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Vertical Shaft Kinetic Turbine Performance Using A Cup-Shape Blade

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ABSTRACT

The abundant availability of alternative energy sources forms the fundamental foundation for rural energy development. In particular, renewable energy sources are indispensable in rural areas due to their eco-friendly nature and widespread accessibility, which helps preserve the environment by avoiding pollution. Indonesia, a country blessed with vast water resources, especially its rivers, holds enormous potential for harnessing kinetic energy derived from fast-flowing river waters. Effective utilization of this kinetic energy has the potential to address energy shortages in the country. In this context, there is a pressing need to enhance the efficiency of kinetic turbines designed to function as electricity generators in rural regions. This study focuses on evaluating the impact of variables such as the guide angle, water flow speed, and turbine rotation on turbine power and efficiency. The study employs an experimental approach to achieve its objectives, involving tests to assess the performance of a vertical shaft kinetic turbine equipped with bowl blades. Data analysis based on the experimental findings enables the determination of both turbine power and efficiency. The study outcomes demonstrate that the bowl blade type turbine outperforms the curved blade type, primarily due to its larger water capacity, which significantly exceeds that of the curved blade variant. This study emphasizes the potential for harnessing kinetic energy efficiently in rural areas to support sustainable energy development.

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Keywords: *Water energy, velocity, energy potential, kinetic turbine*

I. Introduction

Renewable energy sources, particularly in rural areas, play a vital role in sustainable energy development. These sources, such as hydropower, offer the advantage of being widely accessible without causing harmful environmental pollution. Water energy resources, abundant in Indonesia, are a prime candidate for harnessing energy through hydroelectric power plants [1]. The significant potential of water energy in the country can be harnessed by utilizing natural features like waterfall height and flow speed. The energy derived from water resources is not only valuable for irrigation but can also be effectively channeled to drive hydroelectric power generation. As part of addressing the growing demand for electrical power and mitigating energy crises in various regions, it becomes imperative to tap into the abundant natural potential, particularly the untapped water energy, to generate electricity. This strategy provides a sustainable solution to meet the increasing energy demands and reduce reliance on non-renewable energy sources.

The kinetic turbine stands out as an ideal choice, primarily due to its ability to function efficiently at low water velocities, precisely suited to the typical flow speeds of rivers. Furthermore, this type of turbine offers several distinct advantages, including its

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straightforward construction, which rural communities can easily undertake. Operating the kinetic turbine is straightforward and environmentally friendly, ensuring pollution-free energy generation. Numerous studies have explored the potential of kinetic turbines in river water [2]-[6]. This study seeks to enhance the performance of kinetic turbines further, aiming for optimal outcomes. In this pursuit, two distinct types of kinetic turbines have emerged: horizontal shaft kinetic turbines and vertical shaft kinetic turbines. These advancements represent significant steps toward maximizing the efficiency and applicability of kinetic turbines in various settings, especially in rural areas with low water velocities.

This study focuses on a kinetic turbine equipped with a vertical shaft, which harnesses the kinetic energy from the surface water flow of a river. The choice of a vertical shaft configuration is made to facilitate generator installation and simplify the operational aspects. The turbine blade design for this study adopts a bowl-shaped structure. The utilization of bowl-shaped blades ensures a smooth redirection of the passing water mass along the blade's curves. This design encourages an even force distribution, allowing the blade to withstand the flow effectively. The intended outcome is an increase in the resulting tangential force, generating higher torque and enhancing the overall turbine performance. The study optimizes the bowl-shaped blade that impacts turbine performance. Key variables to control and monitor include the blade's orientation (pilot angle), the speed of the water flow, and the turbine's rotation to gain insights into their effects on power generation and efficiency in the context of the kinetic turbine.

Yang and Lawn [7],[8] observed an improvement in the fluid dynamic performance of vertical axis turbines for both upstream and downstream currents following blade modifications. Their approach involved attaching a hinge to one side inside each blade, subsequently connected to the runners. Golecha et al. [9] demonstrated enhanced performance of a modified Savonius water turbine by incorporating 1 and 2 guide plates. These plates served to streamline water flow, ensuring a more precise flow alignment on the blade's front surface, ultimately boosting the turbine's efficiency. Soenoko et al. [10] conducted a study to evaluate the performance of a prototype double-wheel kinetic turbine designed to serve as a power source in rural areas. The primary objective was to minimize water flow backpressure. Their findings revealed that this dual-wheel kinetic turbine produced higher torque than traditional water wheels. Notably, the maximum force exerted by the two runners was recorded at 50 rpm, with a water discharge rate ranging from 2 to 2.5 liters per second.

Williamson et al. [11] conducted a study focused on the performance of a Turgo Pico-Hydro Turbine, specifically under conditions of low head water flow. The study outcomes underscore the Turgo Turbine's reliability, robustness, and ability to operate efficiently across various flow rates. This turbine is typically employed in applications characterized by medium to high head conditions. Lempoy et al. [12] conducted experiments on a vertical shaft kinetic turbine equipped with eight bowl blades. The study employed Response Surface Methodology (RSM) to establish a mathematical equation that describes the turbine's performance under optimal conditions. The study's results aim to identify the optimal operating conditions for maximizing the performance of a vertical shaft kinetic turbine with bowl blades.

Lempoy and colleagues conducted a series of studies focused on optimizing the performance of vertical shaft kinetic turbines with arc blades. In their 2017 study [13], laboratory-scale kinetic turbines were manufactured to determine the optimal operating conditions for arc-bladed kinetic turbines. Response surface methodology was applied to derive mathematical equations describing turbine performance under optimal conditions. The study examined independent variables, including flow steering angles of 30°, 40°, and 50°, flow rates of 1.7, 2.2, and 2.7 m/s, and turbine rotations of 35, 45, and 55 rpm, leading to the development of a mathematical model. Subsequently, in their 2019 study [14], a visual test was conducted to investigate factors contributing to low performance and unstable turbine rotation. The visual examination revealed that incomplete contact between water and turbine blades, along with delayed blade opening, led to inefficiencies in water flow. Certain blade positions hindered water flow between the blades, resulting in decreased torque and unstable turbine rotation. To enhance turbine performance, it was suggested to increase the number of turbine blades, as this design adjustment would promote more efficient water flow and ultimately stabilize turbine rotation. In their 2021 study [15], the focus was on the impact of flow direction angles and blade count on kinetic turbine performance at the laboratory scale, involving variations in flow direction angles by 10°, 20°, and 30°. The observations highlighted the significance of the flow direction angle in influencing the kinetic performance, particularly in terms of power and efficiency, further contributing to the understanding of turbine behavior.

In this study, a vertical shaft kinetic turbine is positioned vertically to ensure complete submersion of all blades in the water, facilitating generator installation. The turbine harnesses the velocity of the river's surface water flow and employs two distinct blade shapes: the bowl blade and the curved blade. The blades, attached to the turbine runner via hinges on their inner sides, come in both bowl and curved shapes. Utilizing both bowl-shaped and curved blades effectively redirects the water mass passing through the blades. The design ensures a smooth rebound of the water in all directions, enabling the turbine to control the flow effectively. This configuration is crucial in enhancing the tangential force generated, subsequently increasing the torque. As a result, the overall performance of the turbine is significantly improved, contributing to its efficiency and effectiveness in harnessing kinetic energy. This investigation aims to determine the effect of a combination of guide angle, water flow velocity, and turbine rotation on turbine power and efficiency.

II. Material and Methods

1. Research design

The method used in this study is a true experimental method that conducted at the Laboratory of Mechanical Engineering, Faculty of Engineering, UNSRAT. The research time was carried out in 2023.

The study applies tools and materials such as kinetic turbines:

1. Turbine Runners; turbine runners include 2 main parts, namely the turbine shaft, turbine disc, and turbine blade. The turbine shaft is made of steel with a diameter of 3 cm and a length of 30 cm, the turbine disc is made of steel with a diameter of 11 cm, and the turbine blade is made of acrylic material with a thickness of 2 mm. The turbine shaft and disc are assembled together and then supported by 2 bearings placed at the top and bottom of the shaft. Kinetic turbine *runner* as shown in Figure 1.
2. Turbine blades: Kinetic turbine blades function to transmit the kinetic energy of the water flow to rotate the turbine. The turbine blades are made in the shape of a bowl, and the blades are attached to the turbine disc. Turbine blades are made of acrylic material with a thickness of 2 mm. The turbine blade circuit is shown in Figure 1.

Fig. 1 . Kinetic turbine with bowl blades

3. Channels and guide water flow
   Channels for water flow are made to channel water, and as a place for turbines, the direction angle for water flow is made to direct water to hit the turbine blades. The guide angle was made in 3 variations, namely 30°, 40°, and 50°, the channel and the water flow guide are shown in Figure 2.

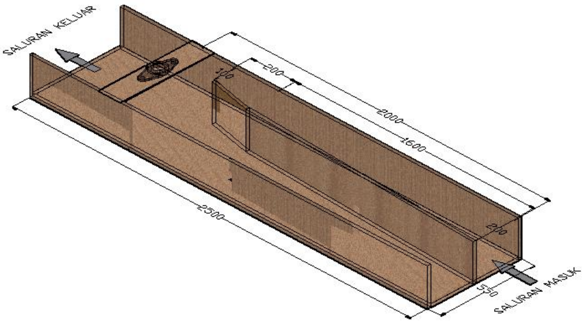

Fig. 2. Channels and water flow guides

2. Testing Procedure

In the process of making the tool, the first thing to do is make the turbine runner. Where the turbine runner is made, it consists of a turbine shaft and a turbine disc. The material for making turbine runners is steel. Next, make the blade, making the turbine blade in the shape of a bowl. These blades are made of 8 pieces each, and these blades are made from acrylic material with a thickness of 2 mm. Finally, create channels and direct the flow of water.

Next, in the preparation stage, the first thing to do is prepare and install all research installations. Then, the necessary measuring equipment is installed. Then, finally, the condition of the measuring instruments and other supporting equipment is checked.

Implementation of turbines with curved blade type apply the following procedure: the first thing to do is set the flow guide in the channel at an angle of 30°, then turn on the pump and adjust the water flow rate in the channel. The water flow rate is set at 1.7 m/s, and a load to the turbine until the turbine rotation reaches 35 rpm. Next, record the data obtained, including pump discharge (m^3/hour), water flow width (m), water flow height (m), force (kg), and pulley arm length (m). Each experiment was carried out 3 times. The independent variables used include lead angles: 40° and 50°; flow speed: 2.2 m/sec and 2.7 m/sec; turbine rotation 45 rpm and 55 rpm.

III. Results and Discussions

From the laboratory experiment, the test results are shown in Table 1. The results of this test are carried out in accordance with variations in the water flow rate of 35 m^3/s, 40 m^3/s, 45 m^3/s, and 0 m^3/s, and a runner braking variation to get a turbine rotation of 90 rpm, 70 rpm, 50 rpm, 30 rpm and finally, a maximum braking turbine rotation equal to 0 rpm.

Table 1. Kinetic turbine test results

Q (m^3/h)	n (rpm)	ΔF (N)	V (m/s)	T (Nm)	Water Power (Watt)	Turbine Power (Watt)	Eff. (%)
35	90	3.2	2.6	0.448	32.8	4.22	12.86
35	70	4.7	2.6	0.658	32.8	4.82	14.69
35	50	6.6	2.6	0.924	32.8	4.84	14.74
35	30	8.5	2.6	1.190	32.8	3.74	11.39
35	0	11.2	2.6	1.568	32.8	0.00	0.00
40	90	4.0	2.86	0.560	45.36	5.28	11.63
40	70	6.1	2.86	0.854	45.36	6.26	13.79
40	50	8.7	2.86	1.218	45.36	6.37	14.05
40	30	10.4	2.86	1.456	45.36	4.57	10.08
40	0	12.8	2.86	1.792	45.36	0.00	0.00
45	90	5.8	3.25	0.822	65.896	7.65	11.61
45	70	7.8	3.25	1.092	65.896	8.00	12.14
45	50	9.6	3.25	1.344	65.896	7.03	10.67
45	30	10.9	3.25	1.526	65.896	4.79	7.27
45	0	14.5	3.25	2.030	65.896	0.00	0.00
50	90	8.6	3.6	1.204	89.838	11.34	12.62
50	70	11.1	3.6	1.554	89.838	11.38	12.67
50	50	13.0	3.6	1.820	89.838	9.52	10.6
50	30	16.2	3.6	2.268	89.838	7.12	7.93
50	0	17.3	3.6	2.422	89.838	0.00	0.00

Figure 3 shows that the highest average turbine torque is achieved at a water flow rate of Q = 35 m^3/s when the turbine runner is subjected to maximum braking. The second-highest torque is recorded at a water flow rate of Q = 45 m^3/s. In contrast, the lowest turbine torque readings are observed at water flow rates of Q = 50 m^3/s and Q = 40 m^3/s.

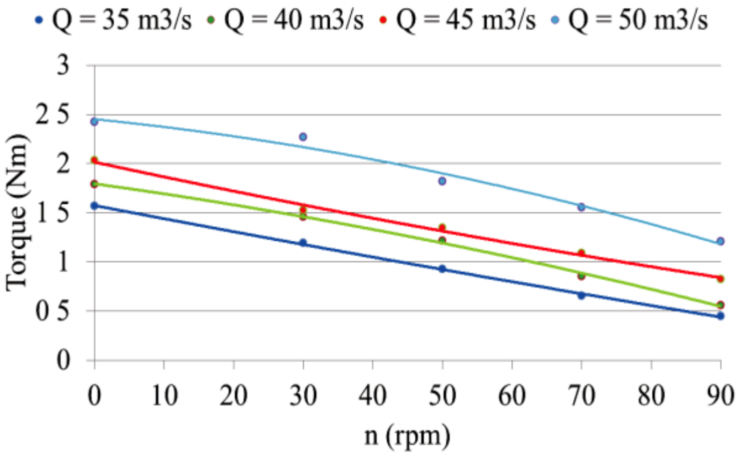

Fig. 3. The relationship between the turbine torque vs turbine rotation

Figure 4 shows that the average highest turbine efficiency is at a water flow rate $Q = 35$ m^3/s. The highest turbine efficiency is at $Q = 35$ m^3/s and a turbine rotation $n = 60$ rpm. The second highest turbine efficiency is at the water flow rate $Q = 40$ m^3/s and a turbine rotation $n = 60$ rpm. While the lowest efficiency occurs at the time of the water flow rate $Q = 45$ m^3/s and $Q = 50$ m^3/s.

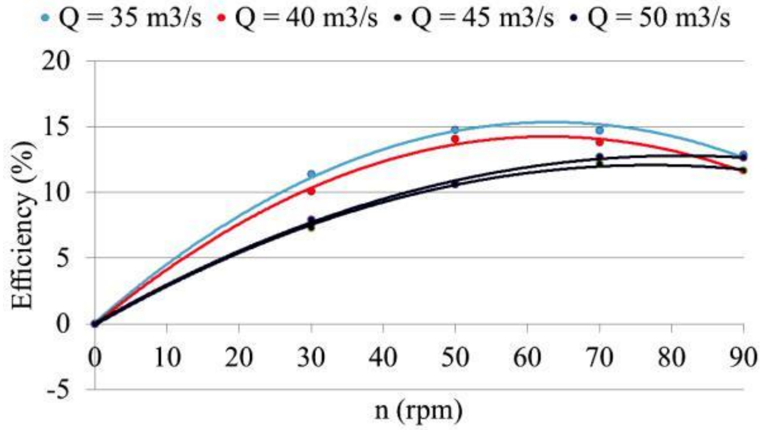

Fig. 4. The relationship between the turbine efficiency vs turbine rotation

From the graph in Figure 5, it appears that the average highest power produced is at the water flow rate $Q = 50$ m^3/s. The highest produced turbine power is at $Q = 50$ m^3/s and at a turbine rotation $n = 80$ rpm. The second highest power turbine is produced at the water flow rate $Q = 45$ m^3/s and at a turbine rotation $n = 70$ rpm. While the lowest turbine po- wer production occurs at the water flow rate of $Q = 40$ m^3/s and at $Q = 35$ m^3/s.

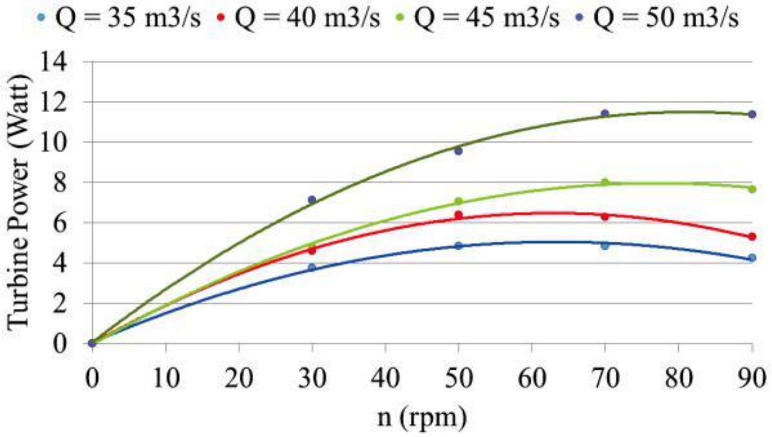

Fig. 5. The relationship between the turbine power vs turbine rotation

Water flow and turbine blade movement on the first rotor position are shown in Figure 6. All images are observed as a blade movement in the first position in the turbine room extracted from the frame image of the video recording were taken at the time of observation. In the first blade movement position, it is shown that there are several water flow directions entering the turbine blade.

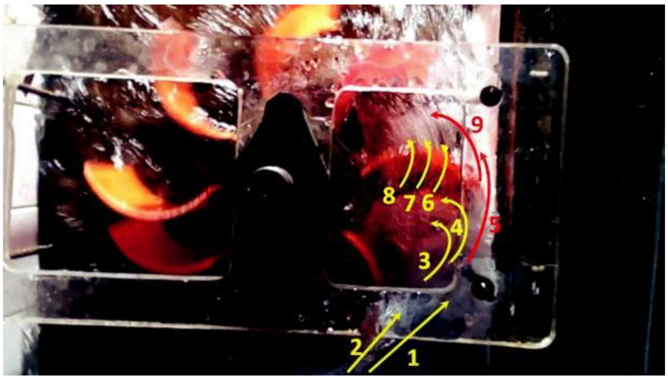

Fig. 6. Turbine blade at the first position

Looking at flowline number 1 and flowline number 2, it is indicated that the initial flow of water is entering the turbine runner. Flowline number 3 and flowline number 4 indicated that the water flow enters the blade to push the turbine blade, spinning the turbine rotor and producing mechanical energy. This is based on the momentum theory, which says that the momentum of a moving object is defined as the result of mass and velocity. In straight-moving objects, the momentum is also called linear momentum.

Flowline number 5 is the water flow that does not enter the blade area and immediately leaves the turbine runner without giving any effect on the blade. Flowline number 6–8 indicates that part of the water is flowing over the top of the turbine so that the water flow does not fully push the turbine blade. The effect of water flow passing through the blade top area reduces the mechanical energy produced. Furthermore, flowline number 9 shows that some water does not push the blade before entering the next blade chamber, resulting in no additional mechanical energy generated.

Water flow and turbine blade movement on the second rotor position are shown in Figure 7. Blade movement at the second position is the blade movement after the first movement. At the second blade movement position, several directions of water flow entering the turbine blade are shown. From the picture in Fig. 3, it is seen that flowline 1 and flowline 2 indicate the initial flow of water entering the turbine runner. Secondly, flowline 3 is the flow of water that does not enter the blade area and immediately leaves the turbine runner without giving a momentum effect to the blade. Thirdly, flowline 4 indicates that the water flow enters the blade to push the turbine to spin and produce mechanical energy. Flowline 5 and 6 shows that a vortex developed in the blade chamber. The vortex produce mechanical energy provided by the blade. Furthermore, flow lines 7–9 indicate that part of the water flow jumps over the top of the turbine. The effect of the flow of water passing through the top of this blade reduces the mechanical energy produced.

At the third blade movement position, it is shown that several water flows are entering the turbine blade. It could be seen that flowline 1 and flowline 2 indicate that the initial water flow is entering the turbine runner. Flowline 3 is the flow of water that does not enter the blade area and immediately leaves the turbine runner without giving any effect on the turbine blade. Flowline 4 indicates that the water flow enters the blade and pushes the turbine blade to spin the turbine and produce mechanical energy.

Flowline 10 indicates that some of the water that does not push the previous blade enters the next blade chamber so that the blade also produces mechanical energy. Flowline 11, 12, and 13 push the next turbine blade and also produce mechanical energy. Finally, in this section, there is no indication that there is a flow of water that jumps over the blade.

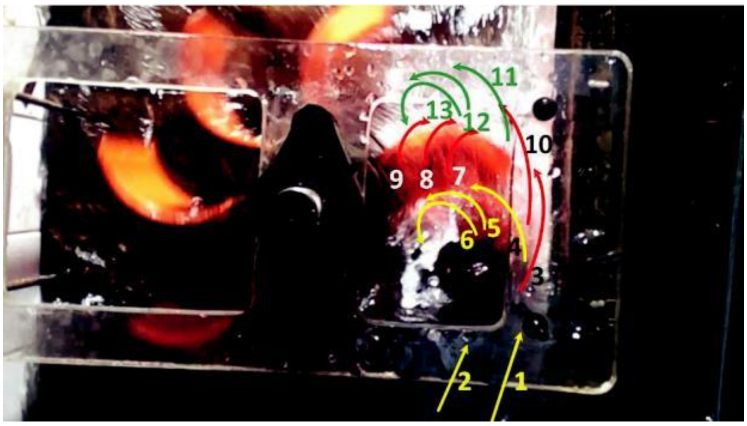

Fig. 7. Turbine blade at the second position

Water flow and turbine blade movement on the third rotor position are shown in Figure 8. Blade movement in the third position is the blade movement after the second blade movement.

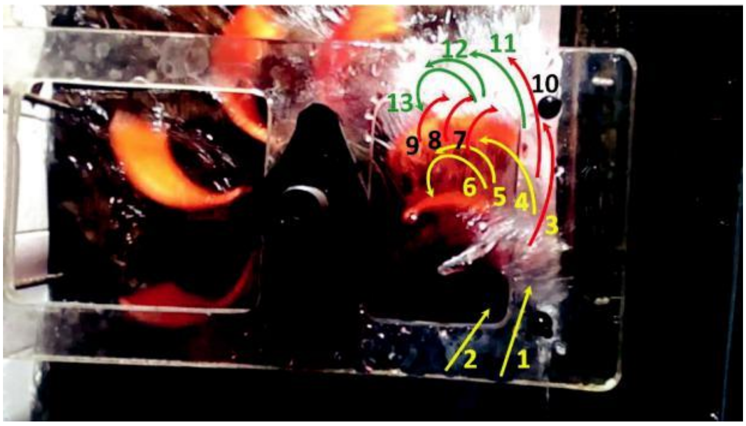

Fig. 8. Turbine blade at the third position

Flowline 5 and 6 shows that a vortex developed in the blade chamber. The vortex produces mechanical energy provided by the blade. Flowline 7–9 indicate that part of the water flow jumps over the top of the turbine. The effect of the flow of water passing through the top of this blade reduces the mechanical energy produced. Flowline 10 indicates that some of the water that does not push the previous blade enters the next blade chamber so that the blade also produces additional mechanical energy. So the flow line 11, 12, and 13 push the next blade and also produces additional mechanical energy.

In this section, there is no indication that there is a flow of water that jumps over the blade. What is visible is the water that leaves the blade after the water rotates in the blade area, providing mechanical energy, and immediately leaves the blade chamber to the turbine chamber exit. The observation was also taken to indicate the lowest turbine performance by choosing. Figure 9 shows the picture of the lowest turbine performance.

In Figure 9, it is seen that there is a blade that has not been filled with water. So that the drive on the turbine as a whole is reduced, because only the blade gets the water flow pressure. The sign(*x*) shows the space between two blades that are not driven by the water power. While the flow of water denoted by an arrow shows the flow of water that pushes the other blade, and there is also a flow of water that does not push the blade but directly leaves the turbine. The turbine blade gets a boost, as proven by the action in the blade area (rotating arrow). Compared to the images that get two or three blades pushed by the water flow, this picture shows that the weakest turbine drive occurs when only one blade gets a boost. This blade visual observation is the worst water and turbine blade behavior.

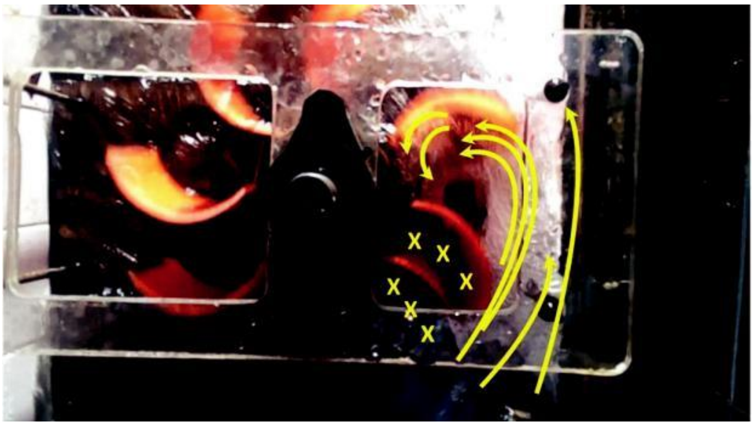

Fig. 9. The Lowest Turbine Performance

IV. Conclusions

Based on the results, it can be concluded that the optimization process conducted to enhance the power and efficiency of the curved blade-type turbine is guided by the "largest the best" principle, which dictates that optimization is considered successful when the value reaches its maximum. In this context, the closer the composite desirability function value gets to the ideal maximum, the more effective the optimization. The highest recorded turbine power for the curved blade type stands at 5.97 watts, achieved through a combination of specific independent variables: a guide angle of 35.753°, a flow speed of 2.7838 m/s, and a turbine rotation of 61.82 rpm. Similarly, the maximum turbine efficiency in the curved blade type is 19.74%, resulting from the optimal combination of independent variables: a pilot angle of 55.46°, a flow rate of 1.359 m/s, and a turbine rotation of 61.82 rpm.

In the context of the bowl blade type, the optimization process for both turbine power and efficiency follows the principle of "bigger is better," signifying that optimization is considered successful when the value reaches its maximum point. The closer the composite desirability function value approaches its ideal maximum, the more effective the optimization is deemed. The highest attainable power for the bowl blade type turbine reaches 7.85 watts, achieved through a specific configuration of independent variables: a pilot angle of 33.71°, a flow rate of 2.701 m/s, and a turbine rotation of 61.82 rpm. Similarly, the pinnacle of turbine efficiency for the bowl blade type stands at 30.91%, resulting from an optimal combination of independent variables: a guide angle of 56.82°, a flow rate of 1.359 m/s, and a turbine rotation of 61.82 rpm.

The turbine power and efficiency of the bowl blade type are greater than that of the curved blade type because, in the bowl blade type, the amount of water that is accommodated is greater than the amount of water that is accommodated. water is collected in a curved blade type.

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