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The Effect of Blade Distances on the Performance of Double-Stage Gravitational Water Vortex Turbine

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ABSTRACT

A gravitational water vortex turbine is a turbine that generates electricity by rotating its runner under vortex flow through basins. The present experimental study investigated the effect of blade distance through a double-stage vortex turbine. The study used rotational speeds, torque, and efficiency to describe the vortex turbine performance under different applied discharges and blade distances. Each blade has a different profile, such as Savonius and a curved blade profile. Each blade independently generates its performance because they constructed under different hollow and solid shafts. The results illustrated that an increased distance between blades produces the best performance with a higher flow rate. A discharge of $9.5\times10^{-3} m^3/s$ and a distance of 150 mm has a total mechanical power of 28,51 W with an efficiency of 28.92%. The longest distance between the stage 1 (S1) and stage 2 (S2) turbine causes the smaller air core diameter. It has given an advantage in their performances on rotational speeds, mechanical power, torque, and efficiency generated by the Gravitational Water Vortex Turbine (GWVT).

1. Introduction

Energy is a requirement for everyday human life. The word total energy usage was dominantly on fossil energy such as oil, gas, and coal [1]. Due to the limited quantity of fossil energy, the potential renewable energy, such as hydropower, wind power, and geothermal energy, becomes the answer to shifting the dominance of energy usage [2,3]. Electrical energy became the essential energy needed to supply all everyday human activity. Electricity production in 2018 reached 283.8 TWh, generated by power plants using coal fuel at 56.4%, gas fuel at 20%, and fuel at 6.3%, while only 17.1% came from renewable energy sources [4]. Because of the relatively high construction cost, applications of renewable energy to power generation have been limited utilization, and the shifting dominance of fossil energy has been slowed [5].

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Among all renewable energies, hydroelectric power plants are an energy source that can be optimized significantly to reduce environmental damage and global warming [6,7]. Energy consumption, especially in developing countries, grew increasingly along with the population. The existence of hydropower as renewable energy technology allows for supplying the required electricity. Moreover, this technology is affordable as it uses a hydrokinetic turbine with a low head and low-cost installation. This turbine type is called a Gravitational Water Vortex Turbine (GWVT) [8]. GWVT is a turbine in which vortex flow acts as the driven fluid, and the generating process occurs on some basins (Vortex Forming Media). This turbine is categorized into ultra-low and medium-head operations [9]. GWVT has relatively lower construction costs than water turbines that use head-increasing dams. Moreover, this micro-hydro turbines have a much higher efficiency than the Savonius water turbine, which is 30% [31], and easy to maintain. The GWVT consists of the basin, turbine, and vertical shaft [14].

Commonly, the vortex turbines were applied on the place with a head range from 0.7-3 m with an average discharge of 5 $\times 10^{-2} m^3/s$ [10,11]. The advantages of these turbines are their applicable technology, easy maintenance, and environmentally friendly. This turbine was mainly applied on several narrow channels near residents' homes because for generating electric power, the minimum head operation was 0.7 m [12]. A vortex is aotating fluid that flows tangentially at the inlet and outlet basin, with the vortex core as the maximum stored energy to move the turbine [13]. Then, gradually, the rotating water has a higher rotational speed as it approaches the orifice hole. The decreasing pressure under the atmospheric pressure causes the air core formation. The vortex turbine rotates through the vortex, and the rotating shaft is coupled to the generators to generate electricity [14]. GWVT was a promising technology for generating electricity because these turbines can provide electricity ranging from Watt (W) to kilowatt (kW) scale [15,16]. A micro-hydro hydroelectric power system is very influential to be installed in tropical areas with rivers and heavy water flow throughout the year. A relatively small investment cost adds convenience and enthusiasm for rural communities, where obtaining electricity is hard and expensive [17]. Therefore, developing the shape and design of the vortex turbine is needed to get maximum efficiency at an affordable application price.

The study of Gautam *et al.,* found that GWVT blade modification efforts influence changes in the electrical power generated. The modified conventional variation of the GWVT blade into a booster runner increases the performance by 6% [32]. Other studies focused on the type of turbine, such as curved blade, straight blade, and flat blade, resulted in different efficiency performances of 82.4%, 63.5%, and 46.3%, respectively. The most appropriate number of blades GWVT turbine present in the study of Sritram *et al.,* with the efficiency of the five blades generated at 36.65%. It is defined as the total struck surface by the water, which strongly affects the power output [21]. The wider-catching surface area is mostly better at extracting energy from the vortex motions. For example, the baffle plate increased on the top and bottom by 50%, and the efficiency improved by up to 10.25% [23]. Handoko *et al.,* also found another improvement in blade profile with the type-L blade. Type-L blade almost resembles a curved turbine, but only the tip has an arc angle. GWVT turbine with 90° performs almost better in their experiment [24].

The major component of the GWVT Turbine is the vortex chamber or basin. Basins have a function to change the laminar water flow into vortex motion. Generally, cylindrical and conical basins have been used in recent GWVT turbine studies. The higher water velocity that enters the basin produces a significant output power [33]. Dhakal *et al.,* [27] conducted a comparative study on the utilization of cylindrical and conical basins. As a result, the conical basin performs better than a cylindrical basin in strong vortex motions and at its highest near the bottom orifice hole. However, if the turbine is installed in the same positions, it would have different rotational speeds, power outputs, and efficiency. Chattha *et al.,* conducted numerical studies on the geometry of the basin to increase efficiency and form strong vortexes in the GWVT [17]. Basin design variations are carried out using the computational fluid dynamics (CFD) approach. Several parameters were modified in the past study, such as inlet velocity, basin aspect ratio, and outer diameter. The result showed that the increasing vortex height and tangential velocity are linearly proportional to the increasing discharges. Therefore, this study concluded that increasing the depth of the inlet has more effect on increasing the flow velocity [18,19]. In addition, the main influencing parameters were investigated in past studies, such as the effects of flow rate, vortex height, diameter hub, and blade position on the vortex turbine performances. Thus, blade distance (Hb) 30 mm from the orifice provides optimal brake power value. By reducing the notch angle, the water flow will produce a vortex with a higher rotational speed. The existence of an inclination angle on the blade increases the torque value as the blade with the inclination is pressed by the flow radially or axially [14].

An experimental study by Ullah *et al.,* investigated the multi-stage vortex turbine performance under conical basin usage [19]. Inter-staging and intra-staging methods were used to evaluate the vortex turbine with rotor profile and blade distance as variations. Inter-staging is a GWVT experimental method that compares the output of turbine A in single-stage mode with the output of turbine A when installed in a double-stage mode. Besides that, the intra-staging method compares the performances of each turbine installed in a double-stage or multi-stage mode.

Numerous studies have been researched on improving the performance of GWVT turbines. The GWVT single-stage studies involved changes in the number of blades [21], the addition of baffle plates [22], the type of turbine [23], the blade inclination angle [24], the material of the turbine [25], etc. The literature covering the two stages of the GWVT is limited number. The first is a study by Ullah *et al.,* which concerns an experimental study on multi-stage turbines which employ conical basins [19]. The second is a study conducted by Cheema *et al.,* They conducted a study on a two-stage GWVT turbine [20]. The conservation of vortex velocity in the conical basin is essential to be investigated [26]. Thus, this study emphasized the essential scope of optimizing the vortex by the distance variations between the turbines in the conical basin. Double vortex turbines were tested under $7.5\times10^{-3}m^3/s$, $8.5\times10^{-3}m^3/s$, and $9.5\times10^{-3}m^3/s$ of discharges. The important parameters measured during the process are rotational speeds, torque, turbine power, and efficiency.

2. Experimental Methodology

2.1 Experimental Setup

This study utilized the water tunnel to create a free surface vortex since it has a simple design. A pump transported the tub's water from the intake system to the outlet. Water more steadily after passing through the honeycomb, the water was directed to the basin and rotated the turbine [27]. Figure 1 below shows the schematic of a low-speed water tunnel.

Double-stage vortex turbines were tested using different discharges and variations in the distance between blades. The first stage in conducting this study is determining the blade position in the basin. We identified the turbine's bottom and then the upper position. In stage 2 (S2), we used reference positions 701 mm from the inlet basin, whereas stage 1 (S1) was variated with 50, 100, and 150 mm. The visualization of the position installed turbine presents in Figure 2, and the experimental variations are presented in Figure 3. Variations in the discharges are defined as $7.5\times10^{-3}m^3/s$, $8.5\times10^{-3}m^3/s$, and $9.5\times10^{-3}m^3/s$ and adjusted using the valve to obtain different submergence conditions. After getting the rotational speed and torque value, the efficiency value was calculated using the available equations.

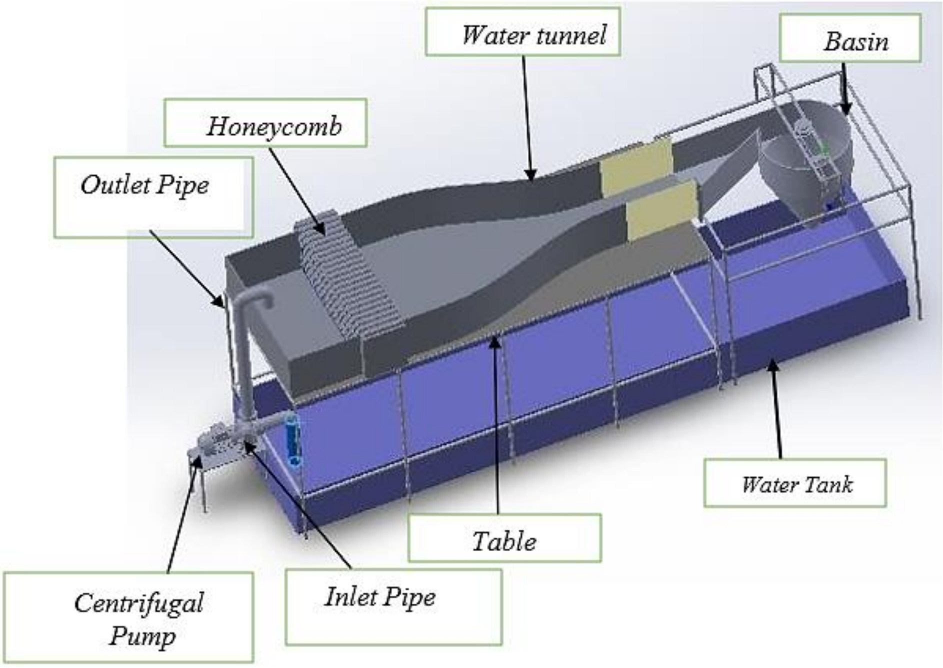

Fig. 1. Water Tunnel

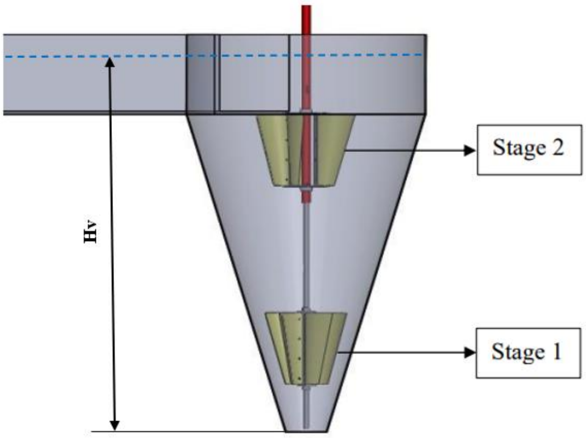

Fig. 2. Blades installation schematic

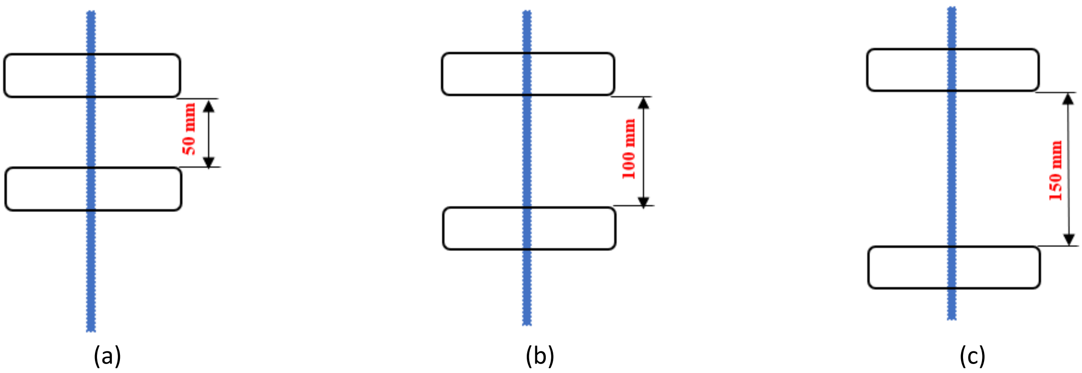

Fig. 3. The variations of distance (a) 50 mm, (b) 100 mm, and (c) 150 mm

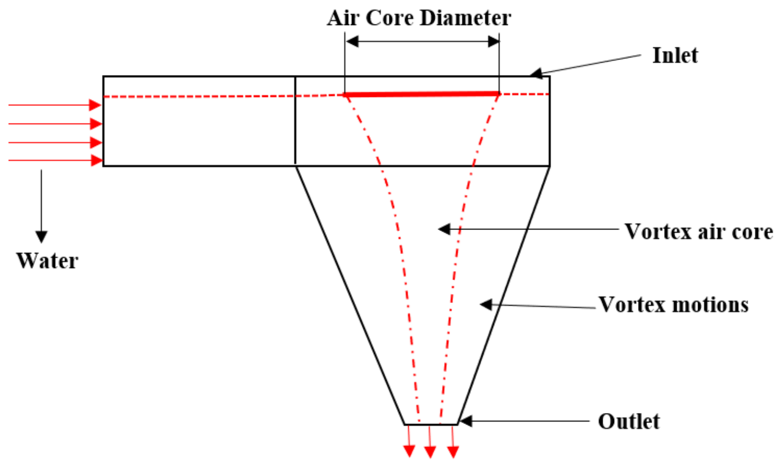

Fig. 4. The vortex schematic

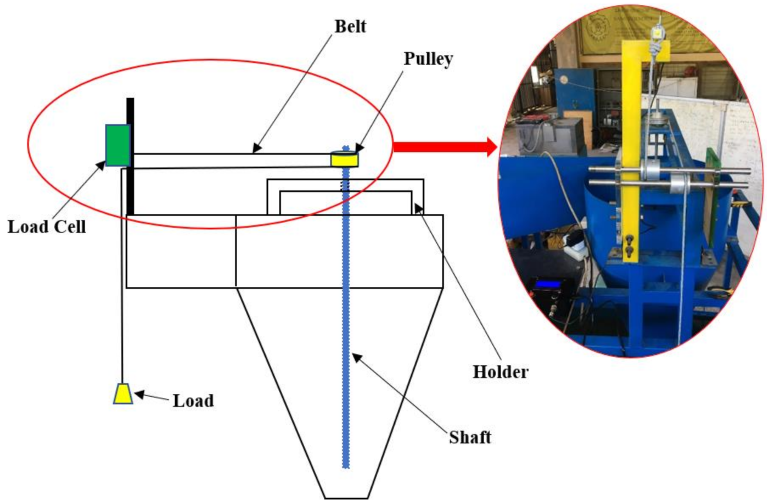

Fig. 6. Prony brake

2.2 Blade Design

The runner used on S1 was a curved profile. Based on the previous study, the S1 runner profile was better at extracting angular momentum and produced the highest efficiency [28]. Savonious wind turbine (SWT) runners were used in S2 blades with the profile corresponding to the conical basin shape. These S2 profiles were proven to maximally extract tangential velocity and energy stored on the driven fluid [19]. The telescopic arrangement shafts were used with a 12 mm inner hub diameter and 2 mm inner hub diameter. The following figure (Figure 7) shows the blades used during the experiment.

(a) (b)

Fig. 7. Blade Design (a) Stage 2 Up (b) Stage 1 Down

Table 1
Turbine Specification of Blade Design

No.	Parts	Symbol	Velocity (ms–1)
1	Inlet angle	α1	30°
2	Outlet angle	α2	45°
3	Diameter Blade	R	60 mm
4	Height	L	180 mm
5	Number of Blades	n	5

2.3 General Equation

Hydraulic power (P_{in}) comes from the fluid that flows with a specific discharge to the basin and rotates to form a vortex at a certain height.

$$P_{in} = \rho g Q H v \quad (1)$$

ρ is the density of the fluid, *g* as the gravitational acceleration is 9.8 m/S2, *Q* is the fluid discharge, and *Hv* is the vortex's height. The vortex height was presented in Eq. (2) as

$$P_m = T\omega \quad (2)$$

The turbine's power output primarily serves as the (Cp) coefficient of power [29]. However, the turbine power outputs were measured and performed as mechanical power (P_m) obtained from the experiment. *T* is the torque (N/m), and *ω* is the angular velocity (rad/s). Angular velocity is taken with a value of N(rpm) and then converted to rad/s using Eq. (3).

$$\omega = \frac{2\pi N}{60} x100 \quad (3)$$

Based on Eq. (1), the power input is proportional to the value of discharges. Usually, S1 can withstand more loads compared to S2. The turbine load was measured and calculated using the prony brake mechanism in line with the study of Handoko *et al.,* (See. Figure 6) [24]. This mechanism produces a load the turbine receives with a braking force system. The load cell outputs on the prony brake system (See. Figure 6) are weight data (in grams). Hence, the data were converted into force units by multiplying using the acceleration of gravity.

$$F = mg \quad (4)$$

The produced torque (T) is equivalent to the forces received by the rotating shaft, as defined in Eq. (5) with *r* is radius of the shaft

$$T = Fr \quad (5)$$

The value of efficiency as a comparison of mechanical power (*Pm*) and hydraulic power (*Pin*) obtained is defined as follows:

$$\eta = \frac{Pm}{Pin} \, x \, 100\% \quad (6)$$

3. Results

3.1 Rotational Speed of Two-Stage Turbine

The performance of the rotational turbine was tested at three different discharges with varying valve openings. After the water flows, the steadier rotational speed is measured by the tachometer. The water discharge is flowing continuously, passing through the tunnel. Turbine rotation is measured to obtain the angular velocity value (ω). Then, the value obtained in the form of RPM is converted into rad/s using Eq. (3). The results are used to calculate the achievement of the mechanical power of the turbine produced using Eq. (2).

Figure 8 shows that S1 and S2 have a flow rate of $9.5\times10^{-3}m^3/s$ and a distance of 150 mm, producing the highest rotational speeds with S1 at 24.76 rad/s and S2 at 18.37 rad/s. Meanwhile, the lowest rotational speeds were 23.5 rad/s and 11.95 rad/s generated at 150 mm distance with the applied $7.5\times10^{-3}m^3/s$ of discharges. The results showed that increasing distance and discharges are linearly proportional to the rotational speeds of the S1 turbine, while the rotational speed at S2 remains constant. It is due to the position of blade S1, which is closer to the orifice, so the vortex can rotate the S1 turbine maximally. The rotational speed of S2 tends to remain constant due to the blade position not changing and moving away from the orifice. The closer position to the orifice increases the turbine rotational speed when applied to S1 and remains constant if applied to S2.

The appearance of the turbine rotational speed data is used to validate the statement of a previous study conducted by Dhakal *et al.,* which found various velocities in the conical basin from the upper inlet to the lower outlet orifice hole [26]. The results of this study show that the rotational speeds obtained in S1 and S2 are different. It proves that the S1 position near the orifice has a greater velocity than the S2 position. Therefore, when implemented in the field, the study process with positions of the GWVT turbine installation position in the basin needs to be considered.

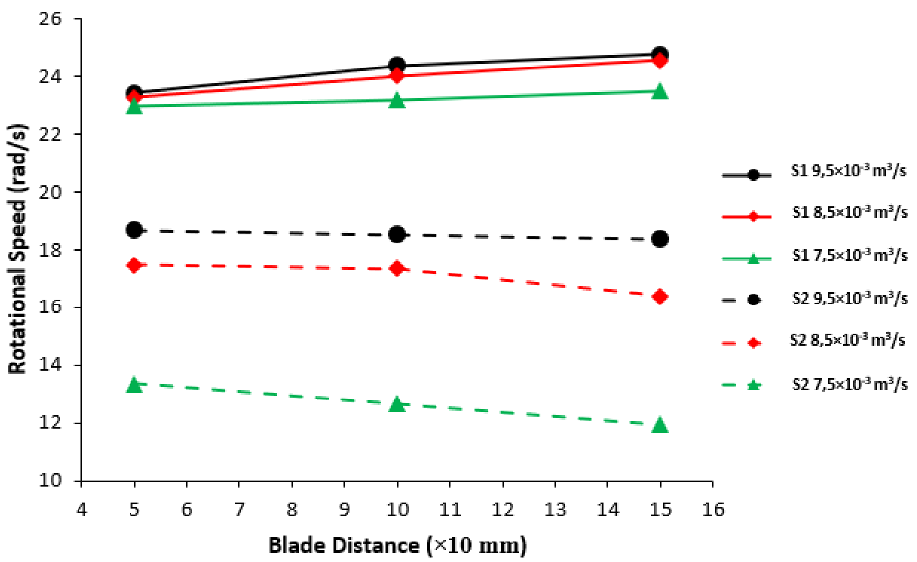

Fig. 8. Rotational speed of Two-Stage turbine

3.2 Torque of Two-Stage Turbine

In this experiment, torque was calculated using Eq. (3). Each discharge variation generated a different maximum torque; thus, the turbine's water momentum absorption climbs linearly along with increasing discharge. Therefore, half of it will be chosen as the most appropriate load condition [30]. The loading system was used with the prony brake mechanism with a mass of 0.5 kg, 1 Kg, 1.5 Kg, 2.0 Kg, 2.5 Kg, and 3.0 Kg. The greater the mass used in the prony brake, the faster the turbine rotational speeds gradually decreased. As the use of 2.0-3.5 Kg turbine rotation is unstable and makes the shaft sway, the data of this study used the maximum torque obtained from loading with a weight of 1.5 Kg (half of the load applied to the prony brake).

Figure 9 below shows the highest torque produced at a discharge condition of $9.5\times10^{-3}m^3/s$ on a turbine that has a distance between stages of 100 mm with a blade torque of S1 of 1.21 Nm and S2 of 0.52 Nm. In addition, the lowest torque was generated at 150 mm distance under the lowest discharges applied, with a value of 0.33 Nm in S1 and 0.27 Nm in S2. S1 and S2 tend to provide the same torque value at the same discharge. The load on the shaft strongly influences this torque, so the greater the number of loads, the result of torque rises. Continuously increasing the load until the rotating shaft stopped during the experiment was conducted to obtain maximum torque. The torque value is strongly influenced by the amount of received load on the shaft, so the increased torque is linear with the greater loads. The increased load the shaft receives continuously until the rotating shaft stop is defined as the maximum torque generated [34]. Thus, the load at maximum conditions is only used half of the maximum torque load. It is in line with Kueh *et al.,* study [27], which emphasizes that the optimal load values were half of the maximum torque workload of the shaft.

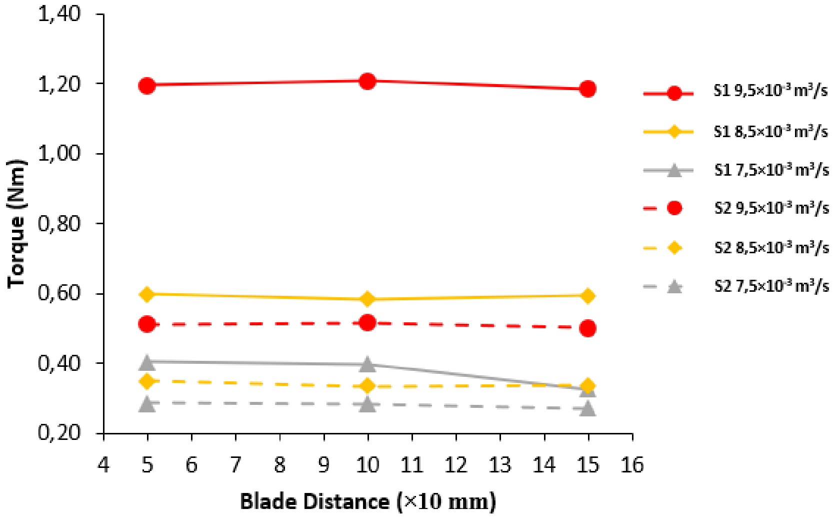

Fig. 9. Torque of Two-Stage turbine

3.3 Mechanic Power of Turbine

Mechanic powers were defined as a turbine power output that depends on the torque and rotational speed. Mechanic power was measured by using Eq. (2), which the results are presented in Figure 10. The figure below presents the highest mechanical power value obtained at a discharge condition of $9.5\times10^{-3}m^3/s$ which has a distance between stages of 150 mm with S1 turbine mechanical power of 23.96 W and S2 turbine of 4.55 W. The lowest mechanical power is obtained at a discharge condition of $7.5\times10^{-3}m^3/s$ which has a distance between stages of 150 mm with S2 turbine mechanical power of 7.37 W and S2 turbine of 0.34 W. The value of the mechanical power generated in blade S1 tends to remain constant at a distance of 100 mm and 15mm. It was shown that the discharge of $8.5\times10^{-3}m^3/s$ and $9.5\times10^{-3}m^3/s$ produces optimal values at a distance of 100 mm and 150 mm.

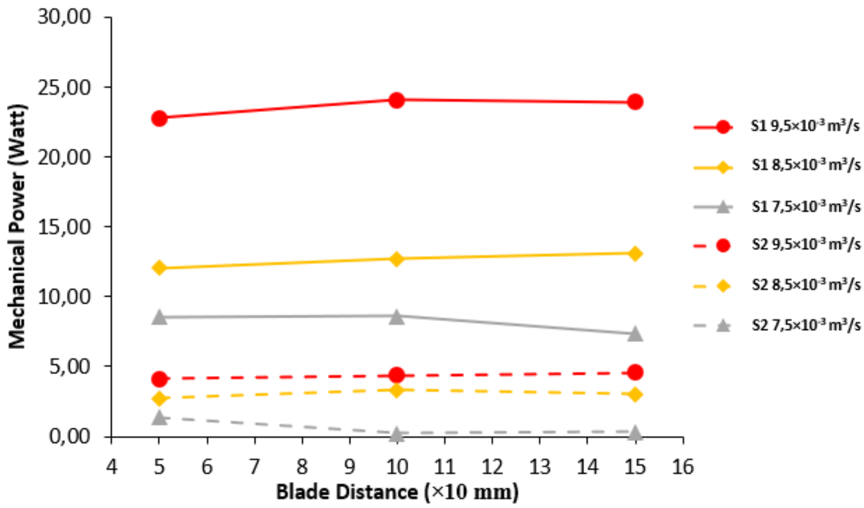

Fig. 10. Mechanic power of Two-Stage turbine

The results showed that the applied discharges influenced the varied vortex height. During the experiment, the input discharges significantly affect the generated torque. When the load on the shaft exceeds the vortex's strength, it significantly reduces the mechanical power. The increasing distance between the turbine is linearly proportional to the mechanical power generated by the turbine. It happened because the damaged vortex flow after hitting the S2 turbine had been developing before hitting the S1 turbine. S2 generated increasing mechanical power as the small air core vortex formed under the increased applied discharges. Thus the conclusion drawn from the study is that the turbine performance grows linearly with an increasing distance between S1 and S2. The increase in turbine performance is due to two factors. First, increasing discharge causes the input power and rotational speed to rise and reduces the vortex height and air core diameter. Second, the small diameter of the air core increases the contact of water with the turbine surface and the mechanical power generated by S2 [35]. The rotational speeds of the S1 turbine were increased when the distance was close to the orifice hole, which is identical to the CFD simulation conducted by Dhakal *et al.,* and Sallem *et al.,* [14],[27]. At a certain distance, the damaged vortex, after striking the S1, was developed and rotated to drive S1. Therefore, the longer distance between turbine stages resulted in better mechanical power.

3.4 Total Efficiency of Two-Stage Turbine

The Eq. (6) was used to determine the generated efficiency. Each blade was measured independently at the same time. Figure 11 presents the highest turbine efficiency at a distance between stages of 150 mm with a discharge of $9.5\times10^{-3}m^3/s$ resulting in an efficiency value of 28.92%. In comparison, the lowest efficiency is produced at a discharge condition of $7.5\times10^{-3}m^3/s$ with a distance between stages of 150 mm, of which the value is 10%. The water discharge strongly influenced the vortex height, where the minimum discharges provided lower vortex height and strength. The decreasing efficiency at a flow rate of $7.5\times10^{-3}m^3/s$ is caused by the S1 turbine, which is closer to the orifice, so the vortex is less than optimal to reach S2. The drawn efficiency has the same trendline as the mechanical power, which is linearly proportional with the increasing discharges.

The amount of water flowing in the basin significantly affects the height of the vortex head and air core diameter. The greater the discharge ($9.5\times10^{-3}m^3/s$), the highest the vortex head with a small air core. Small diameter air core makes the wider active surface contact area S2. Vortex motion energies are maximally extracted when the total surface has contact with the turbines. The optimal performance of S1 is influenced by two factors, namely the vortex flow factor after hitting S1 and the position of proximity to the orifice. At a distance variation of 150 mm, after striking S1, the damaged vortex redevelop following the basin space that flows into the bottom orifice and strikes the S1. As a result, its distance has the highest efficiency dominantly, along with the applied discharges of $7.5\times10^{-3}m^3/s$, $8.5\times10^{-3}m^3/s$, and $9.5\times10^{-3}m^3/s$. A schematic of the height and diameter of the water core in the conical basin presents in Figure 12 below.

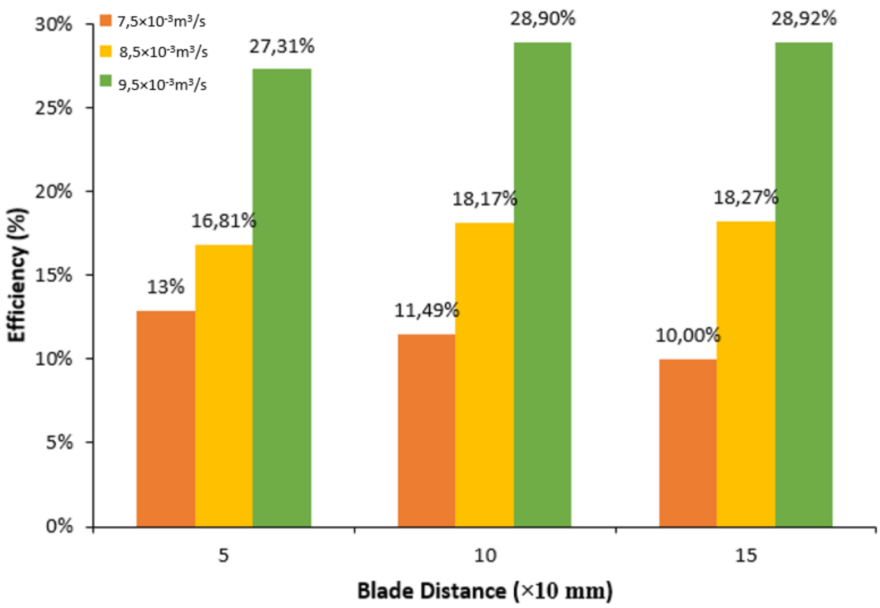

Fig. 11. Total efficiency of the turbine

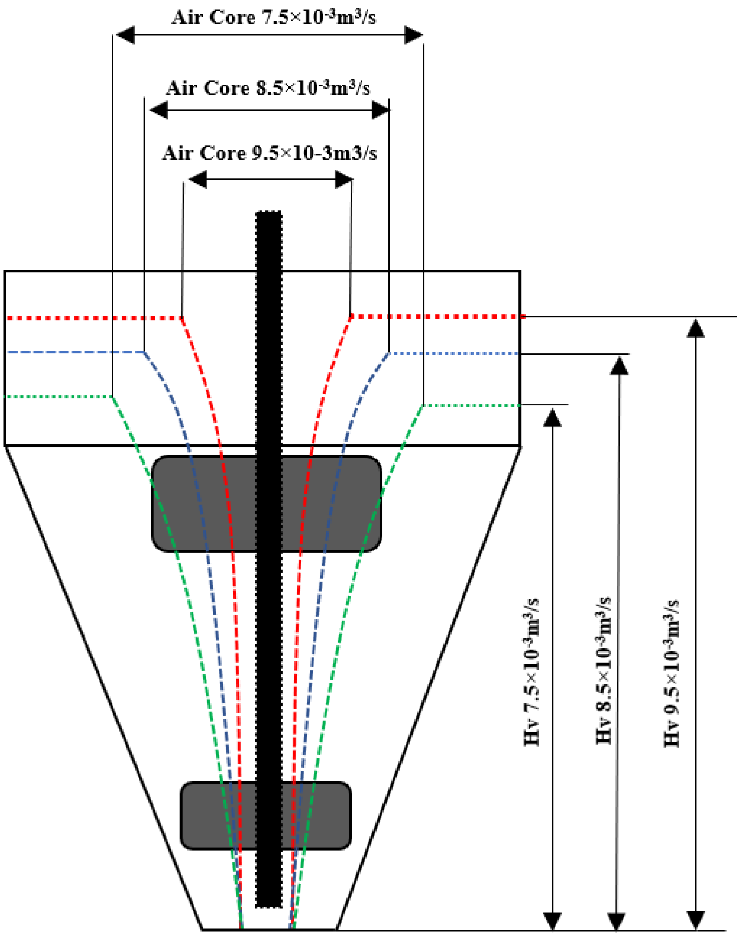

Fig. 12. Air core and heigh of vortexs

If the result in maximum efficiency was compared with the other experimental scale micro-hydro, this double-stage GWVT turbine was classified as having medium cluster efficiency of 28.92%. Comparatively, the efficiency of bidirectional crossflow turbines [36], conical Savonius [37], Savonius [38], and Horizontal Spiral Turbines (HSTs) [39] are 2.6%, 8.6%, 33%, and 38.10%. They were, moreover, remembering that GWVT turbines have been widely applied in this world, including Austria, Switzerland, Australia, Peru, Indonesia, Belgium, and Chile, with a range of output power issued by 1-20 kW [31],this technology has the opportunity to be developed for achieving the sustainable future.

4. Conclusions

Double-stage GWVT study with variations in the distance between turbine stages has been successfully conducted. This study proves that it is necessary to vary the double-stage turbine to extract the variation of vortex motion speed in the conical basin. It showed in the different rotational speeds of S1 at each variation of its distance from S2. Furthermore, the maximum speed is proven to occur at the lower orifice end of the conical basin. This study found that the 150 mm spacing turbine variation has the best-accumulated performance compared to 50 mm and 100 mm. The highest power achieved in this variation was 23.96 W at a discharge of $9.5\times10^{-3} m^3/s$. As GWVT turbine has good potential to be developed as an alternative technology to provide electricity in remote areas, thus future studies on double-stage turbines can continue to achieve this goal. Considering the limitations of this study, the researchers suggest that future studies need to concern developing GWVT turbines using a generator as an intermediary for the electrical power generated, as in this study, only the mechanical power of the turbine is measured. This aims to observe the actual electrical power generated by the generator so that future GWVT studies can produce applicable prototypes.

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