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- Judul Artikel : Impact of Angle Cap and Water-Filled Blade Modification On The Output of Overshot Waterwheels
- Penulis : Rizki Afif Afandi, Dan Mugisidi, Giri Parwatmoko, **Oktarina Heriyani.**
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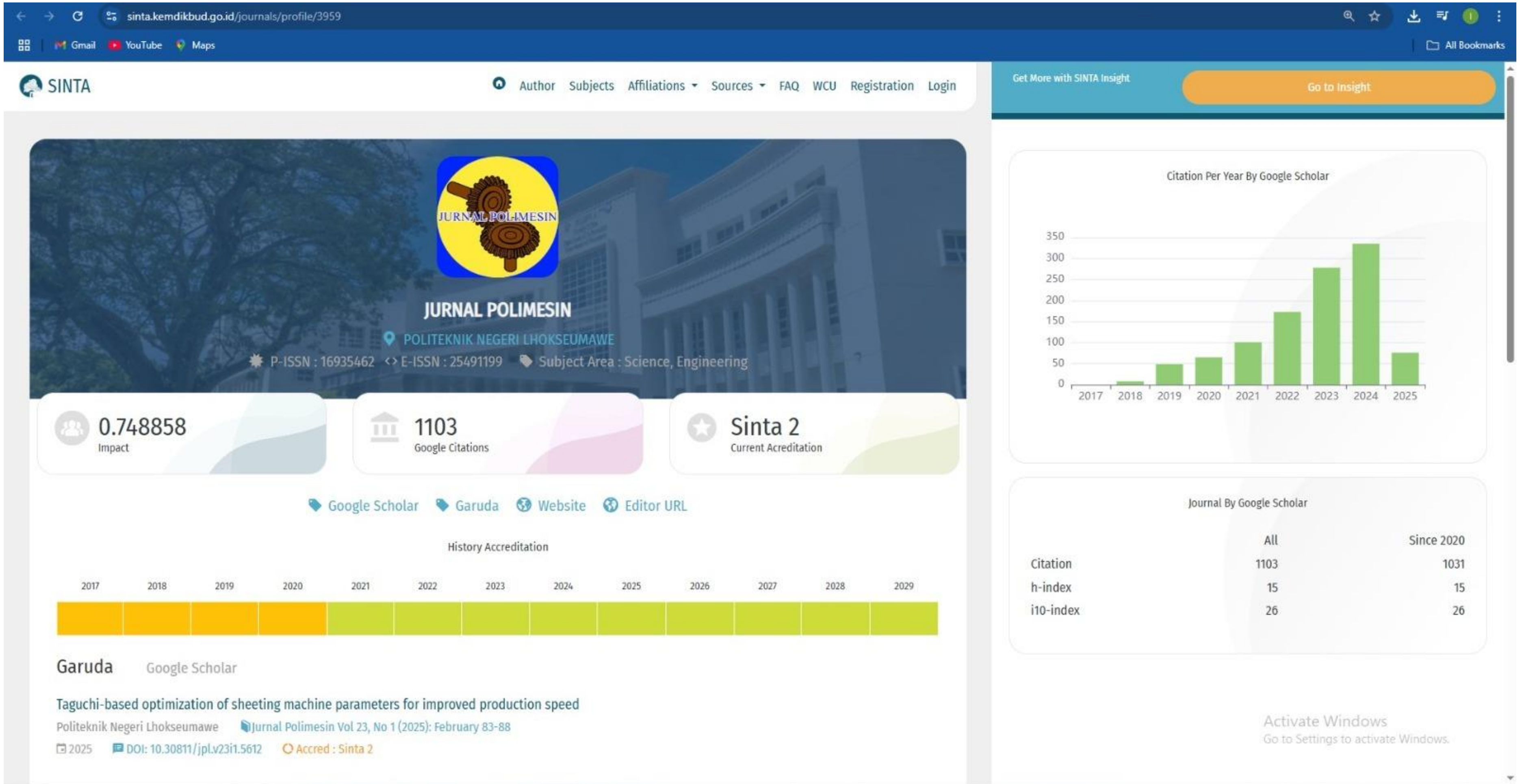

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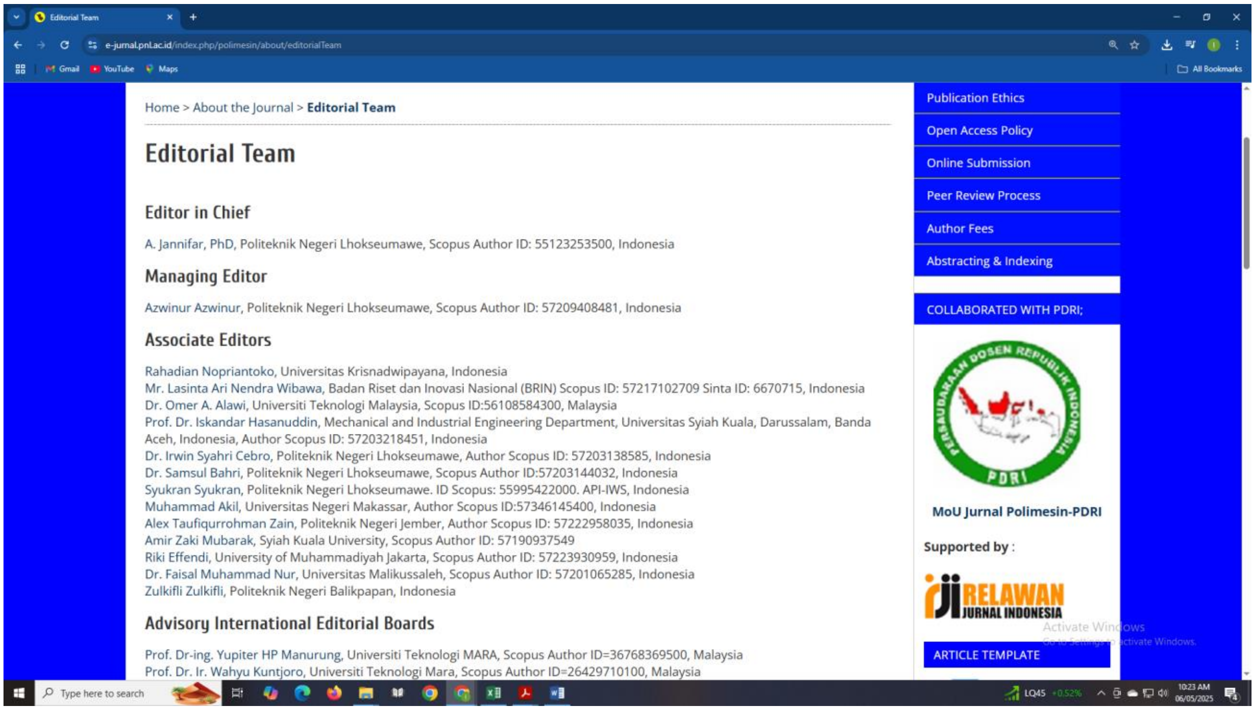

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#6543 Summary

SUMMARY REVIEW EDITING

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Title and Abstract

Title: Impact of angle cap and water-filled blade modification on the output of overshot waterwheels

Abstract

The utilization of water resources as renewable energy through waterwheels presents an environmentally friendly alternative, however, its efficiency requires improvement through technological modification. This research investigates two design modifications: a 45° Angle Cap (AC) and a Water-Filled Angle Cap (WFAC), in comparison with a waterwheel without a Cap (WC). Experiments were conducted at discharges from 1 to 10 m^3/h with a constant torque load of 0.05 N-m. The highest

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efficiency of 57.08% was achieved in the AC 45° configuration at 1 m^3/h, generating 1.09 watts of power, while the WFAC 45° yielded the highest power output of 2.88 watts at 10 m^3/h with an efficiency of 14.50%. Although increasing discharge generally led to higher power input, it was accompanied by a decrease in efficiency across all configurations. Among all three variations, WFAC 45° demonstrated superior performance at higher discharges, indicating its potential for enhancing the power and efficiency of overshot waterwheels.

Indexing

Keywords	Waterwheel, renewable energy, rotational kinetic energy, moment of inertia, efficiency
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#6543 Review

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Submission

Authors	Rizki Afif Afandi, Dan Mugisidi, Giri Parwatmoko, Oktarina Heriyani
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Section	
Editor	Irwin Cebro

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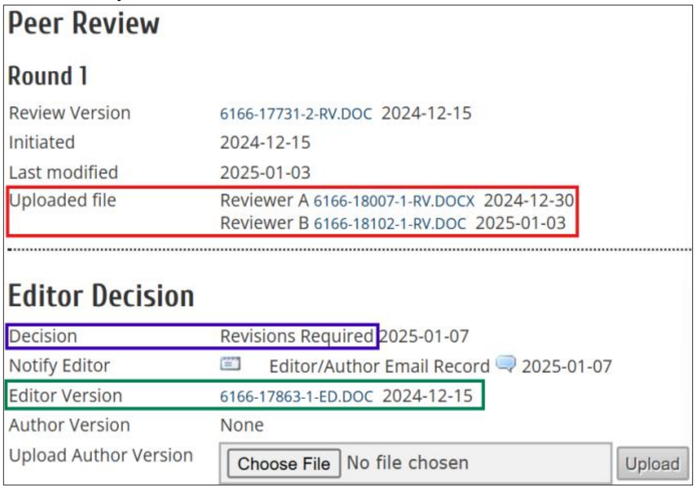

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6. Complying with all instructions will expedite the processing of your manuscript.

TABLE of COMMENT-RESPONSE

Reviewer's A comments		Page	Author's Response	Page
TITLE				
1.	Replace the dash (-) characters!	**1**	Thank you for your valuable suggestion. I agree with your comment to replace the hyphen character (-). The title has been revised to: "The impact of angle cap and water filled blade innovations on the efficiency and power of overshot waterwheel."	**1**
2.	Repair the title; the title should be in line with purposes and conclusion; the title close to performance test of…	**1**	Thank you for your valuable suggestion. I agree with your comment that the title should match the objective and conclusion. The title has been revised to: "The impact of angle cap and water filled blade innovations on the efficiency and power of overshot waterwheel."	**1**
ABSTRACT				
1.	State the innovation in question directly!	**1**	Thank you for your valuable suggestions. I agree with your comment to mention the innovation directly. I have revised the abstract to mention the innovation directly in sentence 2: "The innovation in this study is the 45° water-filled angle cap which is included in the research variables that aim to determine the power performance and performance efficiency of the waterwheel"	**1**

2.	The sentence in method is odd; replace or repair with effective sentence!	**1**	Thank you for your valuable suggestions. I agree with your comment for the replacement of the abstract effective sentence in sentence 3: The revised text is as follows: “Experiments were conducted using 1 waterwheel applied to three variable conditions: without cap, 45° angle cap and, 45° water-filled angle cap. Tests were carried out with a variation of discharge 1-10 m^3/h (interval 0.5 m^3/h) and torque 0.05 N-m.”	**1**
INTRODUCTION				
1.	Rewrite the paragraph to be effective sentences	**1**	Thank you for your valuable suggestion. I agree with your comment to rewrite paragraphs into effective sentences. Revised paragraph 1 starting from sentence 2 to finish using effective sentences: “Indonesia is one of the developing countries that has abundant renewable natural resources and one of them is water [1]. Water as a renewable natural energy has great potential to be converted from kinetic energy into electrical energy [4]. Hydropower plants are designed to generate electricity on a large scale, while small-scale plants are known as Micro hydro Power Plants (MHP) [5], [6], [7]. MHP utilises the flow of rivers or other water sources to generate electricity on a sustainable basis, meeting the needs of residential, agricultural and community facilities [8], [9], [10].” And Revise paragraph 3 sentence 7, the first sentence of this objective should be in line with the title: “Therefore, this study aims to determine the performance of the power generated by the wheel and the efficiency of the wheel's performance, by comparing a straight blade water wheel with a water wheel that has a blade cover to direct water in, as well as a wheel that contains water in the blade.”	**1**
2.	Make sure the writing is correct; do proof reading whole document	**1**	Thank you for your valuable suggestion. I have reconfirmed that the writing is correct and have re-read it: There are improvements in the first paragraph to improve the sentence into an effective sentence. and improvement in the 3 paragraph, sentence 7, the purpose is in accordance with the title.	**1**
METHOD				
1.	Rewrite the method carefully	**1**	Thank you for your valuable suggestion. Have rechecked the handwriting on the method there is a correction in the first paragraph of sentence 4. Corrected the writing of Figure 1, Torque and caption using english. Correction of decimal numbers. The revised text is as follows: “The cap that forms a 45° angle on the blades serves to expand the area outside the blades, so that the water flow is concentrated in the blade area to achieve maximum rotation.”	**1**

2.	This research aims to calculate or measure efficiency but does not write the formula		Thank you for your valuable suggestion. The revised text is as follows: The efficiency formula is written in equation 4 after equation 3 of the waterwheel power formula (P_{out}).	**1-3**
RESULT & DISCUSSION				
1.	Rewrite carefully; what is discussed must be delivered in the introduction and written down in the formulation in the method and all of that leads to the research objectives	**6**	Thank you for your valuable advice. I agree with your comments. Table 4 is my addition to try to compare the efficiency of waterwheel performance in previous studies. I agree to provide a discussion in the introduction section. I have added the discussion of efficiency material in the 3rd paragraph of the 2nd sentence in the introduction chapter. I agree to provide the calculation formula and discussion. I have provided the efficiency formula in the methods chapter in equation 4.	**6**
2.	Rewrite into effective sentences (accurate on word and punctuation (. and,), and consistent; i.e. 81/2 with 8.5)	**4**	Thank you for your valuable advice. I agree with your comments to rewrite into effective sentences (precise on words and punctuation (. and,), and consistent; i.e. 81/2 with 8.5) I have revised the results and discussion section of the first paragraph as follows: 'After obtaining torque and rotation data for each discharge variation. Calculation of water power, waterwheel power, and overshot waterwheel efficiency using equations 1, 3, and 4.' I have made revisions to consistently specify 8.5 for all decimals.	**4**
CONCLUSION				
1.	Write the research results briefly referring to the research objectives	**6-7**	Thank you for your valuable suggestion. I agree with your comment to complete the conclusion by referring to the research objectives. The revised conclusions are as follows: "The waterwheel with a 45° angle cap (AC 45°) shows better rotation performance at a discharge of 10 m^3/h which is 48.56 rpm, the variable water fill angle cap (WFAC 45°) is 47.47 rpm and the variable waterwheel without a cap (WC) is 41.47 rpm weaker because the flow of water directly falling down is not maximally concentrated on the blade of the waterwheel. In addition, in producing waterwheel power with a discharge of 10 m^3/h. The variable without a cap (WC) produces a waterwheel power of 2.29 W, the 45° angle cap variable (AC 45°) produces a waterwheel power of 2.85 W and the 45° water-filled angle cap variable (WFAC 45°) produces a waterwheel power of 2.88 W higher than the without a cap and 45° angle cap. The addition of load by filling water on the waterwheel can increase the moment of inertia and affect the increase in rotational kinetic energy which results in an increase in wheel power. As for the efficiency of waterwheel performance at a discharge of 10 m^3/h. The efficiency of the waterwheel performance on the variable without	**6-7**

			a cap is 11, 50%, the variable angle cap 45° is 14, 32% and the 45° water-filled angle cap variable is 14, 50% higher than the variable without a cap and angle cap 45°. The variable water-filled angle cap (WFAC 45°) with the provision of water on the closed blade gives the best results in terms of waterwheel power and waterwheel performance efficiency at a discharge of 10 m^3/h. Further research is recommended to use a higher water discharge than this study in order to obtain more maximum waterwheel power and waterwheel performance efficiency in overshot waterwheels.	
2.	Remove unnecessary sentences!	**6**	Thank you for your valuable suggestion.	**6**
CITED LITERATURE				
1.	Rewrite accurately in English to this journal format!	**7-8**	Thank you for your valuable suggestion. To write the reference is in accordance with the journal using English. There are references from national journals where the titles use Indonesian, and there are also international journals whose titles are already in English. So that in writing there are writing references using Indonesian and English.	**7-8**
2.				
FINAL REVIEW				
Major revision				

TABLE of COMMENT-RESPONSE

Reviewer's B comments		Page	Author's Response	Page
TITLE				
1.	Don't use dash in the title	**1**	Thank you for your valuable suggestion. I agree with your comment not to use hyphens in the title. The title has been revised to: "Impact of angle cap and water filled blade innovations on the efficiency and power of overshot waterwheel."	**1**
2.				
ABSTRACT				
1.	Good	**1**	Thank you for your positive feedback. I am glad to know that the abstract I wrote is good and in accordance with the research I conducted.	**1**
2.				
INTRODUCTION				
1.	There are some words that are still written in Indonesian	**1**	Thank you for your valuable suggestions. I have made the corrections that still use Indonesian sentences into English.	**1**
2.				
METHOD				

1.	The method should be accompanied by a flow diagram.	**2**	Thank you for your valuable suggestions. I agree with your comment that the study is accompanied by a flow chart. I have made revisions by providing additional research flow charts, I placed them in the methods chapter section in figure 2. I have completed figure 4, by providing additional image information for the location of the overshot waterwheel research data collection.	**2**
2.				
RESULT & DISCUSSION				
1.	The results obtained should be compared with other studies.	**6**	Thank you for your valuable advice. I agree with your comment that the results obtained should be compared with other studies. I have made revisions to provide a comparison of the results of the research data with previous studies. I revised the comparison table and provided a brief description below the 4 table.	**6**
2.				
CONCLUSION				
1.	Conclusions should be made concisely and clearly	**6-7**	Thank you for your valuable suggestion. I agree with your comment conclusion should be made concisely and clearly.	**6-7**
2.				
CITED LITERATURE				
1.	Ok	**8**	Thank you for the approval. The reference section has been corrected and we have ensured that it conforms to the prescribed format.	**8**
2.				
FINAL REVIEW				
Minor revisions				

The impact of angle cap and water filled blade innovations on the efficiency and power of overshot waterwheel.

Abstract

The utilisation of water resources as renewable energy through waterwheels is an environmentally friendly alternative, but its efficiency still needs to be improved through technological innovation. The innovation in this study is (WFAC 45) which is included in the research variables to determine the power performance and efficiency of the waterwheel performance. The experiment used 1 waterwheel applied to three variable conditions, namely (WC, AC 45° and WFAC 45°. Tests were carried out with a variation of discharge 1-10 m³/h (interval 0.5 m³/h) and torque 0.05 N-m. The results showed that the maximum efficiency of 23.30% occurred in the variable (WC) with a discharge of 2 m³/hr producing 0.89 watts of power; meanwhile, 57.08% efficiency was achieved in the variable (AC 45°) at a discharge of 1 m³/hr capable of producing 1.09 watts of power; and 37.53% efficiency was achieved in the variable (WFAC 45°) at a discharge of 1.5 m³/hr producing 1.07 watts of power. Although an increase in discharge generally tends to increase the power generated by the waterwheel, it results in a decrease in efficiency across the tested variables. On the other hand, the water-filled angle cap variable (WFAC 45°) showed superiority in producing the highest power at a discharge of 10 m³/h, which was 2.88 watts resulting in an efficiency of 14.50%, compared to the angle cap variation (WC 45°) which was only able to produce 2.85 watts of power with an efficiency of 14.32%.

Keywords

Waterwheel, Renewable energy, Rotational kinetic energy, Moment of inertia, Efficiency.

Introduction

Sustainable utilisation of natural resources is one of the central issues in the global effort to deal with climate change and environmental degradation [1], [2], including Indonesia. Indonesia is one of the developing countries that has abundant renewable natural resources and one of them is water [3]. Water as a renewable natural energy has great potential to be converted from kinetic energy into electrical energy [4]. Hydropower plants are designed to generate electricity on a large scale, while small-scale plants are known as Micro hydro Power Plants (MHP) [5], [6], [7]. MHP utilizes the flow of rivers or other water sources to generate electricity in a sustainable manner to meet the needs of housing, agriculture, and community facilities [8], [9], [10].

The utilization of water as a renewable energy source requires a waterwheel that plays an important role in converting kinetic energy from water flow into other forms of energy and is usually converted into electrical energy through a generator that operates without reducing the volume of water [11], [12]. In this context, waterwheels were chosen because they are more environmentally friendly and cost-effective [13]. Waterwheels have 3 types including overshot, breastshot, and undershot waterwheels. [14]. In an overshot waterwheel, water flows from the top of the wheel and spins it as it falls to a lower surface. In a breastshot waterwheel, water flows over the center of the waterwheel which is positioned parallel to the top [15]. Meanwhile, in an undershot waterwheel, the waterwheel is placed slightly above the water flow so that only the bottom part of the waterwheel enters the water. The difference between the three types of waterwheels lies in the type of energy transferred to the waterwheel which affects the efficiency and the exact conditions of use of each waterwheel. [16], [17].

Various studies have been conducted on waterwheels, including the effect of adding angled caps, blade thickness on flat-bladed waterwheels, and the relationship between blade height and power and efficiency [18], [19]. The efficiency of waterwheels is influenced by a variety of factors, including aspects of the geometry of the wheel, such as diameter size, number of blades and their curved shape, as well as operational factors such as water level (head), flow discharge, load torque, and water flow position [20], [21]. In order to achieve high efficiency, more in-depth research is needed related to these factors with experimental methods under field conditions [22]. Previous research shows that the shape of the waterwheel blades is very important, because a certain shape makes it easier for water to enter between the blades and is one of the causes of the rotation of the wheel. In addition, the moment of inertia of the waterwheel is also an important factor that affects the efficiency and stability of the waterwheel [23]. Although research on waterwheels has been going on for a long time, until now no waterwheel has been equipped with a director to force water to enter between the blades, even though this has the potential to increase the power generated. Another attempt that has not yet been made is to introduce water into the waterwheel to increase its moment of inertia.

Therefore, this study aims to determine the performance of the power generated by the wheel and the efficiency of the wheel's performance, by comparing a straight blade water wheel with a water wheel that has a blade cover to direct water in, as well as a wheel that contains water in the blade.

Method

The waterwheel used in the study is an overshot waterwheel with 16 blades. There are 2 models of blade caps, namely closed water-filled and 45° angled caps to the outside as shown in Figure 1. The closed water-filled blades aim to produce a moment of inertia and increase the kinetic energy of the wheel. The cap that forms a 45° angle on the blades serves to expand the area outside the blades, so that the water flow is concentrated in the blade area to achieve maximum rotation.

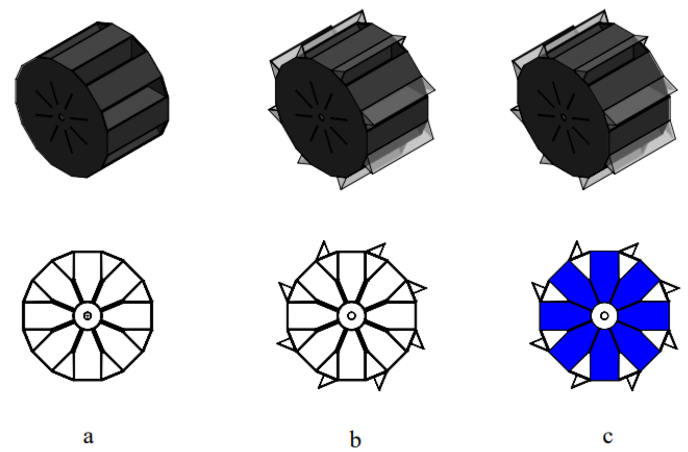

Fig 1. a) Isometric and Side View (WC) Without Cap b) Isometric and Side View (AC 45°) Angle Cap c) Isometric and Side View (WFAC 45°) Water-filled Angle Cap

The test method applied in the overshot waterwheel research is the actual experimental method on a laboratory scale. The test was carried out in the Mechanical Engineering laboratory of University Prof. Dr Hamka Muhammadiyah. Tests were carried out using dependent variables and independent variables. The dependent variable consists of rotation, torque, waterwheel power, and waterwheel efficiency. While the independent variables are without cap, angle cap 45° and water filled angle cap 45° shown in Figure 1. The flowchart of the overshot waterwheel research can be seen in Figure 2.

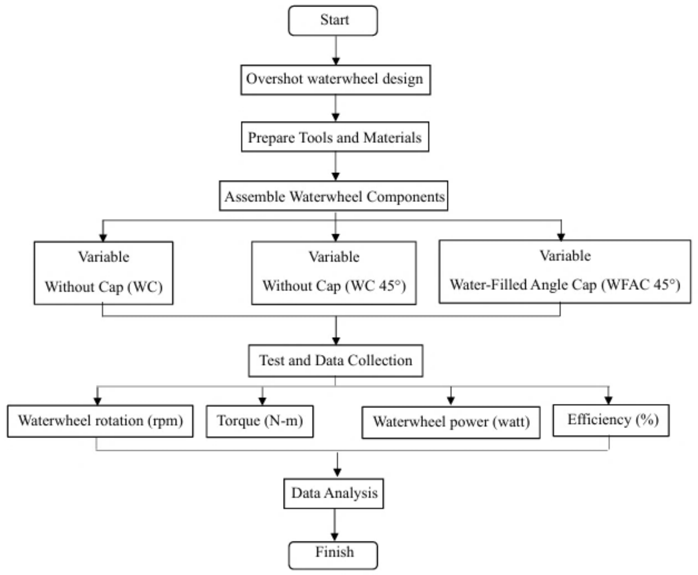

Fig 2. Flowchart of Overshot Waterwheel Research Systematic

Figure 2 is a systematic way of conducting overshot waterwheel research. This research consists of three interconnected stages. The first stage includes preparation of the design concept, equipment needed for research, and assembly of the waterwheel components. The second stage is a trial to ensure the research tool functions properly. The third stage is data collection through recording which is then followed by the data analysis process.

The design of the overshot waterwheel involved design, cutting, welding, and testing. The manufacture of the waterwheel housing uses melamine multiplex material, with the inside coated with resin and the outside coated with waterproof paint. The wheel house is 100 cm high, 100 cm long, and 37 cm wide. The lid is made of acrylic material with a 45° tilt angle. Meanwhile, the wheel is made of iron material with a thickness of 3 mm.

The wheel mounting frame plays a role in supporting the pillow block to support the wheel shaft, ensuring optimal wheel rotation. The waterwheel shaft is solid with a diameter of 25 mm, while the waterwheel has a diameter of 45 cm and a thickness of 30 cm. The geometry design of the overshot waterwheel in millimetres (mm) is shown in Figure 3 below:

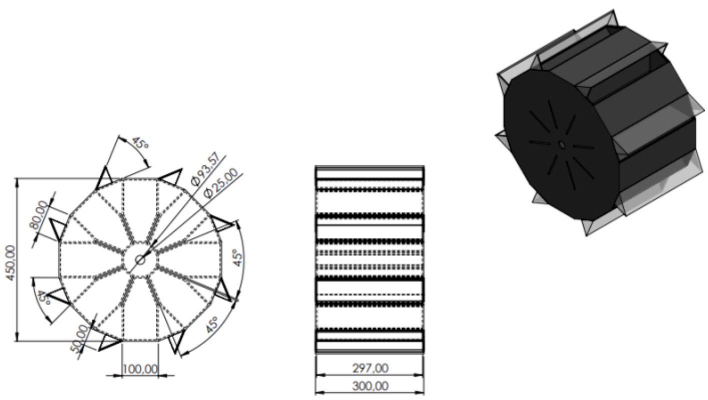

Fig 3. Geometri of waterwheel

Measuring instruments used for the data collection process include, Torque meter functions to collect Torque data from the waterwheel. Data collection of waterwheel rotation using a Tachometer measuring instrument [24]. Water discharge settings using Rotameter measuring instrument and water flow rate measured using Flow velocity meter tool [25], according to the specifications listed in table 1 below:

Table 1. Specifications of waterwheel test measuring instrument.

Measurement tool	Type	Capacity
Torque meter	Lutron TQ-8800	0 - 0.15 (N-m)
Tachometer	KW06-563	0 - 20.000 (rpm)
Rotameter	LZT-50S105/N	1 - 10 m³ /h)
Flow velocity meter	Flowatch FL-03	2 - 150 (km/h)

This study utilised one waterwheel to collect data on the independent variables. The four red-coloured dots shown in the figure below indicate the data collection locations required during the testing process. Data was collected using flow rates of 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6, 6.5, 7, 7.5, 8, 8.5, 9, 9.5, up to 10 m³/h, which were circulated using a pump. The independent variables tested included 45° angle cap, no cap, and 45° angle cap with water content. Data was taken more than once to ensure the test results remained consistent.

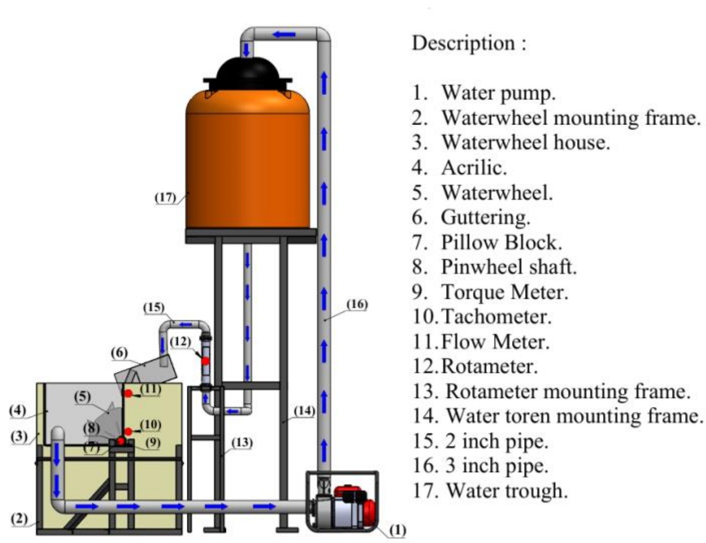

Fig 4. Schematic design of overshot waterwheel testing installation

The installation scheme of the overshot waterwheel test consists of 17 components, each of which plays a crucial role with different functions, starting from the water pump in charge of maintaining the continuity of water flow through the pipe from the waterwheel house, forwarded to the water trough according to the design shown in Figure 4. The water trough, which acts as the main reservoir, is designed to facilitate the precise regulation of water discharge, which is done with the help of a rotameter gauge to control the flow of water into the gutter. The gutter acts as a guide, concentrating the water flow precisely on the 45° tilt angle of the blades, ensuring an even distribution of water across the surface of the blades. The blade's main function is to maximise the efficiency of the waterwheel rotation by adjusting its rotation rate to the volume and velocity of the incoming water flow, which ultimately determines the overall performance of the waterwheel. As a control and reference in this test, the detailed specifications of the waterwheel are presented in Table 2 below, providing a clear guide to the technical parameters tested.

Table 2. Waterwheel specifications.

Spesifikasi	Parameter
Weight of Waterwheel Without Cap (WC)	41 kg
Weight of Waterwheel Angle Cap (AC 45°)	42.5 kg
Weight of Waterwheel Water-filled Angle Cap (WFAC 45°)	60 kg
Toque	0.05 N-m

The precision-designed components of the waterwheel are then assembled into a highly complex and interconnected circuit, where each element contributes to the functionality of the entire system. The artificial waterways, whose continuity is supported by the use of pumps, serve to maintain a steady and controlled flow of water, which in turn allows for high accuracy testing of the efficiency of the waterwheel. The overall result of the waterwheel assembly, which incorporates various aspects of technical design and construction, can be seen in Figure 5 below.

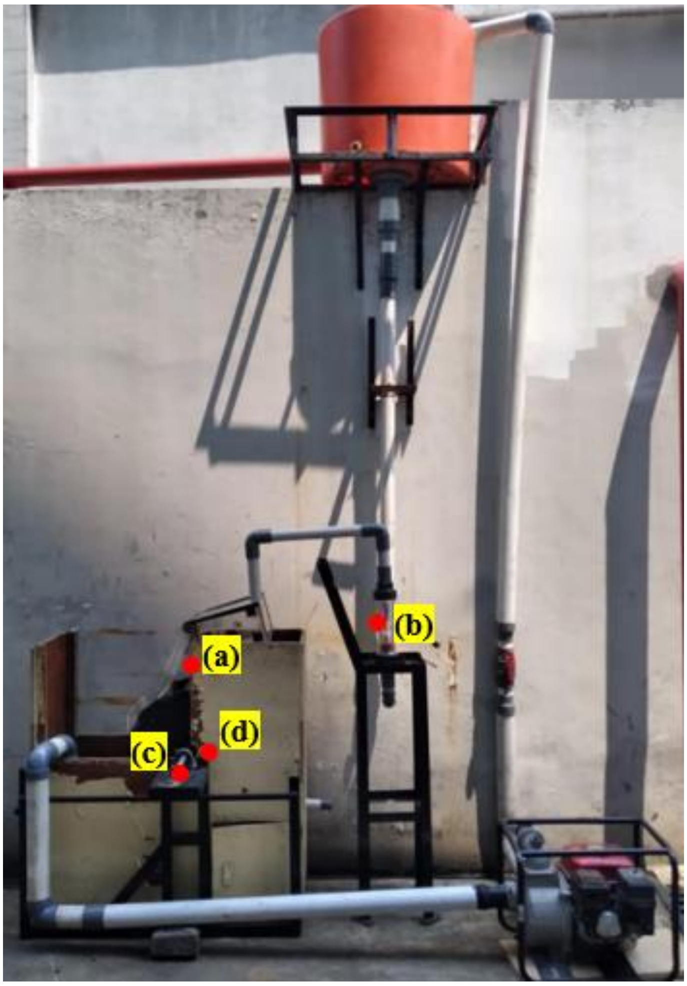

Fig 5. The assembled overshot waterwheel installation and data collection location. (a) Water flow velocity data, (b) Water discharge data, (c) Waterwheel torque data, (d) Waterwheel rotation data

Experimental results were processed to determine the efficiency of the waterwheel. Energy from water can be obtained through water flowing into the blades of the waterwheel. The power generated by the water (P_{in}) can be calculated using the equation 1 [26].

$$P_{in} = \rho . g . h . Q \quad (1)$$

Description:

P_{in}	= Water power	(watt)
ρ	= Density of water	(998,2 kg/m^3)
g	= Gravitational acceleration	(m/s^2)
h	= Water fall height	(m)
Q	= Water discharge	(m^3/h)

Where head is the height difference between the surface of the base of the waterwheel housing and the height of the water surface before entering the waterwheel blades [27]. The circumferential speed of the wheel or commonly known as angular velocity (ω) is obtained from equation 2 [28]. Meanwhile, to calculate the waterwheel power (P_{out}) using the equation 3 [29].

$$\omega = \frac{2 . \pi . n}{60} \quad (2)$$

$$P_{out} = T . \omega \quad (3)$$

Description:

ω	= Angular velocity	(rad/s)
n	= Waterwheel rotation	(rpm)
T	= Torque	(N-m)

The efficiency of the waterwheel (η) is the ratio between the power generated by the waterwheel and the water power, which can be calculated using equation 4 [30].

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% \quad (4)$$

The rotation of a solid body with mass (m) moving translational (linear) with velocity (v) using equation 5 can be explained through kinetic energy according to equation 6 [31].

$$v = \omega . r \quad (5)$$

$$Ek = \frac{1}{2} . m . v^2 \quad (6)$$

Description:

Ek	= Kinetic Energy	(Joule)
v	= Water flow velocity	(m/s^2)

It is assumed that the kinetic energy measured in a solid cylinder results in rotational kinetic energy (Ek_{rot}) which is related to the moment of inertia (I) and can be obtained through equation 7 [32].

$$Ek_{rot} = \frac{1}{2} . I . \omega^2 \quad (7)$$

Description:

Ek_{rot}	= Rotational kinetic energy	(Joule)
I	= Moment of inertia	($kg.m^2$)
ω	= Angular velocity	(rad/s)

Moment of inertia (I) is the property of an object that allows it to maintain its position in rotational motion [33]. A stationary object tends to maintain its position, so a moving object will try to maintain its rotational motion. Mathematically, the moment of inertia can be obtained from equation 8.

$$I = m.r^2 \tag{8}$$

Description:

I	= Moment of inertia	($kg.m^2$)
m	= Mass of the wheel	(kg)
r	= Distance of the waterwheel to the shaft	(m)

Results and Discussion

After obtaining torque and rotation data for each discharge variation. Calculation of water power, waterwheel power, and overshot waterwheel efficiency using equations 1, 3, and 4. The results of testing and data processing are presented in the form of tables and figures that show the relationship between these factors. The complete results of data processing can be seen in Table 3

Table 3. Data processing results of variable waterwheel WC, AC 45°, WFCC 45°

Q	n (rpm)			P_{in} (watt)			P_{out} (watt)			efficiency (%)		
(m^3/h)	WC	AC 45°	WFAC 45°	WC	AC 45°	WFAC 45°	WC	AC 45°	WFAC 45°	WC	AC 45°	WFAC 45°
1	7.41	19.62	8.95	1.91	1.91	1.91	0.41	1.09	0.51	21.70	57.08	26.55
1,5	11.96	25.66	18.31	2.86	2.86	2.86	0.66	1.43	1.07	23.21	50.09	37.53
2	16.22	30.02	19.91	3.82	3.82	3.82	0.89	1.70	1.21	23.30	44.50	31.69
2,5	19.41	34.12	24.96	4.68	4.68	4.68	1.05	1.88	1.41	22.02	39.46	29.60
3	21.62	37.33	28.46	5.72	5.72	5.72	1.22	2.01	1.64	21.37	35.07	28.64
3,5	23.70	38.27	30.13	6.68	6.68	6.68	1.32	2.22	1.68	19.70	33.21	25.21
4	25.06	40.50	32.29	7.63	7.63	7.63	1.41	2.26	1.94	18.45	29.64	25.38
4,5	26.28	41.55	33.43	8.58	8.58	8.58	1.46	2.29	1.94	16.99	26.70	22.57
5	28.12	42.34	34.90	9.54	9.54	9.54	1.55	2.35	2.01	16.26	24.64	21.07
5,5	28.66	42.77	36.21	1049	10.49	10.49	1.56	2.42	2.01	14.88	23.05	19.16
6	29.75	43.38	37.39	11.77	11.77	11.77	1.66	2.36	2.23	14.11	20.07	18.96
6,5	31.95	43.96	38.42	12.75	12.75	12.75	1.74	2.30	2.21	13.64	18.05	17.35
7	33.11	44.13	39.06	13.73	13.73	13.73	1.80	2.43	2.32	13.13	17.72	16.88
7,5	34.20	45.06	39.67	14.72	14.72	14.72	1.91	2.52	2.20	12.98	17.10	14.96
8	36.04	45.86	40.58	15.70	15.70	15.70	1.95	2.67	2.35	12.42	17.03	14.98
8,5	36.68	46.51	41.68	16.68	16.68	16.68	2.09	2.63	2.37	12.52	15.77	14.22
9	38.99	46.87	42.59	17.90	17.90	17.90	2.14	2.60	2.51	11.94	14.53	14.03
9,5	39.91	47.30	44.73	18.90	18.90	18.90	2.24	2.68	2.58	11.87	14.15	13.63
10	41.47	48.56	47.47	19.89	19.89	19.89	2.29	2.85	2.88	11.50	14.32	14.50

The rotation of the waterwheel is influenced by the water flow using equation 6 and the head of the waterwheel. At the discharge position of 1-5.5 m³/h, the head value was recorded at 0.7 m, while at the discharge of 6-8.5 m³/h, the head value increased by 0.02 m, and reached its peak at the discharge of 9 to 10 m³/h with a head value of 0.73 m. This increase in head is caused by the increase in water flow in the gutter of the waterwheel. The increase in head is caused by the increase in the flow of water flowing in the gutter of the waterwheel. The waterwheel without the corner cap experiences an obstacle, where the water flow cannot hit the entire blade optimally. As a result, the water flow that enters the blades is focused in the middle and goes straight down to the bottom of the wheel, so it cannot maximise the water flow and causes a small rotation.

On the other hand, the waterwheel with a 45° angle cap shows a larger rotation than the waterwheel without a cap, because the angle cap reduces the opening area of the waterwheel. This causes the flow of water into the blade of the waterwheel not to come out immediately, due to obstruction by the waterwheel cover, so that the water can be concentrated effectively towards the blade of the waterwheel.

Meanwhile, the wheel equipped with a corner cap and filled with water experiences a moment of inertia that causes inertia in the rotation of the wheel to be smaller when the discharge is in the range of 1 to 4 m³/h. However, the rotation began to increase at a discharge of 4 to 10 m³/h due to the work of the moment of inertia helping to increase the kinetic energy of the waterwheel rotation, where at a discharge of 10 m³/hour, the rotation of the waterwheel experienced a significant increase compared to the waterwheel using a 45° angle cap without water content. The following figure shows the comparison of the processed data.

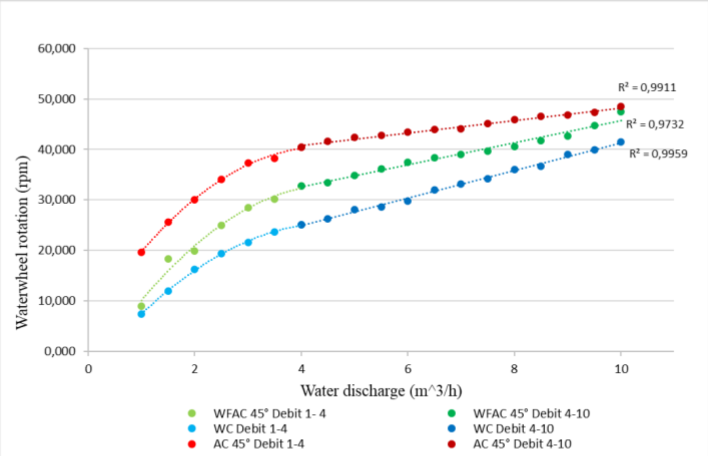

Fig. 5. Waterwheel rotation (rpm)

Figure 5 shows the relationship between water discharge (m³/h) on the horizontal axis and wheel speed (rpm) on the vertical axis. In this figure, there are three turbine configurations, namely AC 45°, WC, and WFAC 45°, with each tested at two water discharge ranges: 1-4 m³/h and 4-10 m³/h.

The 45° AC variable waterwheel represents a polynomial curve at small discharge (1-4 m^3/h), where the rotation of the waterwheel increases gradually from 19.62 rpm to reach 40.50 rpm. The increase in rotation is due to the angle cap which reduces the opening area of the waterwheel so that the water does not fall directly to the bottom of the waterwheel house, resulting in a moment of inertia with the calculation of equation 9 of 2.152 kg/m2 and generating rotational kinetic energy of 12.249 Joules using the calculation of equation 8. At large discharges (4-10 m³/h) shows a more stable and linear increase, where the rotation of the waterwheel increases from 40.50 rpm to reach about 48.56 rpm. There is an increase in rotational kinetic energy of 23.386 Joules. The R^2 value is 0.9911, indicating that the 45° angle cap greatly influences the rotation of the waterwheel.

The 45° WFAC variable wheel represents a polynomial curve at small discharge, where the rotation of the wheel experiences inertia due to the water content of the wheel blades causing the rotation to slow down in contrast to the 45° AC. The rotation starts from about 8.95 rpm and increases to 32.29 rpm. In the increase in rotation there is a moment of inertia of 3.087 kg/m^2 resulting in rotational kinetic energy of 9.242 Joules, with a slower increase when compared to the AC 45° waterwheel. At large discharge, the rotation of the waterwheel increased linearly from 32.29 rpm to 47.47 rpm showing a stable relationship between water discharge and waterwheel rotation. The curve also has a high fit to the data, indicated by the R^2 value of 0.9732. In the no-water-fill condition, with the same water discharge of 9-10 m³/h, the rotation of the waterwheel recorded a continuous increase, which was 46.87 rpm, 47.30 rpm, and 48.56 rpm. A significant increase in the rotation of the 45° water fill angle cap began to be seen at a discharge of 9-10 m³/hour, respectively 42.59 rpm, 44.73 rpm, and 47.47 rpm and produced rotational kinetic energy of 25.946 Joules. Where water filling produces an increase in rotational kinetic energy, it causes a significant increase in wheel rotation. If the discharge continues the possibility is greater than with AC 45° which increases continuously. This is because the rotational kinetic energy is directly proportional to the square of the rotation speed at large discharge, although the difference in rotation is still visible.

The WC variable wheel showed a polynomial curve configuration at small discharge, with the wheel rotation starting from about 7.41 rpm and increasing up to 25.06 rpm. The moment of inertia value of 2.076 kg/m^2 produced 3.653 Joules less rotational kinetic energy compared to AC 45° and WFAC 45°, but still had a very high R^2 value of 0.9959 indicating an excellent match with the data. As the discharge was increased, the wheel rotation was only able to increase from 25.06 rpm to 41.47 rpm resulting in rotational kinetic energy of 12.470 Joules less than AC 45° and WFAC 45°, following a similar linear pattern as the other configurations. Overall, this figure shows that an increase in water discharge is closely related to an increase in waterwheel rotation just as in previous studies [34]. The difference in efficiency varies between wheel configurations and water discharge ranges.

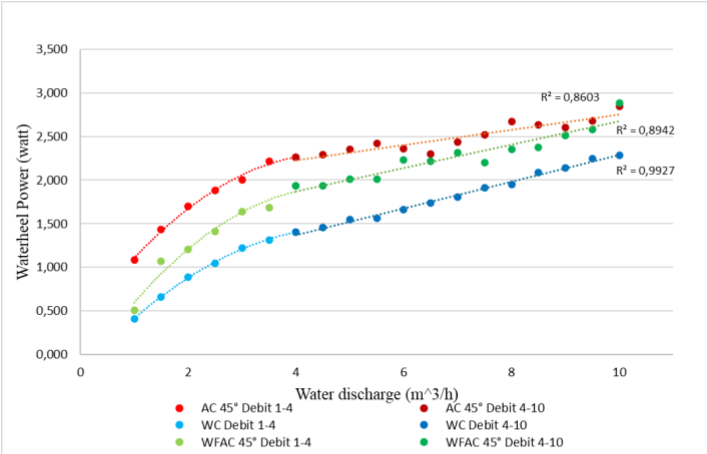

Fig. 6. Waterwheel Power (watt)

Figure 6 shows the relationship between water discharge (m³/h) and waterwheel power (watt), indicating that the higher the water discharge, the more power the waterwheel produces. This graph consists of several sets of data, each representing different conditions, namely AC 45°, WC, and WFAC 45° at discharge ranges of 1-4 m³/h and 4-10 m³/h, respectively. The difference between the small discharge range (1-4) and the large discharge range (4-10) can be seen from the different shapes of the curves used: polynomial curves for discharge 1-4 m^3/h and linear curves for discharge 4-10 m^3/h.

In the variable AC 45° waterwheel, the waterwheel configuration is at a 45° angle. In the discharge range of 1-4 m³/h, the curve shows a polynomial pattern, where the waterwheel power increases sharply from about 1.09 to almost 2.26 watt. In the discharge range of 4-10 m³/hr, the pattern changes to linear, with the power continuing to increase steadily until it reaches 2.85 watts at a discharge of 10 m³/hr. The R^2 = 0.8603 value for this linear curve indicates that the model does a good job of explaining the relationship between water discharge and waterwheel power.

The 45° WFAC variable wheel, where at a discharge of 1-4 m³/h, the curve shows polynomial properties with the resulting wheel power relatively smaller than that of the 45° AC, which ranges from 0.51 watts to 1.94 watts. This phenomenon can be explained by the process of inertia caused by water, which makes the wheel heavier to rotate. So that the power generated is smaller than that of AC 45°. When the discharge increases from 4 to 10 m³/hour, the power of the waterwheel increases linearly until it reaches about 2.88 watts greater than AC 45°. This occurs because the increase in water discharge causes an increase in the moment of inertia, which in turn generates greater rotational kinetic energy, allowing the waterwheel power to reach its maximum point. The value of R^2 = 0.8942 for this linear curve indicates that the relationship between water discharge and waterwheel power is stronger than AC 45° at large discharge.

At the discharge range of 1-4 m³/h, the polynomial curve shows the generated waterwheel power starts from about 0.41 watts and increases up to 1.41 watts. In the discharge range of 4-10 m³/h, the waterwheel power increased linearly from 1.41 watts to 2.29 watts with a very strong relationship $R^2 = 0.9927$.

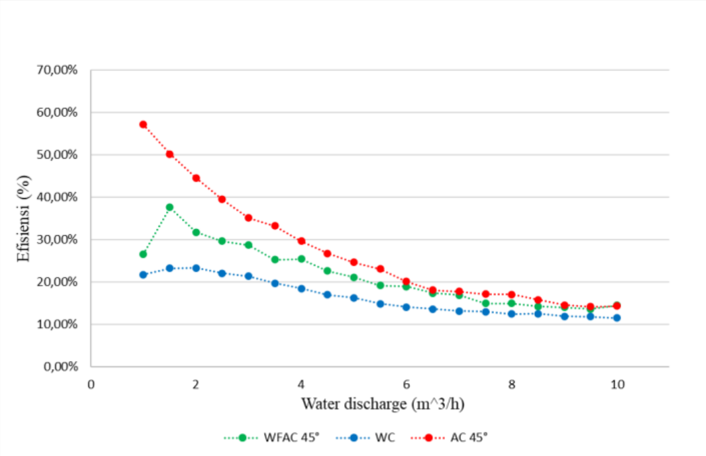

Fig. 7. Waterwheel efficiency (%)

Figure 7 illustrates the maximum and minimum waterwheel performance conditions observed in the operating system. The highest efficiency, recorded at variable AC 45°, occurred at a discharge of 1 m³/h, with an efficiency of 57.08%. In contrast, the lowest efficiency occurred at a discharge of 10 m³/h, with an efficiency of 14.32%. At variable WFAC 45°, the highest efficiency was achieved at a discharge of 1½ m³/h, which resulted in an efficiency of 37.53%. An important phenomenon occurred at a discharge of 1 m³/h, where the efficiency initially decreased but then increased rapidly at a discharge of 1½ m³/h. This phenomenon can be attributed to the rotational inertia at a discharge of 1 m³/h, which causes the rotation of the waterwheel to rotate slowly. However, as the discharge increased, the water mass inside the waterwheel generated a moment of inertia similar to that observed in a previous study [35], which led to an increase in efficiency. The lowest efficiency at variable WFAC 45° was recorded at a discharge of 9½ m³/h, with a value of 13.63%. In addition, at a discharge of 2 m³/h, the maximum efficiency in the WC variable reached 23.30%, while the minimum efficiency at a discharge of 10 m³/h was 11.50%. Next, the efficiencies of the WC, 45° AC, and 45° WFAC compared to previous studies as shown in Table 4, in addition to the results of previous studies.

Table 4. Comparison of waterwheel performance efficiency with previous studies

Variable overshot water wheel	Efficiency	Reference
Waterwheel Without Cap (WC) diameter 0.45 m	23.30%	
Waterwheel Angle Cap (AC 45°) diameter 0.45 m	57.08%	
Waterwheel Water Filled Angle Cap (WFAC 45°) diameter 0.45 m	37.53%	
Waterwheel nozzle angle 30° diameter 0.50 m	25.05%	[36]
Waterwheel using square penstock diameter 0.60 m	42.00%	[37]
Waterwheel bucket configuration -20 diameter 0.90 m	45.00%	[38]

Based on Table 4, the efficiency of an overshot waterwheel is influenced by the blade design and the water flow system. The uncovered waterwheel (WC) was only able to achieve an efficiency of 23.30%. However, the use of a blade cover with a 45° angle (AC 45°) increased the efficiency to 57.08%. When water was introduced into the closed angle (WFAC 45°), the efficiency decreased to 37.53%, possibly due to water content in the closed blade. The use of a nozzle with a 30° angle resulted in an efficiency of 25.05%, which is still lower than the (WFAC 45°) configuration. The square-shaped penstock with a diameter of 0.60 m produced an efficiency of 42.00%, while the 0.90 m diameter bucket configuration showed an increase in efficiency to 45.00%, but still lower than the 0.45 m diameter 45° AC closed blade design. Overall, the closed blade design proved to be the most effective in improving efficiency compared to simply increasing the diameter.

Conclusion

The waterwheel with a 45° angle cap (AC 45°) shows better rotation performance at a discharge of 10 m³/h which is 48.56 rpm, the variable water fill angle cap (WFAC 45°) is 47.47 rpm and the variable waterwheel without a cap (WC) is 41.47 rpm weaker because the flow of water directly falling down is not maximally concentrated on the blade of the waterwheel. In addition, in producing waterwheel power with a discharge of 10 m³/h. The variable without a cap (WC) produces a waterwheel power of 2.29 W, the 45° angle cap variable (AC 45°) produces a waterwheel power of 2.85 W and the 45° water-filled angle cap variable (WFAC 45°) produces a waterwheel power of 2.88 W higher than the without a cap and 45° angle cap. The addition of load by filling water on the waterwheel can increase the moment of inertia and affect the increase in rotational kinetic energy which results in an increase in wheel power. As for the efficiency of waterwheel performance at a discharge of 10 m³/h. The efficiency of the waterwheel performance on the variable without a cap is 11, 50%, the variable angle cap 45° is 14, 32% and the 45° water-filled angle cap variable is 14, 50% higher than the variable without a cap and angle cap 45°. The variable water-filled angle cap (WFAC 45°) with the provision of water on the closed blade gives the best results in terms of waterwheel power and waterwheel performance efficiency at a discharge of 10 m³/h. Further research is recommended to use a higher water discharge than this study in order to obtain more maximum waterwheel power and waterwheel performance efficiency in overshot waterwheels.

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Impact of angle cap and water-filled blade modification on the output of overshot waterwheels

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Abstract
The utilization of water resources as renewable energy through waterwheels presents an environmentally friendly alternative, however, its efficiency requires improvement through technological modification. This research investigates two design modifications: a 45° Angle Cap (AC) and a Water-Filled Angle Cap (WFAC), in comparison with a waterwheel without a Cap (WC). Experiments were conducted at discharges from 1 to 10 m³/h with a constant torque load of 0.05 N-m. The highest efficiency of 57.08% was achieved in the AC 45° configuration at 1 m³/h, generating 1.09 watts of power, while the WFAC 45° yielded the highest power output of 2.88 watts at 10 m³/h with an efficiency of 14.50%. Although increasing discharge generally led to higher power input, it was accompanied by a decrease in efficiency across all configurations. Among all three variations, WFAC 45° demonstrated superior performance at higher discharges, indicating its potential for enhancing the power and efficiency of overshot waterwheels.

Keywords:
Waterwheel, renewable energy, rotational kinetic energy, moment of inertia, efficiency.

1 Introduction

Sustainable utilization of natural resources is one of the central issues in the global effort to deal with climate change and environmental degradation [1], [2], including Indonesia. Indonesia is one of the developing countries that has abundant renewable natural resources and one of them is water [3]. Water as a renewable natural energy has great potential to be converted from kinetic energy into electrical energy [4]. Hydropower plants are designed to generate electricity on a large scale, while small-scale plants are known as Micro-hydro Power Plants (MHP) [5], [6], [7]. MHP utilizes the flow of rivers or other water sources to generate electricity in a sustainable manner to meet the needs of housing, agriculture, and community facilities [8], [9], [10].

The utilization of water as a renewable energy source requires a waterwheel that plays an important role in converting kinetic energy from water flow into other forms of energy and is usually converted into electrical energy through a generator that operates without reducing the volume of water [11], [12]. In this context, waterwheels were chosen because they are more environmentally friendly and cost-effective [13]. Waterwheels have 3 types: overshot, breast shot, and undershot waterwheels. [14]. In an overshot waterwheel, water flows from the top of the wheel and spins as it falls to a lower surface. In a breast shot waterwheel, water flows over the center of the waterwheel which is positioned parallel to the top [15]. Meanwhile, in an undershot waterwheel, the waterwheel is placed slightly above the water flow so that only the bottom part of the waterwheel enters the water. The difference between the three types of waterwheels lies in the type of energy transferred to the waterwheel which affects the efficiency and the exact conditions of use of each waterwheel. [16], [17].

Various studies have been conducted on waterwheels, including the effect of adding angled caps, blade thickness on flat-bladed waterwheels, and the relationship between blade height and power and efficiency [18], [19]. The efficiency of waterwheels is influenced by a variety of factors, including aspects of the geometry of the wheel, such as diameter size, number of blades, and their curved shape, as well as operational factors such as water level (head), flow discharge, load torque, and water flow position [20], [21]. To achieve high efficiency, more in-depth research is needed related to these factors, with experimental methods under field conditions [22]. Previous research shows that the shape of the waterwheel blades is very important because a certain shape makes it easier for water to enter between the blades and is one of the causes of the wheel's rotation. In addition, the moment of inertia of the waterwheel is also an important factor that affects the efficiency and stability of the waterwheel [23]. Although research on waterwheels has been going on for a long time, until now no waterwheel has been equipped with a director to force water to enter between the blades, even though this has the potential to increase the power generated. Another attempt that has not yet been made is to introduce water into the waterwheel to increase its moment of inertia.

Therefore, this study aims to determine the performance of the power generated by the wheel and the efficiency of the wheel's performance by comparing a straight-blade water wheel with a water wheel that has a blade cover to direct water in, as well as a wheel that contains water in the blade.

2 Method

The waterwheel used in the study is an overshot waterwheel with 16 blades. There are 2 models of blade caps, namely closed water-filled and 45° angled caps to the outside as shown in Fig. 1. The closed water-filled blades aim to produce a moment of inertia and increase the kinetic energy of the wheel. The cap that forms a 45° angle on the blades serves to expand the area outside the blades so that the water flow is concentrated in the blade area to achieve maximum rotation.

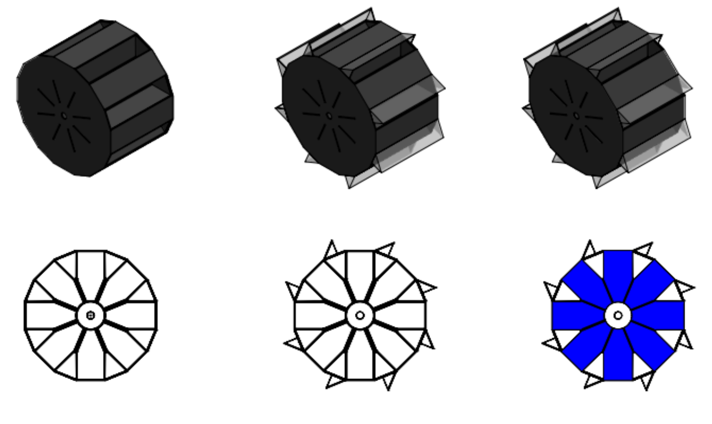

Fig. 1. Overshoot waterwheel. a) Isometric and side view Without Cap (WC), b) isometric and side view Angle Cap (AC) 45°, and c) isometric and side view Water-Filled Angle Cap (WFAC) 45°

The test method applied in the overshot waterwheel research is the actual experimental method on a laboratory scale. The test was carried out in the Mechanical Engineering laboratory of University Prof. Dr Hamka Muhammadiyah. Tests were carried out using dependent variables and independent variables. The dependent variable consists of rotation, torque, waterwheel power, and waterwheel efficiency. While the independent variables are Without Cap (WC), Angle Cap (AC) 45°, and Water-Filled Angle Cap (WFAC) 45° shown in Fig. 1. The flowchart of the overshot waterwheel research can be seen in Fig. 2.

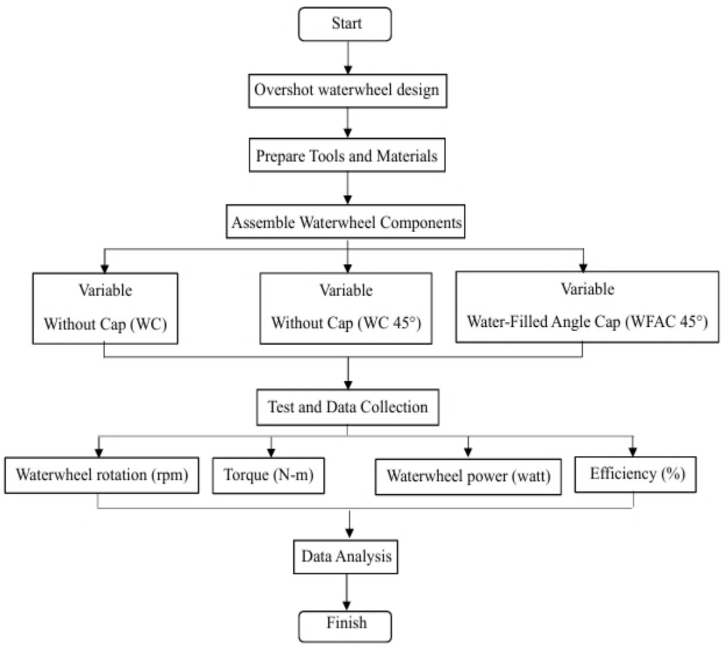

Fig. 2. Flowchart of overshot waterwheel research systematic

Fig. 2 is a systematic way of conducting overshot waterwheel research. This research consists of three interconnected stages. The first stage includes preparation of the design concept, equipment needed for research, and assembly of the waterwheel components. The second stage is a trial to ensure the research tool functions properly. The third stage is data collection through recording which is then followed by the data analysis process.

The design of the overshot waterwheel involved design, cutting, welding, and testing. The manufacture of the waterwheel housing uses melamine multiplex material, with the inside coated with resin and the outside coated with waterproof paint. The wheelhouse is 100 cm high, 100 cm long, and 37 cm wide. The lid is made of acrylic material with a 45° tilt angle. Meanwhile, the wheel is made of iron material with a thickness of 3 mm.

The wheel mounting frame plays a role in supporting the pillow block to support the wheel shaft, ensuring optimal wheel rotation. The waterwheel shaft is solid with a diameter of 25 mm, while the waterwheel has a diameter of 45 cm and a thickness of 30 cm. The geometry design of the overshot waterwheel in millimeters (mm) is shown in Fig. 3.

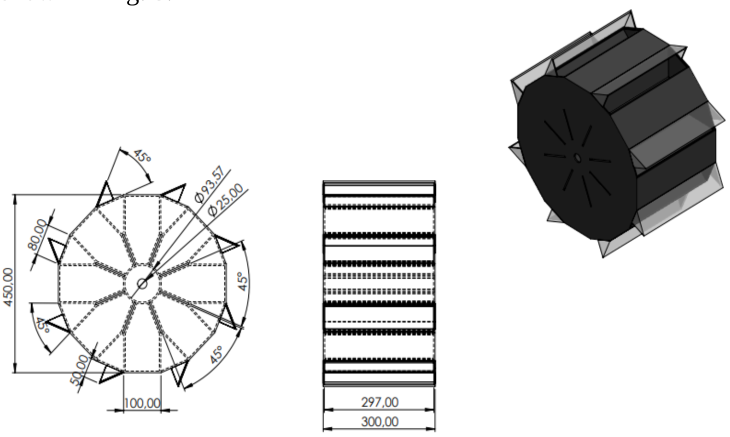

Fig. 3. Geometry of waterwheel

Measuring instruments used for the data collection process include, Torque meter functions to collect Torque data from the waterwheel. Data collection of waterwheel rotation using a Tachometer measuring instrument [24]. Water discharge settings using a Rotameter measuring instrument and water flow rate measured using a Flow velocity meter tool [25], according to the specifications listed in Table 1.

This study utilized one waterwheel to collect data on the independent variables. The four red-colored dots shown in the fig. 4 indicate the data collection locations required during the testing process.

Table 1. Specifications of waterwheel test measuring instrument

Measurement tool	Type	Capacity
Torque meter	Lutron TQ-8800	0 - 0.15 (N-m)
Tachometer	KW06-563	0 - 20.000 (rpm)
Rotameter	LZT-50S105/N	1 - 10 m^3 /h)
Flow velocity meter	Flo watch FL-03	2 - 150 (km/h)

Data was collected using flow rates of 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6, 6.5, 7, 7.5, 8, 8.5, 9, 9.5, up to 10 m^3/h, which were circulated using a pump. The independent variables tested included a 45° angle cap, no cap, and a 45° angle cap with water content. Data was taken more than once to ensure the test results remained consistent.

The installation scheme of the overshot waterwheel test consists of 17 components, each of which plays a crucial role with different functions, starting from the water pump in charge of maintaining the continuity of water flow through the pipe from the waterwheel house, forwarded to the water trough according to the design shown in Fig. 4.

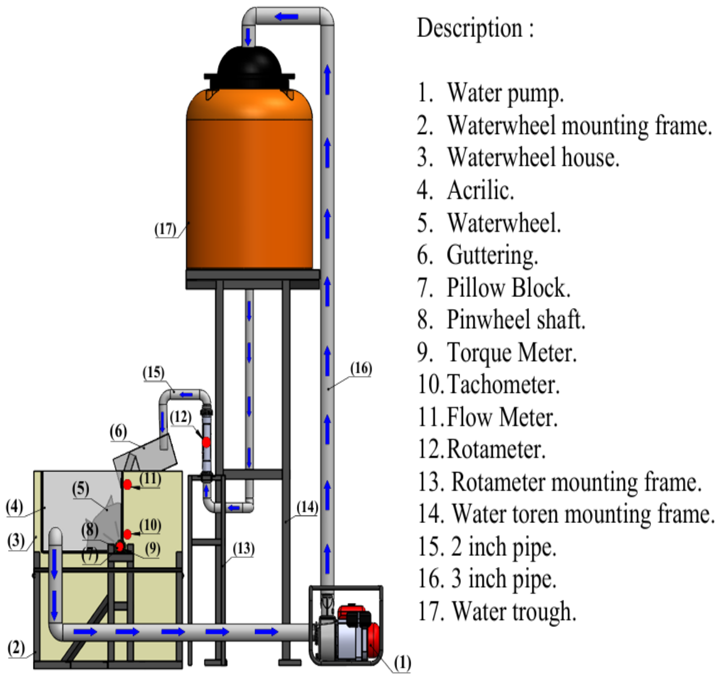

Fig. 4. Schematic design of overshot waterwheel testing installation

The water trough, which acts as the main reservoir, is designed to facilitate the precise regulation of water discharge, which is done with the help of a rotameter gauge to control the flow of water into the gutter. The gutter acts as a guide, concentrating the water flow precisely on the 45° tilt angle of the blades, ensuring an even distribution of water across the surface of the blades. The blade's main function is to maximize the efficiency of the waterwheel rotation by adjusting its rotation rate to the volume and velocity of the incoming water flow, which ultimately determines the overall performance of the waterwheel. As a control and reference in this test, the detailed specifications of the waterwheel are presented in Table 2, providing a clear guide to the technical parameters tested.

Table 2. Waterwheel specifications

Specification	Parameter
Weight of Waterwheel WC	41 kg
Weight of Waterwheel AC 45°	42.5 kg
Weight of Waterwheel WFAC 45°	60 kg
Toque	0.05 N-m

The precision-designed components of the waterwheel are then assembled into a highly complex and interconnected circuit, where each element contributes to the functionality of the entire system. The artificial waterways, whose continuity is supported by the use of pumps, serve to maintain a steady and controlled flow of water, which in turn allows for high-accuracy testing of the efficiency of the waterwheel. The overall result of the waterwheel assembly, which incorporates various aspects of technical design and construction, can be seen in Fig. 5.

Fig. 5. The assembled overshot waterwheel installation and data collection location. (a) water flow velocity data, (b) water discharge data, (c) waterwheel torque data, and (d) waterwheel rotation data

Experimental results were processed to determine the efficiency of the waterwheel. Energy from water can be obtained through water flowing into the blades of the waterwheel. The power generated by the water (P_{in}) can be calculated using Eq. (1) [26].

$$P_{in} = \rho . g . h . Q \tag{1}$$

Where P_{in} is water power (*W*), ρ is density of water (998.2 kg/m^3), g is gravitational acceleration (m/s^2), h is waterfall height (m), and Q is water discharge (m^3/h).

Where the head is the height difference between the surface of the base of the waterwheel housing and the height of the water surface before entering the waterwheel blades [27]. The circumferential speed of the wheel commonly known as angular velocity (ω) is obtained from Eq. (2) [28]. Meanwhile, to calculate the waterwheel power (P_{out}) using the Eq. (3) [29].

$$\omega = \frac{2.\pi.n}{60} \tag{2}$$

$$P_{out} = T.\omega \tag{3}$$

Where ω is angular velocity (*rad/s*), n is waterwheel rotation (*rpm*), and T is torque (*N-m*).

The efficiency of the waterwheel (η) is the ratio between the power generated by the waterwheel and the water power, which can be calculated using Eq. (4) [30].

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% \tag{4}$$

The rotation of a solid body with mass (m) moving translational (linear) with velocity (v) using Eq. (5) can be explained through kinetic energy according to Eq. (6) [31].

$$v = \omega . r \tag{5}$$

$$Ek = \frac{1}{2}.m.v^2 \tag{6}$$

Where r is distance of the waterwheel to the shaft (m), Ek is kinetic energy (J), m is mass of the wheel (kg), and v is water flow velocity (m/s^2).

It is assumed that the kinetic energy measured in a solid cylinder results in Rotational Kinetic Energy (Ek_{rot}) which is related to the moment of Inertia (I) and can be obtained through Eq. (7) [32].

$$Ek_{rot} = \frac{1}{2}.I.\omega^2 \tag{7}$$

Where is Ek_{rot} is rotational kinetic energy (J), and I is moment of inertia ($kg.m^2$).

Moment of Inertia (I) is the property of an object that allows it to maintain its position in rotational motion [33]. A stationary object tends to maintain its position, so a moving object will try to maintain its rotational motion. Mathematically, the moment of inertia can be obtained from Eq. (8).

$$I = m.r^2 \tag{8}$$

3 Results and discussion

After obtaining torque and rotation data for each discharge variation. Calculation of water power, waterwheel power, and overshot waterwheel efficiency using Eqs. (1), (3), and (4). The results of testing and data processing are presented in the form of tables and figures that show the relationship between these factors. The complete results of data processing can be seen in Table 3.

The rotation of the waterwheel is influenced by the water flow using Eq. (6) and the head of the waterwheel. At the discharge position of 1-5.5 m³/h, the head value was recorded at 0.7 m, while at the discharge of 6-8.5 m³/h, the head value increased by 0.02 m, and reached its peak at the discharge of 9 to 10 m³/h with a head value of 0.73 m. This increase in head is caused by the increase in water flow in the gutter of the waterwheel. The increase in head is caused by the increase in the flow of water flowing in the gutter of the waterwheel. The waterwheel without the corner cap experiences an obstacle, where the water flow cannot hit the entire blade optimally. As a result, the water flow that enters the blades is focused in the middle and goes straight down to the bottom of the wheel, so it cannot maximize the water flow and causes a small rotation.

On the other hand, the waterwheel with a 45° angle cap shows a larger rotation than the waterwheel without a cap, because the angle cap reduces the opening area of the waterwheel. This causes the flow of water into the blade of the waterwheel not to come out immediately, due to obstruction by the waterwheel cover, so that the water can be concentrated effectively towards the blade of the waterwheel.

Table 3. Data processing results of variable waterwheel WC, AC 45°, WFAC 45°

Q	n (rpm)			P_{in} (watt)			P_{out} (watt)			efficiency (%)		
(m^3/h)	WC	AC 45°	WFAC 45°	WC	AC 45°	WFAC 45°	WC	AC 45°	WFAC 45°	WC	AC 45°	WFAC 45°
1	7.41	19.62	8.95	1.91	1.91	1.91	0.41	1.09	0.51	21.70	57.08	26.55
1,5	11.96	25.66	18.31	2.86	2.86	2.86	0.66	1.43	1.07	23.21	50.09	37.53
2	16.22	30.02	19.91	3.82	3.82	3.82	0.89	1.70	1.21	23.30	44.50	31.69

Q	n (rpm)			P_{in} (watt)			P_{out} (watt)			efficiency (%)		
(m^3/h)	WC	AC 45°	WFAC 45°	WC	AC 45°	WFAC 45°	WC	AC 45°	WFAC 45°	WC	AC 45°	WFAC 45°
2,5	19.41	34.12	24.96	4.68	4.68	4.68	1.05	1.88	1.41	22.02	39.46	29.60
3	21.62	37.33	28.46	5.72	5.72	5.72	1.22	2.01	1.64	21.37	35.07	28.64
3,5	23.70	38.27	30.13	6.68	6.68	6.68	1.32	2.22	1.68	19.70	33.21	25.21
4	25.06	40.50	32.29	7.63	7.63	7.63	1.41	2.26	1.94	18.45	29.64	25.38
4,5	26.28	41.55	33.43	8.58	8.58	8.58	1.46	2.29	1.94	16.99	26.70	22.57
5	28.12	42.34	34.90	9.54	9.54	9.54	1.55	2.35	2.01	16.26	24.64	21.07
5,5	28.66	42.77	36.21	1049	10.49	10.49	1.56	2.42	2.01	14.88	23.05	19.16
6	29.75	43.38	37.39	11.77	11.77	11.77	1.66	2.36	2.23	14.11	20.07	18.96
6,5	31.95	43.96	38.42	12.75	12.75	12.75	1.74	2.30	2.21	13.64	18.05	17.35
7	33.11	44.13	39.06	13.73	13.73	13.73	1.80	2.43	2.32	13.13	17.72	16.88
7,5	34.20	45.06	39.67	14.72	14.72	14.72	1.91	2.52	2.20	12.98	17.10	14.96
8	36.04	45.86	40.58	15.70	15.70	15.70	1.95	2.67	2.35	12.42	17.03	14.98
8,5	36.68	46.51	41.68	16.68	16.68	16.68	2.09	2.63	2.37	12.52	15.77	14.22
9	38.99	46.87	42.59	17.90	17.90	17.90	2.14	2.60	2.51	11.94	14.53	14.03
9,5	39.91	47.30	44.73	18.90	18.90	18.90	2.24	2.68	2.58	11.87	14.15	13.63
10	41.47	48.56	47.47	19.89	19.89	19.89	2.29	2.85	2.88	11.50	14.32	14.50

Meanwhile, the wheel equipped with a corner cap filled with water experiences a moment of inertia that causes inertia in the rotation of the wheel to be smaller when the discharge is in the range of 1 to 4 m³/h. However, the rotation began to increase at a discharge of 4 to 10 m³/h due to the work of the moment of inertia helping to increase the kinetic energy of the waterwheel rotation, whereas, at a discharge of 10 m³/hour, the rotation of the waterwheel experienced a significant increase compared to the waterwheel using a 45° angle cap without water content. The following figure shows the comparison of the processed data.

Fig. 6 shows the relationship between water discharge (m³/h) on the horizontal axis and wheel speed (rpm) on the vertical axis. In this figure, there are three turbine configurations, namely AC 45°, WC, and WFAC 45°, with each tested at two water discharge ranges: 1-4 m³/h and 4-10 m³/h.

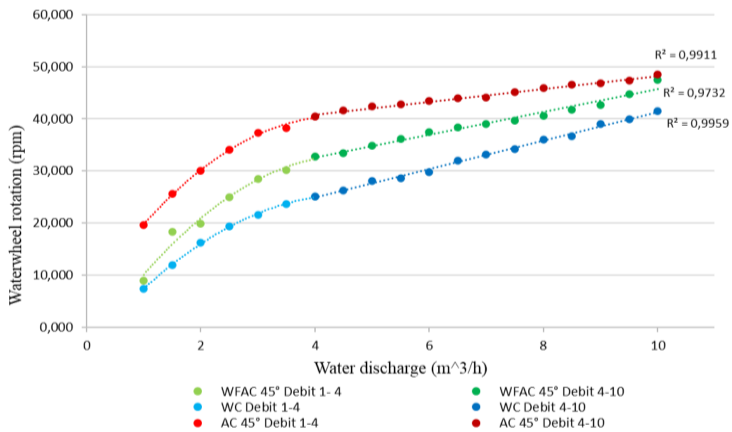

Fig. 6. Waterwheel rotation (rpm)

The AC 45° variable waterwheel represents a polynomial curve at small discharge (1-4 m^3/h), where the rotation of the waterwheel increases gradually from 19.62 rpm to 40.50 rpm. The increase in rotation is due to the angle cap which reduces the opening area of the waterwheel so that the water does not fall directly to the bottom of the waterwheel house, resulting in a moment of inertia with the calculation of Eq. (9) of 2.152 kg/m2 and generating rotational kinetic energy of 12.249 Joules using the calculation of Eq. (8). At large discharges (4-10 m³/h) show a more stable and linear increase, where the rotation of the waterwheel increases from 40.50 rpm to reach about 48.56 rpm. There is an increase in rotational kinetic energy of 23.386 Joules. The R^2 value is 0.9911, indicating that the 45° angle cap greatly influences the rotation of the waterwheel.

The WFAC 45° variable wheel represents a polynomial curve at small discharge, where the rotation of the wheel experiences inertia due to the water content of the wheel blades causing the rotation to slow down in contrast to the AC 45°. The rotation starts from about 8.95 rpm and increases to 32.29 rpm. In the increase in rotation, there is a moment of inertia of 3.087 kg/m^2 resulting in rotational kinetic energy of 9.242 Joules, with a slower increase when compared to the AC 45° waterwheel. At large discharge, the rotation of the waterwheel increased linearly from 32.29 rpm to 47.47 rpm showing a stable relationship between water discharge and waterwheel rotation. The curve also has a high fit to the data, indicated by the R^2 value of 0.9732. In the no-water-fill condition, with the same water discharge of 9-10 m³/h, the rotation of the waterwheel recorded a continuous increase, which was 46.87 rpm, 47.30 rpm, and 48.56 rpm. A significant increase in the rotation of the WFAC 45° began to be seen at a discharge of 9-10 m³/hour, respectively 42.59 rpm, 44.73 rpm, and 47.47 rpm and produced rotational kinetic energy of 25.946 Joules. Where water filling produces an increase in rotational kinetic energy, it causes a significant increase in wheel rotation. If the discharge continues the possibility is greater than with AC 45° which increases continuously. This is because the rotational kinetic energy is directly proportional to the square of the rotation speed at large discharge, although the difference in rotation is still visible.

The WC variable wheel showed a polynomial curve configuration at small discharge, with the wheel rotation starting from about 7.41 rpm and increasing up to 25.06 rpm. The moment of inertia value of 2.076 kg/m^2 produced 3.653 Joules less rotational kinetic energy compared to AC 45° and WFAC 45°, but still had a very high R^2 value of 0.9959 indicating an excellent match with the data. As the discharge was increased, the wheel rotation was only able to increase from 25.06 rpm to 41.47 rpm resulting in rotational kinetic energy of 12.470 Joules less than AC 45° and WFAC 45°, following a similar linear pattern as the other configurations. Overall, this figure shows that an increase in water discharge is closely related to an increase in waterwheel rotation just as in previous studies [34]. The difference in efficiency varies between wheel configurations and water discharge ranges.

Fig. 7 shows the relationship between water discharge (m³/h) and waterwheel power (watt), indicating that the higher the water discharge, the more power the waterwheel produces. This graph consists of several sets of data, each representing different conditions, namely AC 45°, WC, and WFAC 45° at discharge ranges of 1-4 m³/h and 4-10 m³/h, respectively. The difference between the small discharge range (1-4) and the large discharge range (4-10) can be seen from the different shapes of the curves used: polynomial curves for discharge 1-4 m^3/h and linear curves for discharge 4-10 m^3/h.

In the variable AC 45° waterwheel, the waterwheel configuration is at a 45° angle. In the discharge range of 1-4 m³/h, the curve shows a polynomial pattern, where the waterwheel power increases sharply from about 1.09 to almost 2.26 watts. In the discharge range of 4-10 m³/hr, the pattern changes to linear, with the power continuing to increase steadily until it reaches 2.85 watts at a discharge of 10 m³/hr. The R^2 = 0.8603 value for this linear curve indicates that the model does a good job of explaining the relationship between water discharge and waterwheel power.

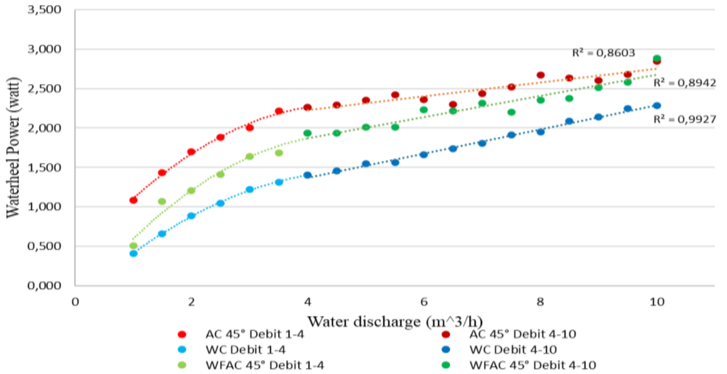

Fig. 7. Waterwheel power (Watt)

The WFAC 45° variable wheel, where at a discharge of 1-4 m³/h, the curve shows polynomial properties with the resulting wheel power relatively smaller than that of the AC 45°, which ranges from 0.51 watts to 1.94 watts. This phenomenon can be explained by the process of inertia caused by water, which makes the wheel heavier to rotate. So that the power generated is smaller than that of AC 45°. When the discharge increases from 4 to 10 m³/hour, the power of the waterwheel increases linearly until it reaches about 2.88 watts greater than AC 45°. This occurs because the increase in water discharge causes an increase in the moment of inertia, which in turn generates greater rotational kinetic energy, allowing the waterwheel power to reach its maximum point. The value of $R^2 = 0.8942$ for this linear curve indicates that the relationship between water discharge and waterwheel power is stronger than AC 45° at large discharge.

At the discharge range of 1-4 m³/h, the polynomial curve shows the generated waterwheel power starts from about 0.41 watts and increases up to 1.41 watts. In the discharge range of 4-10 m³/h, the waterwheel power increased linearly from 1.41 watts to 2.29 watts with a very strong relationship $R^2 = 0.9927$.

Fig. 8 illustrates the maximum and minimum waterwheel performance conditions observed in the operating system. The highest efficiency, recorded at variable AC 45°, occurred at a discharge of 1 m³/h, with an efficiency of 57.08%. In contrast, the lowest efficiency occurred at a discharge of 10 m³/h, with an efficiency of 14.32%. At variable WFAC 45°, the highest efficiency was achieved at a discharge of 1½ m³/h, which resulted in an efficiency of 37.53%.

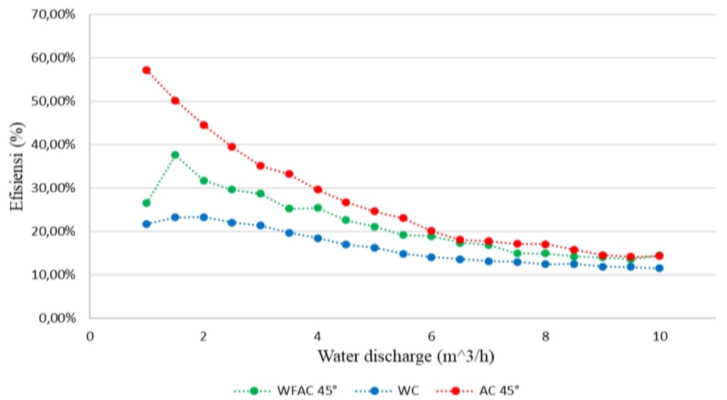

Fig. 8. Waterwheel efficiency (%)

An important phenomenon occurred at a discharge of 1 m³/h, where the efficiency initially decreased but then increased rapidly at a discharge of 1½ m³/h. This phenomenon can be attributed to the rotational inertia at a discharge of 1 m³/h, which causes the rotation of the waterwheel to rotate slowly. However, as the discharge increased, the water mass inside the waterwheel generated a moment of inertia similar to that observed in a previous study [35], which led to an increase in efficiency. The lowest efficiency at variable WFAC 45° was recorded at a discharge of 9½ m³/h, with a value of 13.63%. In addition, at a discharge of 2 m³/h, the maximum efficiency in the WC variable reached 23.30%, while the minimum efficiency at a discharge of 10 m³/h was 11.50%. Next, the efficiencies of the WC, AC 45°, and WFAC 45° compared to previous studies as shown in Table 4, in addition to the results of previous studies.

Table 4. Comparison of waterwheel performance efficiency with previous studies

Variable overshot water wheel	Efficiency	Reference
Waterwheel WC diameter 0.45 m	23.30%	
Waterwheel AC 45° diameter 0.45 m	57.08%	
Waterwheel WFAC 45° diameter 0.45 m	37.53%	
Waterwheel nozzle angle 30° diameter 0.50 m	25.05%	[36]
Waterwheel using square penstock diameter 0.60 m	42.00%	[37]
Waterwheel bucket configuration -20 diameter 0.90 m	45.00%	[38]

Based on Table 4, the efficiency of an overshot waterwheel is influenced by the blade design and the water flow system. The uncovered waterwheel (WC) was only able to achieve an efficiency of 23.30%. However, the use of a blade cover with a 45° angle (AC 45°) increased the efficiency to 57.08%. When water was introduced into the closed angle (WFAC 45°), the efficiency decreased to 37.53%, possibly due to water content in the closed blade. The use of a nozzle with a 30° angle resulted in an efficiency of 25.05%, which is still lower than the (WFAC 45°) configuration. The square-shaped penstock with a diameter of 0.60 m produced an efficiency of 42.00%, while the 0.90 m diameter bucket configuration showed an increase in efficiency to 45.00%, but still lower than the 0.45 m diameter 45° AC closed blade design. Overall, the closed blade design proved to be the most effective in improving efficiency compared to simply increasing the diameter.

4 Conclusion

The utilization of water resources as renewable energy through waterwheels presents an environmentally friendly alternative, however, its efficiency requires improvement through technological modification. This research investigates two design modifications: a 45° angle cap (AC) and a water-filled angle cap (WFAC), in comparison with a waterwheel without a cap (WC). Experiments were conducted at discharges from 1 to 10 m³/h with a constant torque load of 0.05 N-m. The highest efficiency of 57.08% was achieved in the AC 45° configuration at 1 m³/h, generating 1.09 watts of power, while the WFAC 45° yielded the highest power output of 2.88 watts at 10 m³/h with an efficiency of 14.50%. Although increasing discharge generally led to higher power input, it was accompanied by a decrease in efficiency across all configurations. Among all three variations, WFAC 45° demonstrated superior performance at higher discharges, indicating its potential for enhancing the power and efficiency of overshot waterwheels.

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Impact of angle cap and water-filled blade modification on the output of overshot waterwheels

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Fakultas Teknologi Industri dan Informatika

Universitas Muhammadiyah Prof. Dr. Hamka

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Impact of angle cap and water-filled blade modification on the output of overshot waterwheels

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Abstract

The utilization of water resources as renewable energy through waterwheels presents an environmentally friendly alternative, however, its efficiency requires improvement through technological modification. This research investigates two design modifications: a 45° Angle Cap (AC) and a Water-Filled Angle Cap (WFAC), in comparison with a waterwheel without a Cap (WC). Experiments were conducted at discharges from 1 to 10 m³/h with a constant torque load of 0.05 N-m. The highest efficiency of 57.08% was achieved in the AC 45° configuration at 1 m³/h, generating 1.09 watts of power, while the WFAC 45° yielded the highest power output of 2.88 watts at 10 m³/h with an efficiency of 14.50%. Although increasing discharge generally led to higher power input, it was accompanied by a decrease in efficiency across all configurations. Among all three variations, WFAC 45° demonstrated superior performance at higher discharges, indicating its potential for enhancing the power and efficiency of overshot waterwheels.

Keywords:
Waterwheel, renewable energy, rotational kinetic energy, moment of inertia, efficiency.

1 Introduction

Sustainable utilization of natural resources is one of the central issues in the global effort to deal with climate change and environmental degradation [1], [2], including Indonesia. Indonesia is one of the developing countries that has abundant renewable natural resources and one of them is water [3]. Water as a renewable natural energy has great potential to be converted from kinetic energy into electrical energy [4]. Hydropower plants are designed to generate electricity on a large scale, while small-scale plants are known as Micro-hydro Power Plants (MHP) [5], [6], [7]. MHP utilizes the flow of rivers or other water sources to generate electricity in a sustainable manner to meet the needs of housing, agriculture, and community facilities [8], [9], [10].

The utilization of water as a renewable energy source requires a waterwheel that plays an important role in converting kinetic energy from water flow into other forms of energy and is usually converted into electrical energy through a generator that operates without reducing the volume of water [11], [12]. In this context, waterwheels were chosen because they are more environmentally friendly and cost-effective [13]. Waterwheels have 3 types: overshot, breast shot, and undershot waterwheels. [14]. In an overshot waterwheel, water flows from the top of the wheel and spins as it falls to a lower surface. In a breast shot waterwheel, water flows over the center of the waterwheel which is positioned parallel to the top [15]. Meanwhile, in an undershot waterwheel, the waterwheel is placed slightly above the water flow so that only the bottom part of the waterwheel enters the water. The difference between the three types of waterwheels lies in the type of energy transferred to the waterwheel which affects the efficiency and the exact conditions of use of each waterwheel [16], [17].

Various studies have been conducted on waterwheels, including the effect of adding angled caps, blade thickness on flat-bladed waterwheels, and the relationship between blade height and power and efficiency [18], [19]. The efficiency of waterwheels is influenced by a variety of factors, including aspects of the geometry of the wheel, such as diameter size, number of blades, and their curved shape, as well as operational factors such as water level (head), flow discharge, load torque, and water flow position [20], [21]. To achieve high efficiency, more in-depth research is needed related to these factors, with experimental methods under field conditions [22]. Previous research shows that the shape of the waterwheel blades is very important because a certain shape makes it easier for water to enter between the blades and is one of the causes of the wheel's rotation. In addition, the moment of inertia of the waterwheel is also an important factor that affects the efficiency and stability of the waterwheel [23]. Although research on waterwheels has been going on for a long time, until now no waterwheel has been equipped with a director to force water to enter between the blades, even though this has the potential to increase the power generated. Another attempt that has not yet been made is to introduce water into the waterwheel to increase its moment of inertia.

Therefore, this study aims to determine the performance of the power generated by the wheel and the efficiency of the wheel's performance by comparing a straight-blade water wheel with a water wheel that has a blade cover to direct water in, as well as a wheel that contains water in the blade.

2 Method

The waterwheel used in the study is an overshot waterwheel with 16 blades. There are 2 models of blade caps, namely closed water-filled and 45° angled caps to the outside as shown in Fig. 1. The closed water-filled blades aim to produce a moment of inertia and increase the kinetic energy of the wheel. The cap that forms a 45° angle on the blades serves to expand the area outside the blades so that the water flow is concentrated in the blade area to achieve maximum rotation.

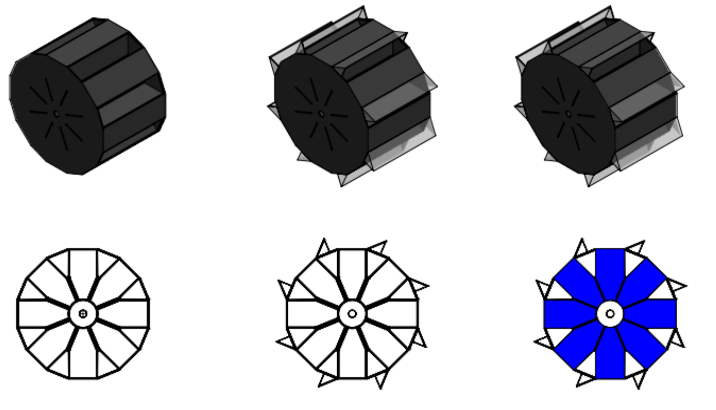

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Fig. 1. Overshoot waterwheel. a) Isometric and side view Without Cap (WC), b) isometric and side view Angle Cap (AC) 45°, and c) isometric and side view Water-Filled Angle Cap (WFAC) 45°

The test method applied in the overshot waterwheel research is the actual experimental method on a laboratory scale. The test was carried out in the Mechanical Engineering laboratory of University Prof. Dr Hamka Muhammadiyah. Tests were carried out using dependent variables and independent variables. The dependent variable consists of rotation, torque, waterwheel power, and waterwheel efficiency. While the independent variables are Without Cap (WC), Angle Cap (AC) 45°, and Water-Filled Angle Cap (WFAC) 45° shown in Fig. 1. The flowchart of the overshot waterwheel research can be seen in Fig. 2.

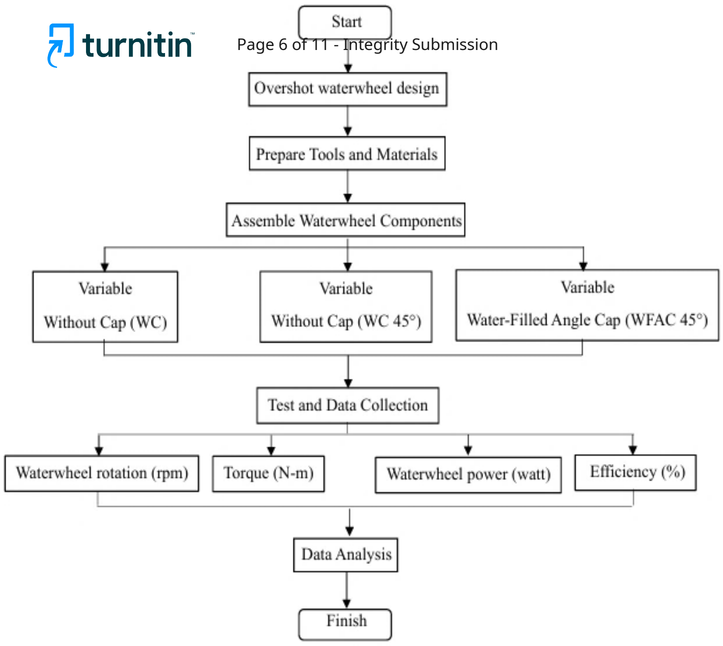

Fig. 2. Flowchart of overshot waterwheel research systematic

Fig. 2 is a systematic way of conducting overshot waterwheel research. This research consists of three interconnected stages. The first stage includes preparation of the design concept, equipment needed for research, and assembly of the waterwheel components. The second stage is a trial to ensure the research tool functions properly. The third stage is data collection through recording which is then followed by the data analysis process.

The design of the overshot waterwheel involved design, cutting, welding, and testing. The manufacture of the waterwheel housing uses melamine multiplex material, with the inside coated with resin and the outside coated with waterproof paint. The wheelhouse is 100 cm high, 100 cm long, and 37 cm wide. The lid is made of acrylic material with a 45° tilt angle. Meanwhile, the wheel is made of iron material with a thickness of 3 mm.

The wheel mounting frame plays a role in supporting the pillow block to support the wheel shaft, ensuring optimal wheel rotation. The waterwheel shaft is solid with a diameter of 25 mm, while the waterwheel has a diameter of 45 cm and a thickness of 30 cm. The geometry design of the overshot waterwheel in millimeters (mm) is shown in Fig. 3.

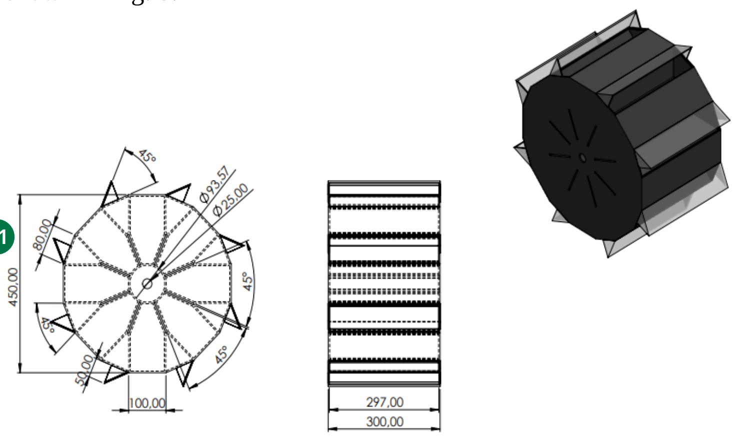

Fig. 3. Geometry of waterwheel

Measuring instruments used for the data collection process include, Torque meter functions to collect Torque data from the waterwheel. Data collection of waterwheel rotation using a Tachometer measuring instrument [24]. Water discharge settings using a Rotameter measuring instrument and water flow rate measured using a Flow velocity meter tool [25], according to the specifications listed in Table 1.

This study utilized one waterwheel to collect data on the independent variables. The four red-colored dots shown in the fig. 4 indicate the data collection locations required during the testing process.

Table 1. Specifications of waterwheel test measuring instrument

Measurement tool	Type	Capacity
Torque meter	Lutron TQ-8800	0 - 0.15 (N-m)
Tachometer	KW06-563	0 - 20.000 (rpm)
Rotameter	LZT-50S105/N	1 - 10 m^3 /h)
Flow velocity meter	Flo watch FL-03	2 - 150 (km/h)

Data was collected using flow rates of 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6, 6.5, 7, 7.5, 8, 8.5, 9, 9.5, up to 10 m³/h, which were circulated using a pump. The independent variables tested included a 45° angle cap, no cap, and a 45° angle cap with water content. Data was taken more than once to ensure the test results remained consistent.

The installation scheme of the overshot waterwheel test consists of 17 components, each of which plays a crucial role with different functions, starting from the water pump in charge of maintaining the continuity of water flow through the pipe from the waterwheel house, forwarded to the water trough according to the design shown in Fig. 4.

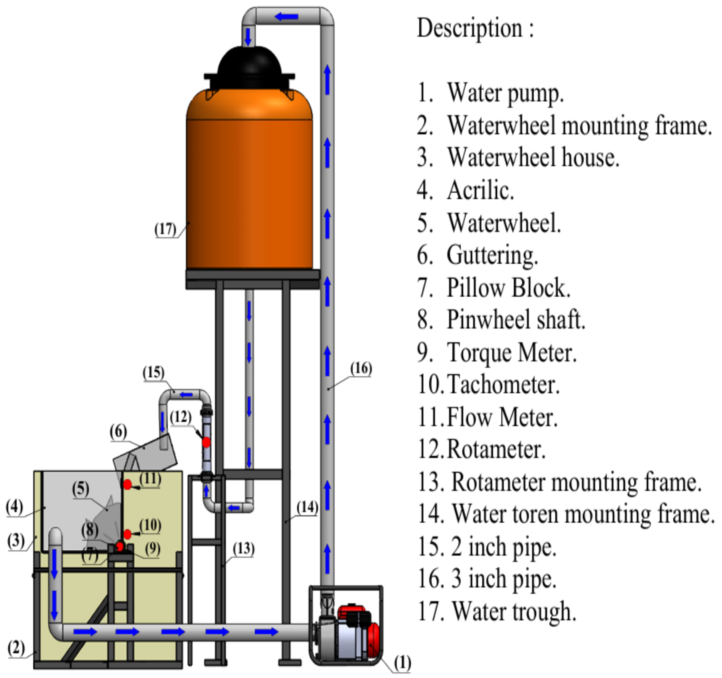

Fig. 4. Schematic design of overshot waterwheel testing installation

The water trough, which acts as the main reservoir, is designed to facilitate the precise regulation of water discharge, which is done with the help of a rotameter gauge to control the flow of water into the gutter. The gutter acts as a guide, concentrating the water flow precisely on the 45° tilt angle of the blades, ensuring an even distribution of water across the surface of the blades. The blade's main function is to maximize the efficiency of the waterwheel rotation by adjusting its rotation rate to the volume and velocity of the incoming water flow, which ultimately determines the overall performance of the waterwheel. As a control and reference in this test, the detailed specifications of the waterwheel are presented in Table 2, providing a clear guide to the technical parameters tested.

Table 2. Waterwheel specifications

Specification	Parameter
Weight of Waterwheel WC	41 kg
Weight of Waterwheel AC 45°	42.5 kg
Weight of Waterwheel WFAC 45°	60 kg
Toque	0.05 N-m

The precision-designed components of the waterwheel are then assembled into a highly complex and interconnected circuit, where each element contributes to the functionality of the entire system. The artificial waterways, whose continuity is supported by the use of pumps, serve to maintain a steady and controlled flow of water, which in turn allows for high-accuracy testing of the efficiency of the waterwheel. The overall result of the waterwheel assembly, which incorporates various aspects of technical design and construction, can be seen in Fig. 5.

Fig. 5. The assembled overshot waterwheel installation and data collection location. (a) water flow velocity data, (b) water discharge data, (c) waterwheel torque data, and (d) waterwheel rotation data

Experimental results were processed to determine the efficiency of the waterwheel. Energy from water can be obtained through water flowing into the blades of the waterwheel. The power generated by the water (P_{in}) can be calculated using Eq. (1) [26].

$$P_{in} = \rho . g . h . Q \tag{1}$$

Where P_{in} is water power (W), ρ is density of water (998.2 kg/m^3), g is gravitational acceleration (m/s^2), h is waterfall height (m), and Q is water discharge (m^3/h).

Where the head is the height difference between the surface of the base of the waterwheel housing and the height of the water surface before entering the waterwheel blades [27]. The circumferential speed of the wheel commonly known as angular velocity (ω) is obtained from Eq. (2) [28]. Meanwhile, to calculate the waterwheel power (P_{out}) using the Eq. (3) [29].

$$\omega = \frac{2 . \pi . n}{60} \tag{2}$$

$$P_{out} = T . \omega \tag{3}$$

Where ω is angular velocity (rad/s), n is waterwheel rotation (rpm), and T is torque (N-m).

The efficiency of the waterwheel (η) is the ratio between the power generated by the waterwheel and the water power, which can be calculated using Eq. (4) [30].

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% \tag{4}$$

The rotation of a solid body with mass (m) moving translational (linear) with velocity (v) using Eq. (5) can be explained through kinetic energy according to Eq. (6) [31].

$$v = \omega . r \tag{5}$$

$$Ek = \frac{1}{2} . m . v^2 \tag{6}$$

Where r is distance of the waterwheel to the shaft (m), Ek is kinetic energy (J), m is mass of the wheel (kg), and v is water flow velocity (m/s^2).

It is assumed that the kinetic energy measured in a solid cylinder results in Rotational Kinetic Energy (Ek_{rot}) which is related to the moment of Inertia (I) and can be obtained through Eq. (7) [32].

$$Ek_{rot} = \frac{1}{2} . I . \omega^2 \tag{7}$$

Where is Ek_{rot} is rotational kinetic energy (J), and I is moment of inertia ($kg.m^2$).

Moment of Inertia (I) is the property of an object that allows it to maintain its position in rotational motion [33]. A stationary object tends to maintain its position, so a moving object will try to maintain its rotational motion. Mathematically, the moment of inertia can be obtained from Eq. (8).

$$I = m . r^2 \tag{8}$$

3 Results and discussion

After obtaining torque and rotation data for each discharge variation. Calculation of water power, waterwheel power, and overshot waterwheel efficiency using Eqs. (1), (3), and (4). The results of testing and data processing are presented in the form of tables and figures that show the relationship between these factors. The complete results of data processing can be seen in Table 3.

The rotation of the waterwheel is influenced by the water flow using Eq. (6) and the head of the waterwheel. At the discharge position of 1-5.5 m³/h, the head value was recorded at 0.7 m, while at the discharge of 6-8.5 m³/h, the head value increased by 0.02 m, and reached its peak at the discharge of 9 to 10 m³/h with a head value of 0.73 m. This increase in head is caused by the increase in water flow in the gutter of the waterwheel. The increase in head is caused by the increase in the flow of water flowing in the gutter of the waterwheel. The waterwheel without the corner cap experiences an obstacle, where the water flow cannot hit the entire blade optimally. As a result, the water flow that enters the blades is focused in the middle and goes straight down to the bottom of the wheel, so it cannot maximize the water flow and causes a small rotation.

On the other hand, the waterwheel with a 45° angle cap shows a larger rotation than the waterwheel without a cap, because the angle cap reduces the opening area of the waterwheel. This causes the flow of water into the blade of the waterwheel not to come out immediately, due to obstruction by the waterwheel cover, so that the water can be concentrated effectively towards the blade of the waterwheel.

Table 3. Data processing results of variable waterwheel WC, AC 45°, WFAC 45°

Q	n (rpm)			P_{in} (watt)			P_{out} (watt)			efficiency (%)		
(m^3/h)	WC	AC 45°	WFAC 45°	WC	AC 45°	WFAC 45°	WC	AC 45°	WFAC 45°	WC	AC 45°	WFAC 45°
1	7.41	19.62	8.95	1.91	1.91	1.91	0.41	1.09	0.51	21.70	57.08	26.55
1,5	11.96	25.66	18.31	2.86	2.86	2.86	0.66	1.43	1.07	23.21	50.09	37.53
2	16.22	30.02	19.91	3.82	3.82	3.82	0.89	1.70	1.21	23.30	44.50	31.69

Q (m^3/h)	n (rpm)			P_{in} (watt)			P_{out} (watt)			efficiency (%)		
	WC	AC 45°	WFAC 45°	WC	AC 45°	WFAC 45°	WC	AC 45°	WFAC 45°	WC	AC 45°	WFAC 45°
2,5	19.41	34.12	24.96	4.68	4.68	4.68	1.05	1.88	1.41	22.02	39.46	29.60
3	21.62	37.33	28.46	5.72	5.72	5.72	1.22	2.01	1.64	21.37	35.07	28.64
3,5	23.70	38.27	30.13	6.68	6.68	6.68	1.32	2.22	1.68	19.70	33.21	25.21
4	25.06	40.50	32.29	7.63	7.63	7.63	1.41	2.26	1.94	18.45	29.64	25.38
4,5	26.28	41.55	33.43	8.58	8.58	8.58	1.46	2.29	1.94	16.99	26.70	22.57
5	28.12	42.34	34.90	9.54	9.54	9.54	1.55	2.35	2.01	16.26	24.64	21.07
5,5	28.66	42.77	36.21	1049	10.49	10.49	1.56	2.42	2.01	14.88	23.05	19.16
6	29.75	43.38	37.39	11.77	11.77	11.77	1.66	2.36	2.23	14.11	20.07	18.96
6,5	31.95	43.96	38.42	12.75	12.75	12.75	1.74	2.30	2.21	13.64	18.05	17.35
7	33.11	44.13	39.06	13.73	13.73	13.73	1.80	2.43	2.32	13.13	17.72	16.88
7,5	34.20	45.06	39.67	14.72	14.72	14.72	1.91	2.52	2.20	12.98	17.10	14.96
8	36.04	45.86	40.58	15.70	15.70	15.70	1.95	2.67	2.35	12.42	17.03	14.98
8,5	36.68	46.51	41.68	16.68	16.68	16.68	2.09	2.63	2.37	12.52	15.77	14.22
9	38.99	46.87	42.59	17.90	17.90	17.90	2.14	2.60	2.51	11.94	14.53	14.03
9,5	39.91	47.30	44.73	18.90	18.90	18.90	2.24	2.68	2.58	11.87	14.15	13.63
10	41.47	48.56	47.47	19.89	19.89	19.89	2.29	2.85	2.88	11.50	14.32	14.50

Meanwhile, the wheel equipped with a corner cap filled with water experiences a moment of inertia that causes inertia in the rotation of the wheel to be smaller when the discharge is in the range of 1 to 4 m^3/h. However, the rotation began to increase at a discharge of 4 to 10 m^3/h due to the work of the moment of inertia helping to increase the kinetic energy of the waterwheel rotation, whereas, at a discharge of 10 m^3/hour, the rotation of the waterwheel experienced a significant increase compared to the waterwheel using a 45° angle cap without water content. The following figure shows the comparison of the processed data.

Fig. 6 shows the relationship between water discharge (m^3/h) on the horizontal axis and wheel speed (rpm) on the vertical axis. In this figure, there are three turbine configurations, namely AC 45°, WC, and WFAC 45°, with each tested at two water discharge ranges: 1-4 m^3/h and 4-10 m^3/h.

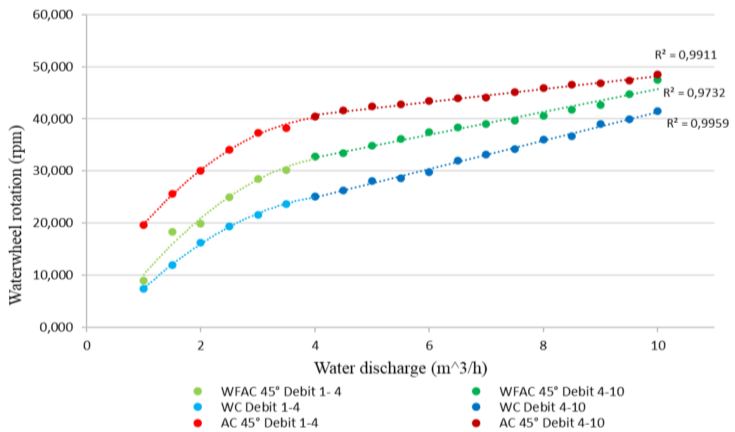

Fig. 6. Waterwheel rotation (rpm)

The AC 45° variable waterwheel represents a polynomial curve at small discharge (1-4 m^3/h), where the rotation of the waterwheel increases gradually from 19.62 rpm to 40.50 rpm. The increase in rotation is due to the angle cap which reduces the opening area of the waterwheel so that the water does not fall directly to the bottom of the waterwheel house, resulting in a moment of inertia with the calculation of Eq. (9) of 2.152 kg/m2 and generating rotational kinetic energy of 12.249 Joules using the calculation of Eq. (8). At large discharges (4-10 m^3/h) show a more stable and linear increase, where the rotation of the waterwheel increases from 40.50 rpm to reach about 48.56 rpm. There is an increase in rotational kinetic energy of 23.386 Joules. The R^2 value is 0.9911, indicating that the 45° angle cap greatly influences the rotation of the waterwheel.

The WFAC 45° variable wheel represents a polynomial curve at small discharge, where the rotation of the wheel experiences inertia due to the water content of the wheel blades causing the rotation to slow down in contrast to the AC 45°. The rotation starts from about 8.95 rpm and increases to 32.29 rpm. In the increase in rotation, there is a moment of inertia of 3.087 kg/m^2 resulting in rotational kinetic energy of 9.242 Joules, with a slower increase when compared to the AC 45° waterwheel. At large discharge, the rotation of the waterwheel increased linearly from 32.29 rpm to 47.47 rpm showing a stable relationship between water discharge and waterwheel rotation. The curve also has a high fit to the data, indicated by the R^2 value of 0.9732. In the no-water-fill condition, with the same water discharge of 9-10 m^3/h, the rotation of the waterwheel recorded a continuous increase, which was 46.87 rpm, 47.30 rpm, and 48.56 rpm. A significant increase in the rotation of the WFAC 45° began to be seen at a discharge of 9-10 m^3/hour, respectively 42.59 rpm, 44.73 rpm, and 47.47 rpm and produced rotational kinetic energy of 25.946 Joules. Where water filling produces an increase in rotational kinetic energy, it causes a significant increase in wheel rotation. If the discharge continues the possibility is greater than with AC 45° which increases continuously. This is because the rotational kinetic energy is directly proportional to the square of the rotation speed at large discharge, although the difference in rotation is still visible.

The WC variable wheel showed a polynomial curve configuration at small discharge, with the wheel rotation starting from about 7.41 rpm and increasing up to 25.06 rpm. The moment of inertia value of 2.076 kg/m^2 produced 3.653 Joules less rotational kinetic energy compared to AC 45° and WFAC 45°, but still had a very high R^2 value of 0.9959 indicating an excellent match with the data. As the discharge was increased, the wheel rotation was only able to increase from 25.06 rpm to 41.47 rpm resulting in rotational kinetic energy of 12.470 Joules less than AC 45° and WFAC 45°, following a similar linear pattern as the other configurations. Overall, this figure shows that an increase in water discharge is closely related to an increase in waterwheel rotation just as in previous studies [34]. The difference in efficiency varies between wheel configurations and water discharge ranges.

Fig. 7 shows the relationship between water discharge (m^3/h) and waterwheel power (watt), indicating that the higher the water discharge, the more power the waterwheel produces. This graph consists of several sets of data, each representing different conditions, namely AC 45°, WC, and WFAC 45° at discharge ranges of 1-4 m^3/h and 4-10 m^3/h, respectively. The difference between the small discharge range (1-4) and the large discharge range (4-10) can be seen from the different shapes of the curves used: polynomial curves for discharge 1-4 m^3/h and linear curves for discharge 4-10 m^3/h.

In the variable AC 45° waterwheel, the waterwheel configuration is at a 45° angle. In the discharge range of 1-4 m^3/h, the curve shows a polynomial pattern, where the waterwheel power increases sharply from about 1.09 to almost 2.26 watts. In the discharge range of 4-10 m^3/hr, the pattern changes to linear, with the power continuing to increase steadily until it reaches 2.85 watts at a discharge of 10 m^3/hr. The R^2 = 0.8603 value for this linear curve indicates that the model does a good job of explaining the relationship between water discharge and waterwheel power.

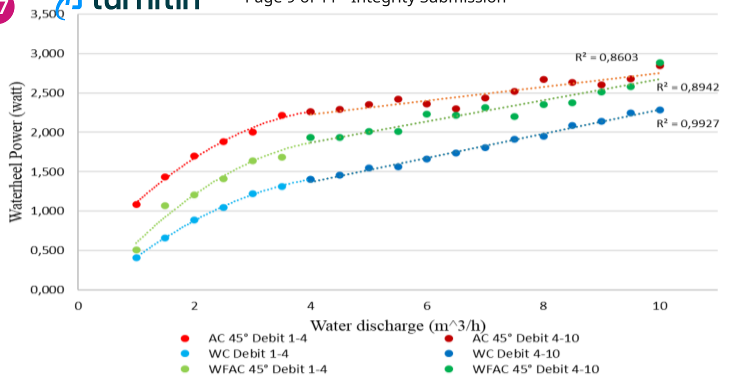

Fig. 7. Waterwheel power (Watt)

The WFAC 45° variable wheel, where at a discharge of 1-4 m³/h, the curve shows polynomial properties with the resulting wheel power relatively smaller than that of the AC 45°, which ranges from 0.51 watts to 1.94 watts. This phenomenon can be explained by the process of inertia caused by water, which makes the wheel heavier to rotate. So that the power generated is smaller than that of AC 45°. When the discharge increases from 4 to 10 m³/hour, the power of the waterwheel increases linearly until it reaches about 2.88 watts greater than AC 45°. This occurs because the increase in water discharge causes an increase in the moment of inertia, which in turn generates greater rotational kinetic energy, allowing the waterwheel power to reach its maximum point. The value of $R^2 = 0.8942$ for this linear curve indicates that the relationship between water discharge and waterwheel power is stronger than AC 45° at large discharge.

At the discharge range of 1-4 m³/h, the polynomial curve shows the generated waterwheel power starts from about 0.41 watts and increases up to 1.41 watts. In the discharge range of 4-10 m³/h, the waterwheel power increased linearly from 1.41 watts to 2.29 watts with a very strong relationship $R^2 = 0.9927$.

Fig. 8 illustrates the maximum and minimum waterwheel performance conditions observed in the operating system. The highest efficiency, recorded at variable AC 45°, occurred at a discharge of 1 m³/h, with an efficiency of 57.08%. In contrast, the lowest efficiency occurred at a discharge of 10 m³/h, with an efficiency of 14.32%. At variable WFAC 45°, the highest efficiency was achieved at a discharge of 1½ m³/h, which resulted in an efficiency of 37.53%.

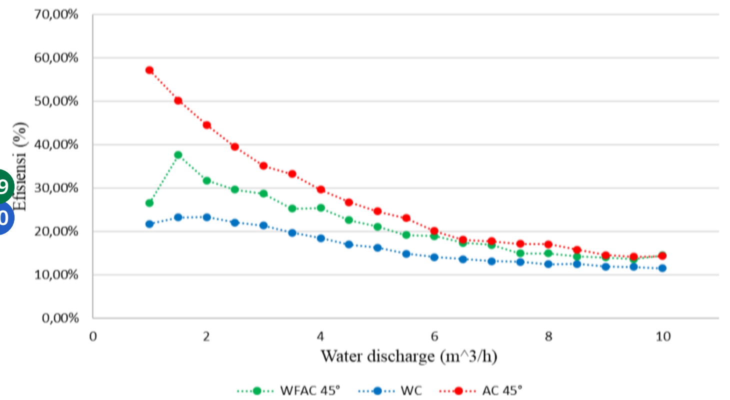

Fig. 8. Waterwheel efficiency (%)

An important phenomenon occurred at a discharge of 1 m³/h, where the efficiency initially decreased but then increased rapidly at a discharge of 1½ m³/h. This phenomenon can be attributed to the rotational inertia at a discharge of 1 m³/h, which causes the rotation of the waterwheel to rotate slowly. However, as the discharge increased, the water mass inside the waterwheel generated a moment of inertia similar to that observed in a previous study [35], which led to an increase in efficiency. The lowest efficiency at variable WFAC 45° was recorded at a discharge of 9½ m³/h, with a value of 13.63%. In addition, at a discharge of 2 m³/h, the maximum efficiency in the WC variable reached 23.30%, while the minimum efficiency at a discharge of 10 m³/h was 11.50%. Next, the efficiencies of the WC, AC 45°, and WFAC 45° compared to previous studies as shown in Table 4, in addition to the results of previous studies.

Table 4. Comparison of waterwheel performance efficiency with previous studies

Variable overshot water wheel	Efficiency	Reference
Waterwheel WC diameter 0.45 m	23.30%	
Waterwheel AC 45° diameter 0.45 m	57.08%	
Waterwheel WFAC 45° diameter 0.45 m	37.53%	
Waterwheel nozzle angle 30° diameter 0.50 m	25.05%	[36]
Waterwheel using square penstock diameter 0.60 m	42.00%	[37]
Waterwheel bucket configuration -20 diameter 0.90 m	45.00%	[38]

Based on Table 4, the efficiency of an overshot waterwheel is influenced by the blade design and the water flow system. The uncovered waterwheel (WC) was only able to achieve an efficiency of 23.30%. However, the use of a blade cover with a 45° angle (AC 45°) increased the efficiency to 57.08%. When water was introduced into the closed angle (WFAC 45°), the efficiency decreased to 37.53%, possibly due to water content in the closed blade. The use of a nozzle with a 30° angle resulted in an efficiency of 25.05%, which is still lower than the (WFAC 45°) configuration. The square-shaped penstock with a diameter of 0.60 m produced an efficiency of 42.00%, while the 0.90 m diameter bucket configuration showed an increase in efficiency to 45.00%, but still lower than the 0.45 m diameter 45° AC closed blade design. Overall, the closed blade design proved to be the most effective in improving efficiency compared to simply increasing the diameter.

4 Conclusion

The utilization of water resources as renewable energy through waterwheels presents an environmentally friendly alternative, however, its efficiency requires improvement through technological modification. This research investigates two design modifications: a 45° angle cap (AC) and a water-filled angle cap (WFAC), in comparison with a waterwheel without a cap (WC). Experiments were conducted at discharges from 1 to 10 m³/h with a constant torque load of 0.05 N-m. The highest efficiency of 57.08% was achieved in the AC 45° configuration at 1 m³/h, generating 1.09 watts of power, while the WFAC 45° yielded the highest power output of 2.88 watts at 10 m³/h with an efficiency of 14.50%. Although increasing discharge generally led to higher power input, it was accompanied by a decrease in efficiency across all configurations. Among all three variations, WFAC 45° demonstrated superior performance at higher discharges, indicating its potential for enhancing the power and efficiency of overshot waterwheels.

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