Feasibility study of pvc pipes as vertical axis wind turbines type savonius bucket for remote areas application

By Amrifan Saladin Mohruni

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Feasibility Study of PVC Pipes as Vertical Axis Wind Turbines Type Savonius Bucket for Remote Areas Application

Dendy Adanta, Kaprawi Sahim, Amrifan Saladin Mohruni

Abstract – *Independent power plant based on renewable energy is a good solution to solve electricity crisis in remote areas. Wind is a source of energy that has every country in the world. A study of the utilization of PVC pipes as a material for Savonius turbine buckets has been carried out in order to reduce the investment costs of wind turbines. The feasibility test has been carried out in four runners: the 2-bucket without and with overlap and the 3-bucket without and with overlap. All the runners are made using PVC pipes. Based on results, the 2-bucket with overlap is the right solution for remote areas because it has a higher coefficient of performance of 8.39%, and the range of tip speed ratio is wider between 0.57-0.65 compared to others. Compared to aluminum bucket material, the PVC pipes are more profitable because they are easy to make, cheap and good performance. Furthermore, the investment cost of a Savonius turbine bucket made from PVC pipe (USD 37.34) is cheaper than the pico hydro type Turgo (USD 48). Thus, the PVC pipes as materials for making Savonius turbine runner are recommended for remote areas application because the materials are cheap and easy to access (widely available in the market).*

Keywords*: Vertical Axis Wind Turbine, Savonius Turbine, Bucket, Remote Areas*

Nomenclature

A	Area of the runner [m^2]
C_p	Coefficient of performance [%]
D	Runner diameter [m]
d_{bucket}	Bucket diameter [m]
D_o	Endplate diameter [m]
DC	Direct Current
e	Overlap [m]
I	Current [A]
H	Runner height [m]
n_{gen}	Rotational of DC generator [rpm]
n	Runner rotational [rpm]
P_w	Potential power of wind [W]
P_{gen}	Generated power [W]
P_T	Turbine performance [W]
R_{bucket}	Bucket radius [mm]
S_{Pgen}	Uncertainty
S_i	Uncertainty of current
S_V	Uncertainty of voltage
t	Thick of the blade [mm]
V_w	Wind speed [m/s]
V	Voltage [V]
λ	Tip speed ratio
β	Overlap ratio
ρ_{air}	Air density [kg/m^3]
τ	Torque [N m]
ω	Angular velocity (rad/s)

I. Introduction

International Renewable Energy Agency (IRENA) has predicted that there will be 650 million people in the world will have no access to electricity by 2030 [1].

These communities are located in remote areas that are difficult to reach [1]. The solution to connecting the community to electricity is the off-grid system [1], [2].

Off-grid system for remote areas is suitable to use independent power plants based on renewable energy such as wind, hydro, and solar. Among them, the wind is a source of energy that has every country in the world [1]-[25]. Therefore, wind turbine as a converter wind energy has been developed in many countries [3], [4].

The wind turbine is classified into two axes, namely vertical and horizontal. For vertical, it is known as the Vertical Axis Wind Turbine (VAWT), while for horizontal as the Horizontal Axis Wind Turbine (HAWT).

Based on the reported, the VAWT has a lower efficiency than HAWT, but the minimum speed of wind for HAWT to operate is 5 m/s, which is rare [3]. The VAWT is widely used and developed because its construction is simple, cheap, it makes low noise, and it can operate with low wind speed (<5 m/s) [5], [6]. The average remote areas have a low wind speed (<3 m/s) [3]. For this conditions, the VAWT type Savonius turbine is suitable because self-starting is better than Darius turbine and H turbine [7], [8].

Furthermore, this turbine is widely used in developing countries because the technology used for manufacturing is not high [9]. The Savonius turbine has a semicircular

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rotor, where it uses a drag force to rotate the shaft (Figure 1) [8]. From Figure 1, the drag coefficient for the concave bucket is higher than the convex bucket.

Consequently, the drag force at the concave bucket is higher than the convex bucket, and this makes the turbine rotate. The Savonius turbines are effective at the power coefficient (C_p) from 0-0.2 with tip speed ratio (λ) between 0-2 [6], the other results show their optimum at C_p of 0.3 with λ of 0.9 [10]. For this reason, the Savonius turbine is suitable at low wind speed conditions. The C_p of the Savonius turbine is categorized as low; in order to increase the C_p of this turbine many studied have been done. Marinić-Kragić, et al. (2020) [11] have optimized the shape of Savonius turbine Bach's bucket types. Bach buckets are chosen because they are simple in shape, consisting of circular arcs and straight segments [11].

Based on the results, optimization has been successful where the performance increases have been up to 10% [11]. Kerikous and Thévenin (2019) [12] have optimized the thickness of the Savonius turbine bucket. From the results, the bucket shape like "hook" is optimum, where Savonius turbine performance has increased up to 12% at a tip speed ratio of 1.2 [12]. However, the blade shape studied by Kerikous and Thévenin (2019) [12] is difficult to produce because of its complicated shape, which is like an aerofoil. Bai, et al. (2019) [13] have studied the feasibility of the Savonius turbine application in the confined long channel by the Computational Fluid Dynamics (CFD) method. This is carried out in order to predict the performance of Savonius turbines if applied on through-building channels [13]. Based on the results, the Savonius turbine is predicted to produce twice the power if placed in through-building channels [13]. Antar and Elkhoury (2019) [14] have optimized the Savonius turbine casing by the CFD method. Based on the results, the Savonius turbine casings can improve the performance. Since the casing directs air towards the bucket with the risk of a low vortex occurring, the energy of air is absorbed maximally by the bucket [14]. The Savonius turbine is a simple wind turbine but this technology is considered inappropriate for remote areas. In terms of life cycle cost, wind turbines are not profitable compared to micro or pico hydro and solar photovoltaic (PV) [15].

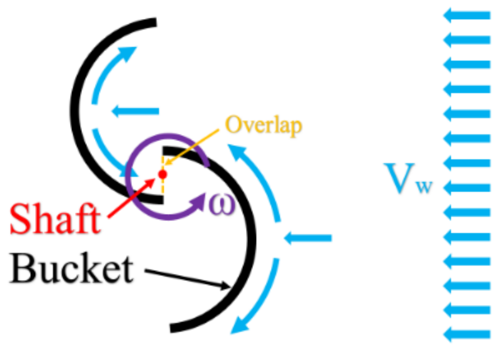


Fig. 1. Front view schematic of Savonius turbine

The life cycle cost of the wind turbine can be increased by reducing the investment cost. Reducing the investment cost of a Savonius turbine can be done by using materials that are widely available in the market.

Although many studies to improve the performance of the Savonius turbine have been carried out, the study of inexpensive material for this turbine has not received attention yet.

The Savonius turbine has a semicircular bucket shape where polyvinyl chloride (PVC) pipes are a good solution as a material. Therefore, this study aims to examine the feasibility of the PVC pipe as a Savonius turbine bucket material to reduce investment costs. Furthermore, this study can give new insights to solve the electricity crisis in remote areas.

The experimental method is used so that the results obtained are more precise. In order to assure the results, the test variations have been carried out in two and three buckets with and without overlap (4 test variations).

From the results of the review above the design runners Savonius turbine using overlap [13] and not [14], where both runner's concepts produce a good performance.

II. Method

II.1. Geometry

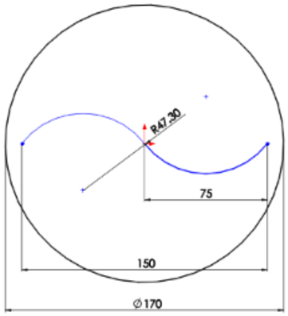
Tests have been carried out in a wind tunnel with a width of 0.4 m and a height of 0.4 m. Based on the consideration of the effect of blockage, the area of the wind turbine is 21.16% of the wind tunnel area.

Therefore, the runner height (H) is of 0.2 m and the runner diameter (D) is of 0.15 m. In order to reduce the investment cost, the blade is made using a D-type pipe with a size of outer diameter 4 inches ≈ 0.1016 m and thick of 0.0035 m.

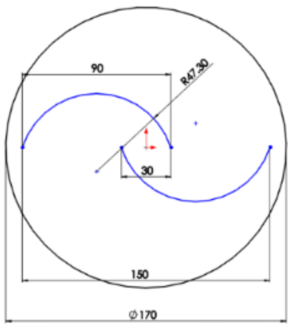
Overlap (e) separates the inside edges of the buckets [8]. Based on the reports, the ratio of the overlap (e) with runner diameter (D) could generate optimum torque (τ) of 0.2 [16], [9], so that e is 0.03 m. Based on e and D, each bucket diameter is as follows: a bucket without overlap is 0.075 m; the bucket with overlap has a diameter of 0.09 m. Since the bucket is made of the 4-inch pipe, the radius of each bucket becomes as follows: bucket without overlap 104.9°, the bucket with overlap 144.55°. A summary of the parameters of the Savonius turbine tested can be seen in Table I and the schematic in Figs. 2.

TABLE I
PARAMETERS DESIGN OF SAVONIUS TURBINE

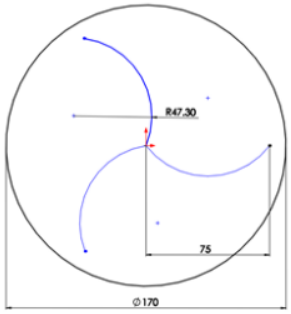
Parameters	Unit
Endplate diameter, D_o	0.17 m
Runner diameter, D	0.15 m
Runner height, H	0.2 m
Overlap ratio, β	0.2
Overlap, e	0.3 m
Thick of blade, t	3.5 mm
Bucket diameter, d_{bucket}	0.946 m
Bucket radius for overlap, R_{bucket}	37.5 mm
Bucket radius for without overlap R_{bucket}	45 mm



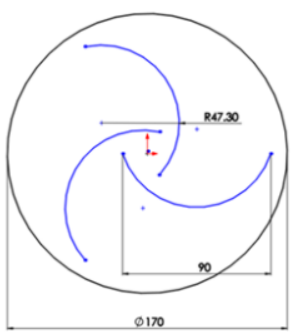
(a) 2-bucket



(b) 2-bukcet with overlap



(c) 3-bucket



(d) 3-bucket with overlap

Figs. 2. Schematic of Savonius turbine bucket

In Fig. 3, 1 is the test section, 2 is the frame of the turbine, 3 is the runner, 4 is the anemometer, 5 is the tachometer, 6 is the multimeter DC, and 7 is the DC lamp.

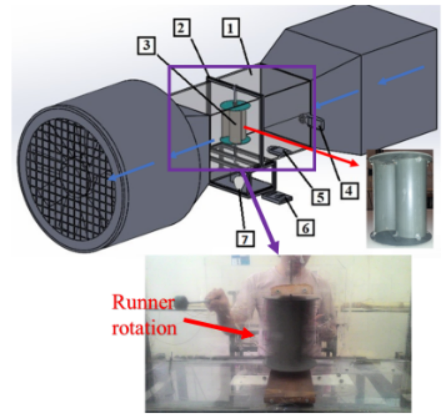


Fig. 3. Experimental setup

II.2. Experimental Setup

Tests have been carried out in the wind tunnel type WT-40 subsonic with wind speeds (V_w) of 5.01 m/s to 11.85 m/s for 10 variations. Three measuring instruments are used: Direct Current (DC) multimeter for measuring current (I) and voltage (V); anemometer for measuring wind speed (V_w); tachometer for measuring runner rotation (n). The uncertainty measuring instrument used are divided into two categories: percentage for DC multimeter and tachometer; reading for the anemometer.

The uncertainties of DC multimeter are for ampere ±0.8% and voltage ±0.5%, for anemometer ±0.2 m/s, and for tachometer ±0.05%. The schematic of the setup experiment can be seen in Fig. 3. The Savonius turbine is connected to a DC generator without a transmission system to determine its performance, whereas a load is used LED lamp with input 2-5 V_{dc} (max. 7 W). The characteristic of the DC generator can be seen in Table II. Based on Table II and Menet's [10] study (the optimum Savonius turbine at λ of 0.9 and C_p of 0.3), the required V_w is 10.9 m/s for the runners producing 5 V_{dc}.

The analysis of the calculation of V_w is in Equation (1). Equation (2) is used for C_p analysis in order to predict the turbine performance (P_T). Based on Equation (2), P_T is 6.99 W:

$$\lambda = \frac{\pi d n_{gen}}{60 V_w} \tag{1}$$

$$C_p = \frac{P_T}{0.5 \rho_{air} V_w^3 A} \tag{2}$$

where A is the area of the runner ($A=DH$), ρ_{air} is the density of air, and $0.5\rho_{air}V_w^3A$ is the potential power of the air (P_w). The power generated (P_{gen}) can be determined using Equation (3):

$$P_{gen} = V \times I \tag{3}$$

TABLE II
CHARACTERISTIC OF THE DC GENERATOR

Voltage (V)	Rotation of the DC generator (n_{gen})
5 V_{dc} ± 0.025 V_{dc}	1250 rpm ± 6.25 rpm
12 V_{dc} ± 0.06 V_{dc}	3000 rpm ± 15 rpm
24 V_{dc} ± 0.12 V_{dc}	5000 rpm ± 25 rpm

Statistical analyses such as filtering data by Chauvenet criteria and uncertainty with a 95% confidence level have been applied in order to minimize the effect of measurement error [17], [18]. The filtering data by Chauvenet criteria has been chosen because it is easy to operate [18]. In determining the combination uncertainty, for example, P_{gen} uncertainty (S_{Pgen}) can use Equation (4):

$$\left(\frac{S_{P_{gen}}}{P_{gen}}\right)^2 = \left(\frac{S_V}{V}\right)^2 + \left(\frac{S_I}{I}\right)^2 \quad (4)$$

where S_V is the uncertainty of voltage, and S_i is uncertainty of current. The detailed statistical analysis conducted refers to Adanta's [18] study.

III. Results

III.1. Relation P_w with V_w

P_w is a function of V_w (Equation (2)). Based on Equation (2), the P_w has made an exponential graph (Figure 4), since the energy equation is derived by the kinetic energy that can be seen from V_w^3. Based on the calculation, the maximum P_w is 29.95 W in V_w of 11.85 m/s.

III.2. Relation of V and I with n

Based on test results, the generator produces a voltage of 2.53 V_{dc} at n of 296.4 rpm (Figure 5(a)). The n of 296.4 rpm is the minimum rotation needed for the generator to produce electricity. In this condition, the lamp is dim. Based on Figure 5(a), n increases, V also increases, where graphs are seen like linear patterns.

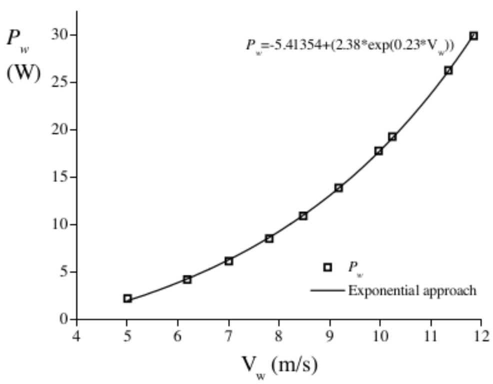
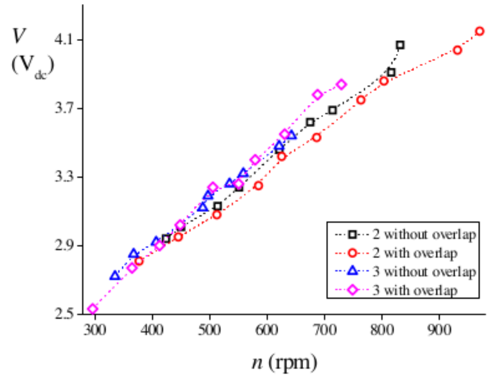
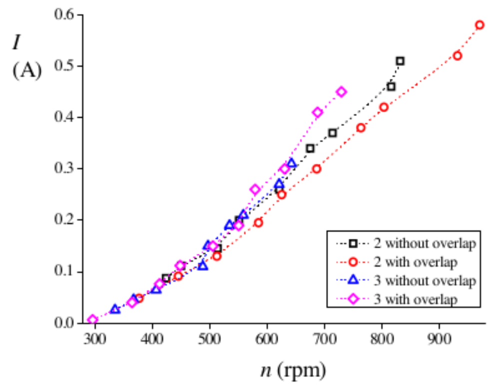


Fig. 4. Relation of P_w with V_w



(a) Relation V with n



(b) The relation I with n

Figs. 5. Relation of P_w with V_w

This shows that n affects the V to be generated. On the other hand, at 296.4 rpm the generator produces I of 0.0064 A (Figure 5(b)). Based on Figure 5(b), increasing n has made I increase with a pattern similar to the linear.

This shows that n affects the production of V and I.

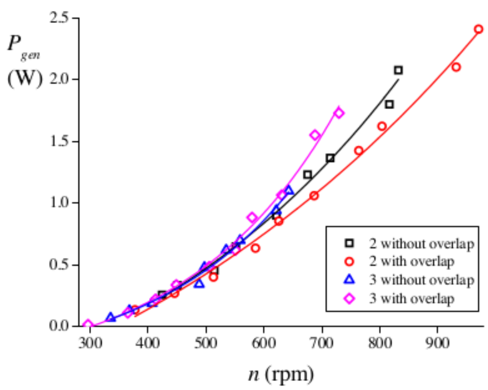
Based on Figures 6, runners with overlaps have better performance than without overlaps. The average runner producing electrical power requires a minimum n of 300 rpm. Based on the test results, the runner with 2-bucket has better performance than the 3-bucket one, where the 2-bucket with overlap runners produces higher power than the others, while the 3-bucket without overlap runners has the lowest performance.

III.3. Relation of P_{gen} and C_p with n

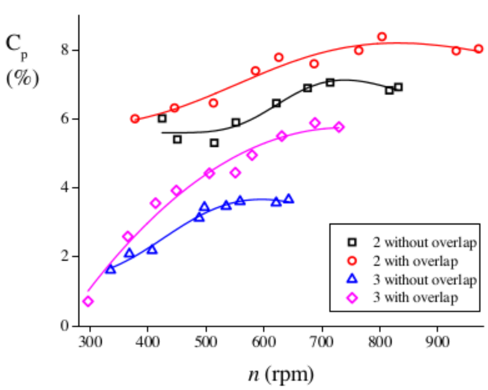
The power generated by each runner has an exponential pattern (Figure 6(a)), where it is similar to the graph of P_w in Figure 4. Based on Figure 6(a), the 2-bucket without overlap produces minimum power of 0.26 W at 424.3 rpm and a maximum power of 2.07 W at 832 rpm. For the 2-bucket with overlap, the minimum power is 0.14 W at 377.3 rpm and the maximum power is 2.41 W at 970.4 rpm. For the 3-bucket without overlap the minimum power is 0.07 W at 335 rpm and the maximum power is 1.1 W at 642.6 rpm, and for the 3-bucket with overlap the minimum power is 0.715 W at the n of 296.4 rpm and the maximum power is 1.728 W at the n of 729.4 rpm. The performance of each runner has a peak point (Figure 6(b)). This indicates that the runner has optimum operating conditions. Based on Figure 6(b), the 2-bucket without overlap has optimum operation at 714 rpm with a C_p of 7.06 %. The 2-bucket with overlap has it at 803.7 rpm with a C_p of 8.39 %. The 3-bucket without overlap has optimum operation at 642.6 rpm with a C_p of 3.66 %, and the 3-bucket with overlap at 687.4 rpm with a C_p of 5.89 %.

III.4. Relation of C_p with λ

In the wind turbine, in order to find out which runners have good performance, the exploration has used a graph of C_p and λ. C_p and λ are determined by Equations (1) and (2), respectively. Figure 7 is the relation of C_p and λ for each runner. From Figure 7, the 2-bucket with overlap has higher C_p and λ than the other ones. The height of λ of the 2-bucket with overlap shows that it has a higher rotation than the others do. This indicates that the kinetic energy of air more is maximally absorbed by the 2-bucket with overlap.



(a) Relation P_{gen} with n



(b) Relation C_p with n

Figs. 6. Relation of P_{gen} and C_p with n

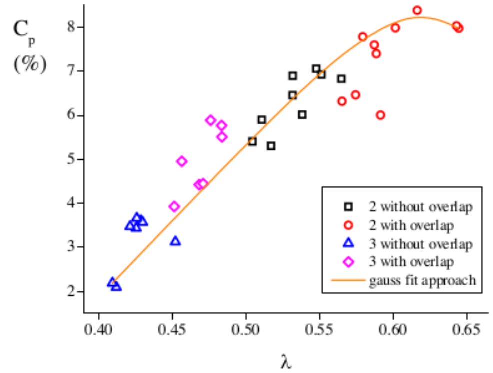


Fig. 7. Relation of C_p with λ

Allegedly, more buckets cause greater drag force because air is trapped between buckets. Even though trapped air between buckets can increase torque (Figure 6(b)), the 3-bucket runner produces a voltage at a lower speed than the 2-bucket, this is less beneficial for turbine performance.

IV. Discussion

The results of this study are similar to the ones of Blackwell's, et al. [8], where the 2-bucket has a better aerodynamics configuration to produce a good performance. Furthermore, the optimum condition occurring at λ of 0.6 to 0.65 has been confirmed (similarly to Blackwell's, et al. [8] study). The Blackwell's, et al. [8] study has reported a C_p of 5 times greater than this study. The difference is due to the function of the P_{gen} equation used. This study uses electrical power (Equation (3)) while Blackwell's, et al. [8] uses mechanical power ($\tau\omega$). This study is considered more applicable because it produces more electricity than Blackwell's, et al. [8]. Besides, investment costs are low because it uses PVC pipes as buckets. The Savonius turbine has lower C_p and λ compared to other wind turbines (ideal propeller, high-speed propeller, Darrieus, American multiblade, Dutch four-arm turbines) [19], since the wind energy is kinetic (Equation (2)) while the Savonius turbine is more dominant in absorbing pressure energy (drag force). This can be viewed by the fact that Savonius turbine design does not use the concept of the triangle velocity, unlike propeller and Darrieus turbines [19]. Due to this, Blackwell et al. [8] have improved the performance of the Savonius turbine using overlap. The kinetic energy of the air that has hit the active blade is then directed through the overlap in order to hit the other blades so that it increases rotation (Figures 6 and 7).

However, this can be proven by using physical phenomenon analysis by the CFD method. It can also review more buckets in the Savonius turbine, making air trapped between the buckets, so that the performance is decreases where it causes air vortex. Therefore, it inhibits the runner rotation. The Savonius turbine bucket manufacturing using PVC pipes is a good alternative. Compared to the previous study [3] using aluminum, the buckets using PVC pipes produce better performance and certainly lower investment costs. Furthermore, the investment cost of making a Savonius turbine runner with PVC pipes (USD 37.43) is cheaper compared to the Turgo turbine in the pico scale where the blades are made from the spoon (USD 48.00) [20]. By using PVC pipes, the investment cost of the Savonius turbine has been reduced. Based on Table III, the investment cost for manufacturing is only USD 64.10. This price is considered realistic for remote areas where there are people with low income per capita. Moreover, if there is damage to the bucket or other components, the turbine can be easily repaired because materials are cheap and available in the market.

TABLE III
LISTS OF MATERIALS PRICES

Materials	Unit	Cost (USD)	Total (USD)
PVC pipes 4 inch	1	12.00	12.00
Generator DC	1	26.67	26.67
Bearing	2	2.00	4.00
Aluminium shaft (0.3 m ø 0.01 m)	1	2.00	2.00
Connecting shaft for ø 0.01 m	2	1.33	2.66
Screw 1 inch	10	0.04	0.4
Hollow iron 2×2 cm	1	5.00	5.00
Spray paint	2	2.00	4.00
Bolt ø 0.003 m	10	0.07	0.70
Welding wages	1	6.70	6.7
Total (USD)			64.19

V. Conclusion

An Independent power plant based on renewable energy is a good solution to solve the electricity crisis in remote areas. Wind is a source of energy that every country in the world has. However, the wind turbine technology is not interested because it has a greater investment cost than pico hydro and solar PV. Reducing the investment costs of wind turbines can be done by the utilization of PVC pipes as a material for Savonius turbine buckets. Based on a comparison with the previous study [3], the PVC pipes materials are better and cheaper than aluminum. The Savonius turbine 2-bucket with overlap is the right solution for remote areas because it has a higher C_p of 8.39% and range λ is wider between 0.57-0.65 compared to the 2-bucket without overlap, the 3 buckets with overlap, and the 3-bucket without overlap. Furthermore, the investment cost of making the Savonius turbine using PVC pipes is even cheaper than the Turgo turbine in the pico scale where the blades are made by spoon. Thus, the PVC pipes are recommended as a material for making the Savonius turbine runner. However, a full-scale test is needed to ensure these results.

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Authors' information

Department of Mechanical Engineering, Faculty of Engineering, Universitas Sriwijaya, Indralaya 30662, South Sumatera, Indonesia.

Dendy Adanta was born in South Sumatera, Indonesia on June 5th. 1993. Degree: M.Eng. (2017) in Mechanical Engineering from Universitas Indonesia, Jakarta-Indonesia. Dr. (2020) in Mechanical Engineering, Universitas Indonesia, Indonesia. He has worked as a lecture at Universitas Sriwijaya, South Sumatera, Indonesia. Dr. Dendy Adanta, M.Eng. some publication had written to the International Journal of Technology; International Journal on Advanced Science, Engineering and Information Technology; CFD Letters; Journal of Advanced Research in Fluid Mechanics and Thermal Science; Energy Reports; Journal of Mechanical Engineering and Sciences; International Review of Mechanical Engineering, and several seminar proceedings.

Kaprawi Sahim (Corresponding author) was born in South Sumatera, Indonesia on January 18th. 1957. Degree: Bachelor's degrees in mechanical engineering from Universitas Sriwijaya, South Sumatera-Indonesia. DEA and Doctor Degree in Mechanical Engineering from Polytechnic University of Hauts-de-France previously known as the University of Valenciennes and Hainaut-Cambrésis (UVHC), Valenciennes-Frances. He has worked as a lecture at Universitas Sriwijaya, South Sumatera, Indonesia. Prof. Dr. Ir. Kaprawi Sahim, DEA. some publication had written to the International Journal of Rotating Machinery, International Journal of Renewable Energy Research, International Journal of Mechanical and Materials Engineering, Frontiers in Heat and Mass Transfer, Potravinarstvo Slovak Journal of Food Sciences, Acta Horticulturae, and Journal of Mechanical Engineering and Sciences, and several seminar proceedings.

E-mail: kaprawi@unsri.ac.id

Amrifan Saladin Mohruni was born in South Sumatera, Indonesia at September 11st 1964. Degree: Bachelor's degrees in mechanical engineering from Universitas Sriwijaya, South Sumatera-Indonesia. Diploma Ingenieur in Mechanical Engineering from Technische Universität Darmstadt Hessen-Germany, Philosophy of Doctor in Universiti Teknologi Malaysia, Johor-Malaysia. He has worked as a lecture at Universitas Sriwijaya, South Sumatera, Indonesia. Dipl. Ing. Ir. Amrifan Saladin Mohruni, Ph.D. some publication had written to the Applied Mechanics and Materials, International Journal on Advanced Science, Engineering and Information Technology, Jurnal Teknologi, and ARPN Journal of Engineering and Applied Sciences, and several seminar proceedings.

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1	Nauman Riyaz Maldar, Cheng Yee Ng, Elif Oguz. "A review of the optimization studies for Savonius turbine considering hydrokinetic applications", Energy Conversion and Management, 2020 Crossref	20 words — 1%

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