (ω)

$$P_o = T \; x \; \omega$$

The efficiency of the wheel, which is a comparison of the waterwheel power and the waterpower, is obtained by

$$\eta = \frac{P_o}{P_i} \; x \; 100\%$$

The moving mass of water ($\dot{m}$) causes the water force (F_a) to push the blade and create a tangential force of the wheel (F_t), which is perpendicular to the shaft of the wheel such that it generates the wheel force (F_e) [26,27]

$$\dot{m} = \rho \; x \; A \; x \; v$$

$$F_a = \dot{m} \; x \; (v_2 - v_1)$$

$$F_t = \frac{F_a}{coscos \; \theta}$$

2.2 Computational Fluid Dynamics

Computational fluid dynamics (CFD) is dedicated to determining fluid flow behaviour using computational simulations [28]. The simulation was performed using Ansys Fluent 18.2 software and divided into two geometry models: DW and dDW. Furthermore, the simulation was carried out using 2D following Cleynen *et al.,* [29]. Each model utilised a geometry consisting of a stationary part and a rotating part to control the rotating motion of the turbine and improve the mesh quality.

The mesh used in this simulation had a maximum size of 20 mm globally and a minimum size of 2 mm in high-gradient areas, such as the rotating region, blade and surroundings, as shown in Figure 5 and Figure 6.

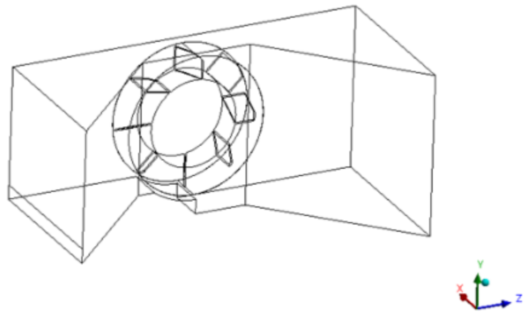


Fig. 5. CFD Wheel Geometry

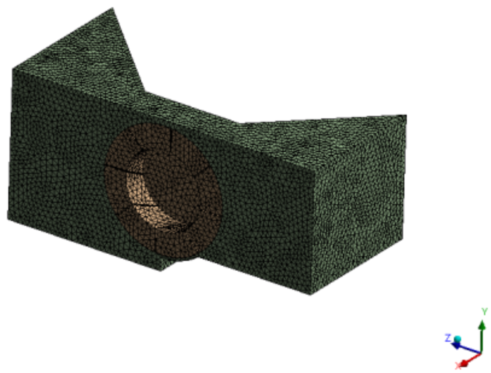


Fig. 6. Global Meshing

3. Results

3.1 Experimental Data

The waterwheel is given a torque load, which is maintained at 7 kg-cm, while the rotation of the wheel follows the discharge flow. The surface height and water flow velocity before and after the waterwheel change according to the increase in discharge flow, as can be seen in Table 2 and Table 3.

Table 2
Setting of CFD

Gravity	–9.81
Turbulent	k-omega, SST
Mesh Motion	Rotating
Fluid	Air and water

Table 3
Water levels of DW and dDW

Q (m^3/h)	Water Level DW (m)		Water Level dDW (m)	
	h_1	h_2	h_1	h_2
20	0.041	0.013	0.040	0.011
30	0.051	0.018	0.056	0.017
60	0.073	0.019	0.068	0.019
90	0.083	0.020	0.074	0.021
120	0.094	0.022	0.088	0.024

The speed of the water before the wheel is different from the water after the wheel. The flow of water before the wheel has a Reynolds number of 2,357 for DW and 2,457 for dDW, which means that the water is in transitional flow and beginning to enter turbulent flow regime. The flow is laminar for Re < 500 in open-channel flow. Also, open channel flow is usually turbulent for Re > 2500 and transitional for 500 < Re < 2500 [30]. The flow also appears wavy under visual observation, although the Froude number of the flow before the wheel is in the range of 0.28–0.42 for DW and 0.32–0.44 for dDW. This means that the flow is subcritical and dominated by gravity. Meanwhile, the flow after the wheel is turbulent, with a Reynolds number of 18,800 for both DW and dDW. Additionally, the Froude number after the wheel is 1.53–2.10 for DW and 1.64–2.07 for dDW, which means that the flow has become supercritical. Although the maximum output of the wheel decreases when the Reynolds number increases, the turbine has a blockage ratio of 0.88; thus, almost all of the flow force drives the wheel to rotate [31-33]. Therefore, according to Eq. (2), the waterpower has also increased, as shown in Figure 7.

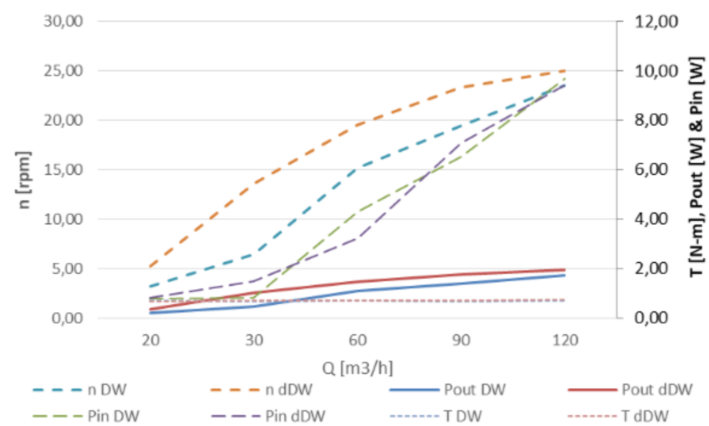


Fig. 7. Wheel rotation (n), torque (T), power of water (P_{in}) and power of wheel (P_{out}) for DW and dDW

In addition to displaying waterpower, Figure 7 also displays torque, wheel rotation and wheel power. The torque was kept at 0.7 N-m for both waterwheel types. The rotation increased with increasing water discharge. Theoretically, if the water discharge increases, the velocity and mass of the flow also increase, which causes the kinetic energy that moves the blade to increase [34-36]. Hence, the turbine power increases.

It appears that the rotation of the dDW is faster than that of the DW, although the difference becomes smaller with an increase in water discharge. The difference in the efficiency of the two waterwheels also decreased, as shown in Figure 8. The highest efficiency occurred at a discharge of 30 m^3/h. At lower water discharge, the mass of water is not strong enough to overcome the waterwheel's inertia [37]. The simulation using CFD produced results that are in line with the experiment, as seen in Table 4.

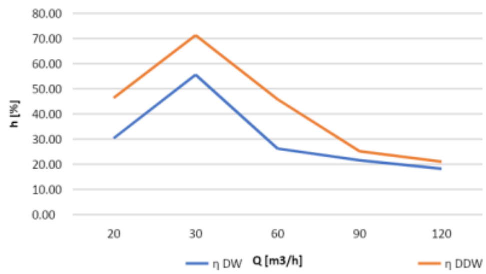


Fig. 8. Efficiency of DW and dDW

Table 4
Velocities of DW and dDW

Q (m^3/h)	Velocity DW (m/s)		Velocity dDW (m/s)	
	v_1	v_2	v_1	v_2
w	0.18	0.55	0.20	0.55
	0.25	0.71	0.27	0.70
	0.32	0.80	0.35	0.83
	0.35	0.92	0.40	0.92
	0.41	0.99	0.42	0.97

Table 5
Torque in CFD simulation [N-m]

Q (m^3/h)	DW	dDW
20	0.0712	0.1160
30	0.1603	0.2609
60	0.6415	1.0440
90	1.4435	2.3484
120	2.5663	4.1749

The water mass discharge varies between the two waterwheels to the different shapes of the blades, as shown in Figure 9.

Figure 9 demonstrates that the water held by the wheel has piled up, and the water piles up higher for greater flows. This happens for both blade shapes. However, the pile of water in the dDW is higher than in the DW because the water in the DW blades can immediately flow when leaving the shroud at the bottom of the wheel. Meanwhile, in the dDW, the water still pushes the blade at the end of the shroud. This can be explained by looking at the direction of the force acting on the blade, as illustrated in Figure 10.

Figure 10 shows the direction of the velocity when the water enters and leaves the DW and dDW, as presented previously by several studies [38-40]. The dDW has a greater effective velocity than the DW. The shape of the dDW blade enables the water to remain at the end of the shroud for longer. This extends the time and magnitude of the force pushing on the blade, thereby increasing the effective force and power [41,42].

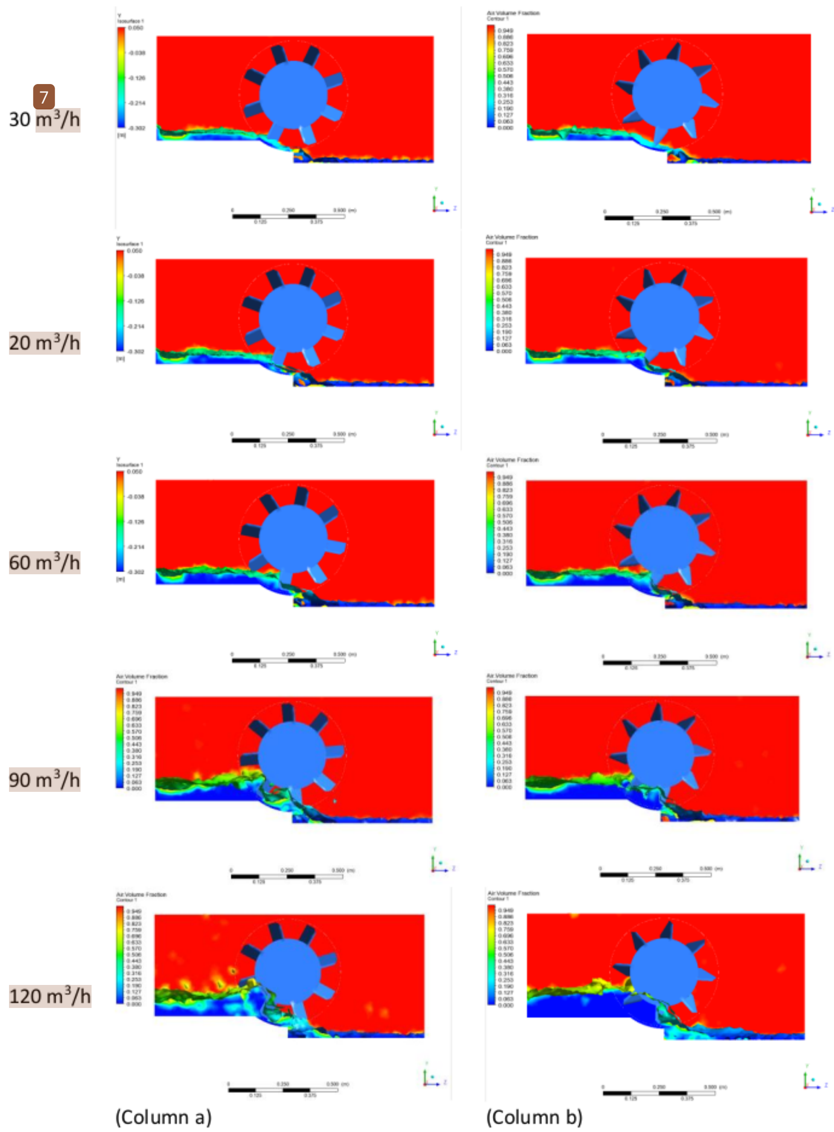
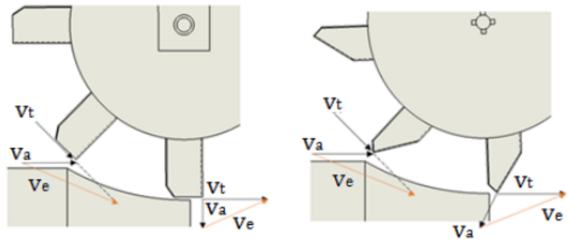


Fig. 9. Water mass discharge of (Column a) DW and (Column b) dDW at water discharges of 20, 30, 60, 90 and 120 m^3/h



(a) (b)

Fig. 10. Forces on DW (a) and dDW (b), v_t is tangential velocity, v_a is the inlet velocity of water, and v_e is an effective velocity

4. Conclusions

Although the head height in irrigation canals is usually relatively low, the energy possessed by the flow of water in irrigation canals has not been fully exploited, even though the energy potential is sufficiently large, especially in areas with hilly terrain. Thus, proper tools are needed to convert the flow of water energy into electrical energy. One tool that is simple and easy to manufacture is the Dethridge wheel.

Therefore, several developments pertaining to the Dethridge wheel blade have been conducted to improve its performance. The experimental results show that the shape of the waterwheel blade affects the power and efficiency. The developed Dethridge wheel utilises a blade shape that allows water to push continuously until the blade leaves the canal bed, causing larger forces for a longer duration, which consequently impacts power and efficiency. The highest efficiency of the Dethridge wheel was found to be 55.56%, while that of the developed Dethridge wheel was 71.72%. Thus, the developed Dethridge wheel increases efficiency by 29% at 30 m^3/h. CFD results are also in agreement with the experiment.

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