The Experimental Study of Hydrokinetic Cross Flow Savonius Horizontal Axis Turbine (CROSSHAT TURBINE)

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***Abstract*—Continuing the previous study about cross flow savonius vertical axis turbine (CROSSVAT) which has the disadvantage of producing side impact in the form of negative torque, this study was using with a horizontal shaft design to improve that weaknesses. This study introduces the new model of Hydrokinetic Cross Flow Savonius Horizontal Axis Turbine (CROSSHAT) using a pair of savonius tandem blades (STB) placed in the center of rotor. The flow coming from the nozzle will first strike the blade on the outer rotor, then crosses inside through the STB, then strike again to the savonius blade. The aim of developing a new model of this turbine is to increase the torque which usually depends on water falling from upper side to the bottom side rotor by gravitation. Meanwhile, this new model using reversing blade also produces jet flow to strike on the concave side of the savonius blade on the center of rotor. Increasing the torque will be followed by increasing efficiency. The research methodology is experimental testing and Response Surface Method (RSM). The variation of the operation of turbine testing is (a) angle of inlet nozzle (α), (b) Head (H), (c) Flow Rate (Q), and Power (P) as the response variable. Based on experimental result, RSM optimization, and analytical review, the optimum value of operating variables were found.**

***Index Terms*—cross flow, horizontal axis, savonius tandem, nozzle angle, RSM**

I. Introduction

Hydrokinetic turbine is an energy conversion machine in order to convert the water's potential energy (head) into mechanical energy in the turbine shaft. The potential energy needs to be converted to kinetic energy before being converted to mechanical energy in turbine shaft. Selection of hydrokinetic turbine type in Micro Hydro Electric Power (MHEP) is adjusted with water discharge, and elevation head and power to be generated by the turbine. One of hydrokinetic turbine types that can be used in the MHEP is the Cross-flow hydrokinetic turbine. Cross-flow hydrokinetic turbine is one of the turbines of action turbine type (impulse turbine). Cross-flow turbines have greater efficiency than the waterwheels, so the use of these turbines is more advantageous than that of waterwheel and other types of micro hydro turbines. The high efficiency of Cross Flow Turbine is derived from the utilization of water energy carried out in two stages, the first of which is the collision energy on the blade at the start of the water impulse, and the second is the water propulsion on the blade when the water leaves the runner. The existence of this steps waterworks proved to be an advantage in terms of its high effectiveness or simplicity in the water discharging of turbine runner system.

There are several factors to consider to gain a turbine with high efficiency. One of the factors that affects the rotation and efficiency produced by Cross-flow turbines is the nozzle angle (α). The nozzle on the cross-flow turbine plays role as a device that drifts water into a rectangular cross section of the inlet turbine with a width conformance to the runner width. In addition to the nozzle angle, the angle blade (ϕ) may also affect the acts of the turbine. The blade is a part of the Cross-flow turbine runner that operates to receive the compressive energy and the incoming working fluid velocity. The blade is set on the impeller seat (impeller) to form an angle with a certain slope. A well-situated angle blade is hoped for increasing the mechanical power and efficiency of the turbine.

According to previous studies, it can be seen that the nozzle angle and angle blade can affect the rotation and efficiency produced by Cross-flow hydraulic turbine. Choi Y D, [1], managed several simulation studies (CFDs) to find out the effect of turbine's structural configurations toward the performance and internal flow characteristics of Cross-flow turbine types by altering the shape of the nozzles, the inlet runner angle, the angle of the runner blade and the number of blades. The outcomes demonstrate the shape of the nozzle, the angle of the runner blade and the amount of the blade influenced the performance and shape of the fluid run in the turbine [2].

The outcomes of energy conversion on this conventional cross flow turbine is still not well performed because at the second collision it is only dependent on the gravitationally collision of water flow. Inspired from the preliminary research of us brings out a new cross flow turbine design where the second collision was designed through the diffuser form as compartment between S blade and Savonius Tandem Blade (STB) that resembles

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a narrowed elbow that forwards the outflow from the first level collision into kinetic energy (jet flow) for a second collision on the concave side of the Savonius blade on central turbine rotor [3]. Cross Flow Savonius Vertical Axis Turbine (CROSSVAT) that utilizes Moving Plate Deflector (MPD) was also introduced to eliminate negative torque with the tangential MPD type, as shown in Fig.2 [4]. Several experimental and numerical studies with a vast amount of physical designs and factors have been tested in and around Savonius rotor to enhance its efficiency. Based on literature study, Kumar and Sani's review of different factors affecting the performance of Savonius hydrokinetic turbine has been executed and presented in their paper which might be efficacious for the upcoming studies to develop the efficiency of that turbine [5]. Elbatran et al showed an evaluation of low head micro-hydropower turbines; focusing on categories, performance, operation, and cost. [6]. Oliver Paish summarized different small hydro technologies, new innovations that were being improved, and the barriers to further enhancement. Based on positive environmental policies now being backed by favourable tariffs for 'green' electricity, the industry society believes that small hydro will have a strong resurgence in Europe in the next 10 years, after 20 years of decline [7].

Previous researchers have modified savonius rotor for applications as hydraulics turbines, some of which are: An effort was made by S Lio to rise the power coefficient of runner by the usage of flat shield plate that is placed upstream of the runner. The variation of the power coefficient was analysed in relation to the clearance between the runner and the bottom wall and the rotation direction of the runner. The flow field around the runner was also analyzed visually to explain influences of setting conditions to the power turbine performance. The study result reported that the power coefficient was attained for 0.47 by only utilizing a flat shield plate; the increase was up to 80% over the runner without the plate [8]. Similar studies of turbine performance improvement on vertical axis rotor applications using plate deflector were also done by Wahyudi B [4], Golecha K [9], [10].

II. Problem and Basic Principle

The problem faced on the internal flow in and around of a cross-flow turbine runner is very complicated because the water passes through only a part of the runner. Therefore, Banki's turbine has been created and manufactured until now existed in the basis of one-dimensional research and empirical results. On the Banki's turbine, the flow inside a cross-flow runner is exceedingly non-uniform along the runner periphery. Usually the fluid works' flow on rotating blade is illustrated using the velocity polygon. Empirical and theoretical studies for determination of fluid forces on the blade in a cross-flow turbine were conducted by Fukutomi [11] and Fukutomi [12]. In this experiment, the tangential and radial forces were measured on a test blade using strain gauges and slip rings. Besides, in the theoretical study, they were calculated numerically using the unsteady momentum theory. The calculated outcomes were compared with empirical data and good performance had been demonstrated. Furthermore, the maximum forces were found to occur immediately before the blade leaves the nozzle exit in both the experimental and theoretical results.

The disadvantage of a conventional Banki's turbine lies in the second stage of the collision due to cross flow on opposite blades relying solely on the gravity and low pressure of the draft tube, so that the remaining forces to produce the thrust on the blade are still weak.

This paper introduces a new additional component of runner turbine using reversing blade which can also produce jet flow to strike on the concave side of the savonius blade on the center of rotor. The new component is the savonius tandem blade (STB) that was introduced by Wahyudi B as shown in Fig.1 [13] on the paper titled: "*A Simulation Investigation of Flow and Pressure Distribution Patterns in and around of Tandem Blade Rotor of Savonius (STB) Hydrokinetic Turbine Mode*l"

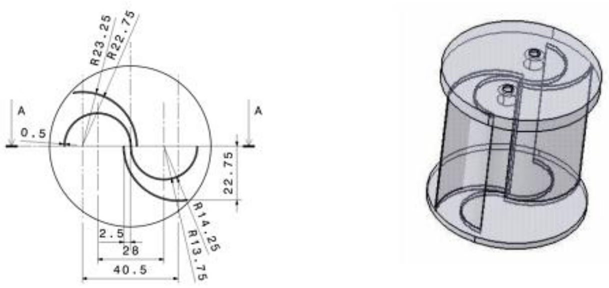


Figure 1 Design of Savonius Tandem Blade (STB) [4].

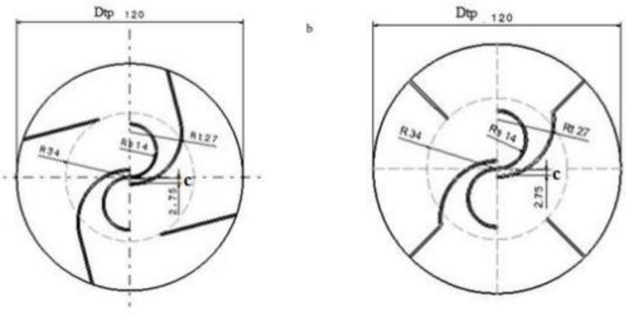


Figure 2. Combined of Savonius tandem blade with tangential and radial moving plate deflector [4].

On its application as cross flow vertical axis hydraulics turbine (CROSSVAT) using CFD simulation, it was shown that STB was able to create jet flow through the compartment close to the edge of the concave blade. The jet flow, shown in red color marking on Fig 3, changed direction (reversed) and reinforced the remaining energy collision to the concave blade in the central section of rotor. In this project, research changed the application from CROSSVAT to Cross Flow Savonius Horizontal Axis Turbine which isabbreviated as CROSSHAT by using concave blade shape to substitute the flat shape of the MPD deflector on the peripheral rotor.

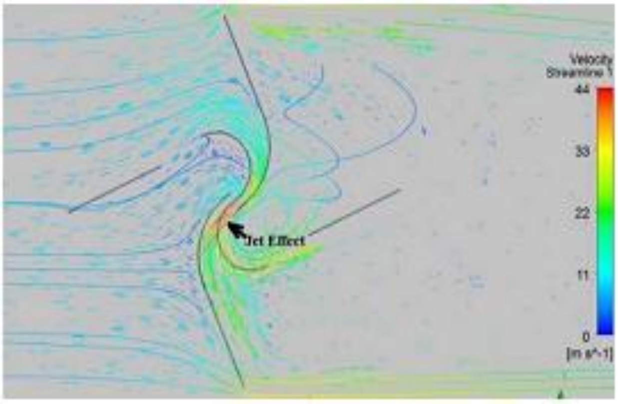


Figure 3. Jet Effect phenomena on the concave blade by using combined STB and Tangential MPD [4].

This research introduces the new modification of hydrokinetics' cross flow turbine using S-letter model savonius blade on the center of disc runner as described in Fig. 4 as well as arranged the velocity polygon inlet and outlet vector parameters as explained in Fig. 5.

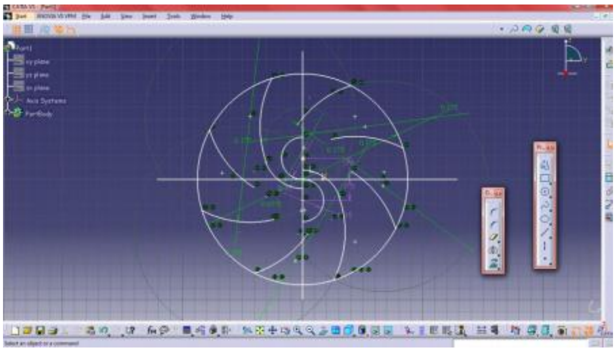


Figure 4. New cross flow runner design with Savonius tandem blade using CAD software (Catia).

If the conventional blades of cross flow turbine as described in Fig. 5 (a) can work effectively at the comparatively low elevation (head) and/or low discharge, then the runner and the turbine profile has been optimized. It was proved by Kokobu by their project in which the model turbine was designed in accordance with the traditional design and added with "current-plate" under guide vane, and then analyzed their performance, and investigated their flow condition experimentally at various conditions of operation [14]. In the CROSSHAT turbine, the flow sprayed from the nozzle produces a first-rate blade collision then proceeds for a second collision on the concave side of the S blade that reverses the 180-degree stream to produce a large momentum force. The velocity polygon for this new model of turbine can be seen in Fig. 5 (b) which shows the following parameters: V = absolute velocity, U = tangential velocity, Vr = relative velocity, α = absolute speed angle and β = relative speed angle.

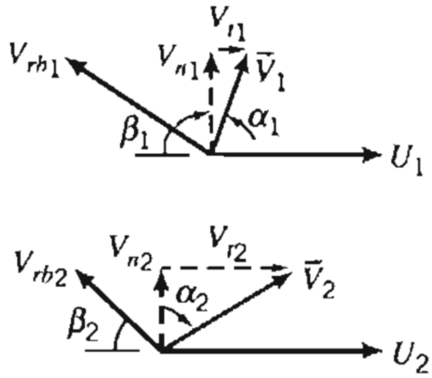


Figure 5. Inlet velocity polygons and outlet velocity polygon.

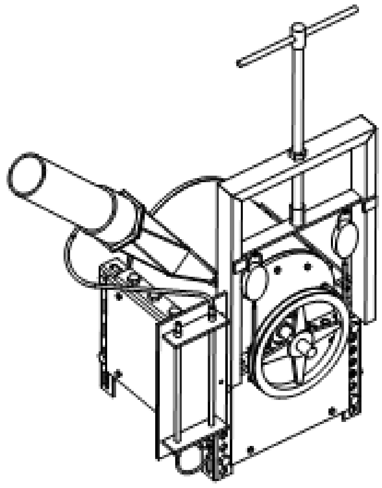


Figure 6. Assembling design of CROSSHAT Testing Turbine Performance.

Based on the velocity polygon as shown in Fig. 5 (b), the following is the description of each point of work at the turbine blade that is usually illustrated on edge of the blade:
U_1 = Tangential Velocity at the edge of outer blade
V_1 = Absolute Velocity of water from nozzle
Vr_1 = Relative Velocity of water on inlet surface blade
Vn_1 = Velocity of water on inlet normal direction
Vt_1 = Velocity of water on inlet tangential direction
α_1 = Nozzle Angle (Absolute Velocity Angle)
β_1 = Relative Velocity Angle at the edge of outer blade

U_2 = Tangential Velocity at the edge of inner blade
V_2 = Absolute Velocity at the edge of inner blade
Vr_2 = Relative Velocity of water on outlet surface blade
Vn_2 = Velocity of water on outlet normal direction
Vt_2 = Velocity of water on outlet tangential direction
α_2 = Absolute Velocity Angle in outlet
β_2 = Relative Velocity Angle at inner edge of blade

The angle of the absolute velocity (nozzle angle), α1, is determined from the normal direction or added with 90o if measured from tangential direction, as shown in Fig. 5. The tangential component of the absolute velocity, Vt1, and the normal component to the flow area Vn1 also are shown in Fig. 5. The inlet and outlet velocity polygons provide all the information needed to calculate the ideal torque or power by using several equations below:

$$T_{shaft} = \rho.Q\,(r_2.Vt_2 - r_1.Vt_1) \qquad [N.m] \quad (1)$$

$$P_{shaft} = \rho.Q.\omega\,(r_2.Vt_2 - r_1.Vt_1)[Watt] \quad (2)$$

$$P_{shaft} = \rho.Q\,(U_2.Vt_2 - U_1.Vt_1) \quad [Watt] \quad (3)$$

$$U = \left[\frac{\pi.D.n}{60}\right] \qquad [m/\sec] \quad (4)$$

$$Vt = V\sin\alpha \qquad [m/\sec] \quad (5)$$

$$Vn = V\cos\alpha \qquad [m/\sec] \quad (6)$$

$$T_{shaft} = (F_1 - F_2)\,R \qquad [N.m] \quad (7)$$

$$F = \rho.Q\,(V\cos\theta_1 - V\cos\theta_2) \quad (8)$$

$$\theta_1 = 0^o \quad \text{and} \quad \theta_2 = 180^o$$

$$F = \rho\,Q\,[V - (-V)] = 2\,\rho\,Q\,V \quad (9)$$

III. Methodology

Fig. 4 above shows the geometry design of Convergent STB as the optimization process using Response Surface Method (RSM). RSM is comprised of statistical and mathematical techniques for optimization process development and improvement, which utilizes the experiement design, regression analysis, and variance analysis. In this case, the response variable Efficiency "η" (y) is affected by two independent variables: Angle of Nozzle "α" or (x1) and Tip Speed Ratio "U/V" or (x2). The optimal values of those independent variables (x1, x2) that lead to maximum efficiency can be obtained from an appropriate model formulation.

Surface fitting can be completed using the subsequent RSM analysis. If the surface fitting is a good estimate of a response function, then the surface fitting analysis would be equal to the actual analysis systems. Variance and regression analyses can be used to estimate regression coefficients in the quadratic polynomial model and to generate an uncertainty measure in the coefficients.

Furthermore, in conditions near the response, a second order model (order II) or more is normally required to estimate ofresponse due to the surface curvatures. In many cases, the second order model (II) expressed in equation (10) is considered sufficient.

$$\hat{y} = \beta_0 + \sum_{i=1}^{k}\beta_i x_i + \sum_{i=1}^{k}\beta_{ii}x_i^2 + \sum_i\sum_j \beta_{ij}x_i x_j,\, i < j \quad (10)$$

The second order equation of the response surface fitting is often related as the canonical analysis. The parameters on the approximation functions are estimated by using the least squares method. Meanwhile, the coefficient of determination (R^2) provides the statistical brief that evaluates how well the regression equation affects the data.

However, a large R^2 value does not necessarily mean that the regression model is good. Append variables to the model will always increase R^2, although the added variables are not statistically significant. Thus, models with large R^2 values may also result in poor predictions of new observations or mean response estimates.

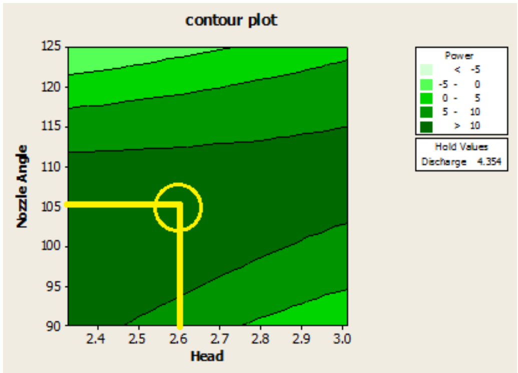
IV. Result and Discussion

The contour plots as shown at Fig. 8 predict the variations in theHead, discharge, and nozzle angle in various operation settings to obtain the turbine shaft power. It can be observed from the power shaft contour plots thatwere measured by using torsion brake as shown Fig. 7and calculated with Eq. 7. This torsion indicates the power extracted by the shaft of CROSSHAT turbine by using variable testing as shown in Table I. The shaft power in table 1 is not represented as a maximum result because the geometry of the outer rotor blade angle is not included as a converting factor. This research uses only a nozzle angle as a factor in the geometry of the water flow angle in the turbine. Theoretically, the dominant factor in the angular momentum (Torque) equation is strongly influenced by the nozzle angle (α) and the angle of the runner blade (β). Increasing torsion occurs due to the high flow velocity in second collision on the concave side of the S blades which able to be reversed up to180 degree. As a result, a momentum change acts across the concave side of the blades that provides the additional forces to increase torque as shown in Eq. 9.

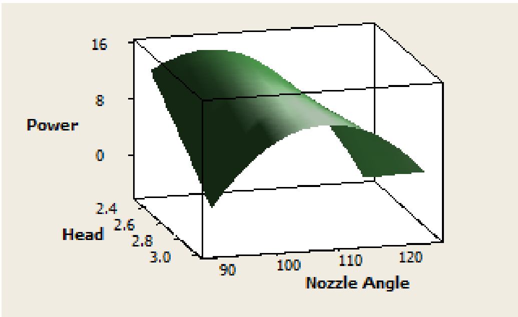
TABLE I. Data Experimental of Crosshat Turbine Model.

No	Head [m]	Debit [ltr/sec]	Nozzle Angle [º]	Torque [N.m]	Revolution [rpm]	Power Shaft [watt]
1	2.33	4.976	90	0.37	318	12.22
2	2.33	4.976	100	0.44	283	13.06
3	2.33	4.976	110	0.50	344	18.11
4	2.33	4.976	115	0.1308	176.5	2.42
5	2.33	4.976	120	0.0981	94.83	0.97
6	2.33	4.976	125	0.0033	52.5	0.02
7	2.68	3.87	90	0.32	207	6.89
8	2.68	3.87	100	0.37	263	10.10
9	2.68	3.87	110	0.39	399	16.37
10	2.68	3.87	115	0.1799	196	3.69
11	2.68	3.87	120	0.1144	90.66	1.09
12	2.68	3.87	125	0.024	70	0.18
13	3.01	3.732	90	0.12	130	1.66
14	3.01	3.732	100	0.27	186	5.24
15	3.01	3.732	110	0.56	241	14.23
16	3.01	3.732	115	0.3333	292.08	10.19
17	3.01	3.732	120	0.1666	297.86	5.19
18	3.01	3.732	125	0.02943	81.5	0.25

Figure 7. Measuring torque and shaft revolution.



(a)



(b)

Figure 8. Contour plots (a) and response surface (b) optimizer of turbine power with variable of Head, Discharge, and Nozzle Angle.

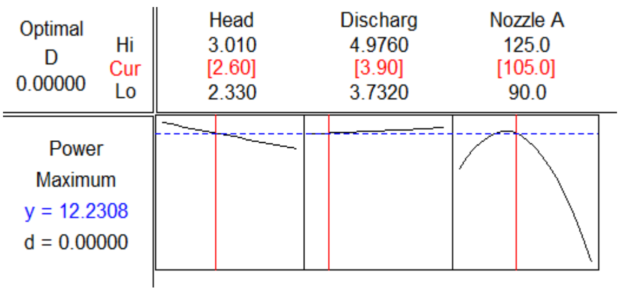


Figure 9. Power maximum at position 2.60 [m], 3.90 [lt/s] and 105[°].

From the contour plot of the image above, it can be concluded that the image does not have a stationary point. Consequently, calculation of the stationary point and surface characteristics of the response is not necessary.

The result of power response (P) optimization will be obtained after value of (H) , (Q) and (α) are substituted into the model full quadratic equation with value of Head H = 2.330 [m] ÷ 3.010 [m] and Rate of Discharge Q = 3.732 [liter/sec] ÷ 4.976 [liter/sec] and Nozzle Angle Variation α = 90 [°] ÷ 125 [°]. By using Minitab Software, it is simpler to obtain the result of peak point in the tangential as shown in Fig. 9 which shows optimal value of H = 2.60 [m] and Q = 3.90 [liter/sec] and α = 105 ° with response to max. P = 12.2308 [Watt].

These experimental results still have not shown optimum performance because blade tip angle variation has not been involved in turbine performance testing. The next research is to develop blade tip angle variation (β) by providing some rotors with different angle variations in the outer edge. To obtain valid data research, several pieces of turbine rotor models with different sizes of blade tip angle are required. At this point of view, it is crucial to investigate the effect of blade tip angle variation toward the mechanical power through turbine shaft.

V. Conclusions

The use of S blade to reverse the flow direction in the central rotor will impact toward the increasing change of momentum and collision on the concave blade due to the increase the torque power. The use of a combination of STB and S Blade as a new design of runner blade of cross flow turbine is an effort to improve the conventional design that still uses gravitational forces in the collision blade in the second step to become a reverse continuous flow which produces “jet effect” on the first step of water collision. From the previous research, Cross Flow Savonius vertical axis turbine (CROSSVAT) normally would results in inflow energy losses due to collision between mainstream flow with the opposing blade movement [4], but now the horizontal axis using the CROSSHAT turbine will be more effective to capture the inflow energy and increase the torque.

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