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RESPONSE SURFACE METHODOLOGY (RSM) APPLICATION TOWARD THE PERFORMANCE OF A VERTICAL SHAFT HINGED ARC BLADE KINETIC TURBINE

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Abstract

Alternative energy sources are essentially inexhaustible for the foreseeable future, alternative energy is not only needed but to the energy transform from one form of energy to another form of energy without creating pollution that would damage the environment. One of these is the water potential energy, especially from rivers. In Indonesia especially the potential of river water is very much. On the river water, one of the enormous energy potential is the kinetic energy due to the flow speed and the flow rate when it can be utilized optimally then the energy crisis can be overcome. Kinetic turbine is one of the options in harnessing the kinetic energy potential in a form of flow rate. The Response Surface Methodology (RSM) is used in this research as design of experiment to obtain the optimum condition of each parameter. This study uses a kinetic turbine vertical shaft with eight arc blades. The kinetic turbine was made under a laboratory scale. The purpose of this study was to obtain an optimum condition for an arc bladed kinetic turbine performance. The Response Surface Methodology was used to obtain a turbine performance mathematical equation at an optimum condition. In this study, the independent variables used are the flow steering angle variations 30°, 40°and 50°; Flow rates of: 1.7; 2.2; 2.7 m/s; and turbine rotation of: 35, 45, 55 rpm. From the observation and analysis it is obtained a mathematical model with *Y* as the Turbine Power = 5.97 Watts; water flow steering angle *X1* = 35,75º; a water flow rate *X2* = 2.78 m/sec; and the turbine rotation *X3* = 61.82 rpm. A turbine efficiency Full Quadratic models based on the response surface models analysis obtained a mathematical model too, where *Y* is the Turbine efficiency as big as 19.74%.

Keywords: Water energy, Potential energy, Kinetic turbine, Response Surface Methodology.

Nomenclatures

D	Overall desirability
di	Individual function desirability
E_a	Energy, Joule
F	Total force, N
L	Arm length, m
P_a	Water power, Watt
P_t	Turbine power, Watt
Q_a	Water flow rate, m^3/s
R^2	Coefficient of determination
S	Standard Deviation
T	Torque, Nm
V	Flow speed, m/s
$X1$	RSM variable for steering angle, deg.
$X2$	RSM variable for flow speed, m/s
$X3$	RSM variable for turbine rotation, rpm
x_m	Variable treated
Y	RSM result for turbine power, Watt

Greek Symbols

α	points on the axial axis, $\alpha = 2k/4$
β_m	Variable treated
η	Turbine efficiency, %
ρ	Water density, kg/m^2
ω	Angular velocity, rad/sec.

Abbreviations

ANOVA	Analysis of Variance
CCD	Central Composite Design
RSM	Response Surface Methodology

1. Introduction

To meet the electrical energy is by utilizing available energy sources where one of the energy sources is from water energy. The Indonesia topography condition, which is mountainous and hilly, would cause a large number of streams and small rivers. These water streams hold the potential of water energy source.

To meet the availability of electrical energy, what could be done is utilizing the natural resources to be converted into electrical energy.

The World Watch Institute [1] said that Indonesia has the potential of hydropower which was divided into two categories, namely the large scale and the small scale. For the large scale category the hydropower potential has a power of 74.67 GW, while for the small scale category the hydropower has a potential of 460 MW.

Some researchers conduct a research to improve more optimal kinetic turbines performance. Monintja et al. [2] conducted a study on the kinetic turbine with an eight bowled blade-type to obtain an optimum turbine condition. The Response Surface Method was used to obtain the turbine performance mathematical equations at an optimum condition. From the observation and analysis obtained by the Full Quadratic Model Empirical Model Testing for the turbine power and turbine efficiency.

Golecha et al. [3] conducted a study to determine the modified savoinus turbine by using two plates to direct the water flow straight forward to the blade performance. Williamson et al. [4] conducted a research to get the Turgo Pico-Hydro Turbine maximum performance. By using a single jet, the Turgo turbine was observe at low head 3.5 m to 1 m. Arslan et al. [5] designed and built a turbine to generate electricity by harnessing the river flow. The blade type used is a bowled shaped blade. The use of this blade type has several advantages, namely: the water volume entering the blade could more compare with the blade without hindrance the turbine design is very simple and can be produced and used in remote areas.

Golecha et al. [6] investigated to get a modified savoinus water turbine performance using one and two deflector plate. The deflector plate is used to direct the water flow straight forward to the turbine blade. Yang and Lawn [7] conducts a research using turbines with a vertical axis, the turbine is called the Hunter turbine. The blade form used in this kind of turbine is a semi-circular form, using a hinge on each blade attached to a turbine disc.

Yang and Lawn [8] conducted a study to determine the three-dimensional effect on a tidal current turbine performance with a vertical axis turbine. Just like in 2011, the blade used is made from steel plate sheet which is formed semi-circle and hinge on the turbine disc. Besides the turbine blade type, the water steering angle would determine the turbine rotation flow. With the steering angle presence, it does not guarantee the flow would always be linear especially with the different turbine rotation. The ideal water steering angle is if the turbine rotation is constant.

Boedi et al. [9] conducted a research on an outer movable blade vertical shaft kinetic turbine performance to determine the performance of a kinetic turbine prototype as a rural area electric power source. The purpose of this study is to minimize the water flow back pressure. Under an experimental research and conducts in a laboratory scale, the result tells that a kinetic turbine would works on a stable rotation if the water steering angle is appropriate.

A stable turbine rotation would produce a better electricity quality [10]. The kinetic turbine used in this study is a vertical axis turbine and mounted by eight blades. These blades is attach on the disc using hinges to make the blade easy to swing in a specific direction. The turbine performance optimization was observed by the Response Surface Methodology.

2. Material and Methods

A kinetic turbine is a turbine that relies on water speed. The type of turbine does not require the height difference or potential head. This turbine is working on a direct current flow of water and hit the turbine blades straight forward. The blades get an energy supplied in a form of kinetic energy. This turbine uses a vertical axis and the turbine disc rotates because of the turbine blade shape. The turbine rotation is also depending on the water flow steering angle value.

The tools and materials used in this study are a kinetic turbine runner which has three main parts. First is the turbine shaft. Second is turbine disc with a diameter of 11.5 cm. The last parts, is the eight pieces turbine blades made from acrylic material with a thickness of 2 mm as shown in Fig. 1. A directional channel flow which is directing the water made from wood with a thickness of 1 cm and 25 cm high as shown in Fig. 2.

Fig. 1. Arc bladed kinetic turbine

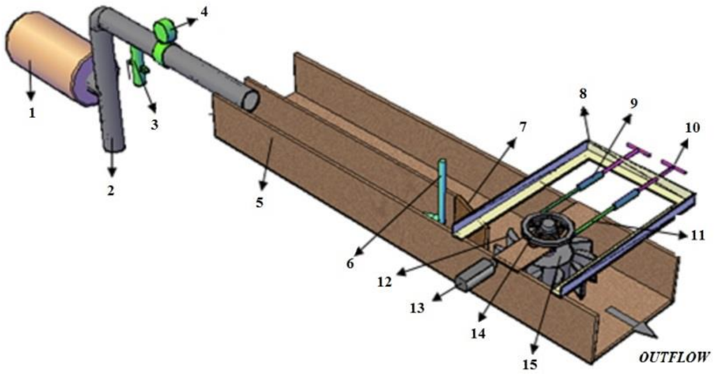

Fig. 2. Research installation

1. Pump; 2. Suction Pipe; 3. Bypass Pipe; 4. Flow meter; 5.Water Flow Duct; 6. Flow meter; 7. Flow Steering; 8. Frame; 9. Torque Scale; 10. Variable Loader; 11. Wire; 12. Turbine Blade; 13. Tachometer; 14. Pulley; 15. Turbine Runner.

In this study, the independent variable used is the water flow steering angle, water flow speed and turbine rotation. While the response variables are the turbine power and turbine efficiency. The turbine performance depends on the turbine power and turbine efficiency [11, 12]. The turbine power is determined by the amount of power produced by the water flow. The water power on a duct cross section is:

Water power is given as:

$$P_a = \frac{1}{2}\rho Q a V^2 \tag{1}$$

To calculate the turbine power generated due to the kinetic energy is:

$$P_t = T.\omega \tag{2}$$

Torque:

$$T = F\,.\,l \tag{3}$$

The turbine efficiency is the ratio between the turbine power and the water horse power:

$$\eta = \frac{P_t}{P_a} \times 100 \tag{4}$$

The objective of this study is to get a new method in optimizing a kinetic turbine. As mentioned above that RSM is used to solve the optimizing problem. From this study the best turbine parameters (such as the steering angle, water flow speed, turbine rotation) could be found to get the optimum Turbine power output and possibly the optimum turbine efficiency.

3. Experimental Design

The level selection is based on the theory of the CCD method RSM. Because the factors used are 3 factors, then the experiment design should consists of 20 experiment numbers which consists of an axial field, center field and the factorial field [13, 14]. To get a first and second order empirical model, a $2k$ factorial experimental design was done. It was observed at a central point and points on the axial axis with $\alpha = 2k/4$ in the Central Composite Design (CCD) form [14, 15]. The level on the axial axis (coded as - α and as + α), for $k = 3$, α value would be 1.682. In this test, there are two types of variables, namely: the independent variable and the response variables. The first independent variable is the steering angle, which is 30°, 40° and 50°. The second variable is the water flow rates, which are 1.7; 2.2 and 2.7 m/sec. Finally, is the turbine rotation which is 35, 45, and 55 rpm.

The independent variables could be determined based on the independent variable as seen in (Table 1).

Table 1. Independent variable level (experimental design).

Variable Name	Steering Angle (°)	Water flow speed (m/second)	Turbine Rotation (rpm)
Level $-\alpha$	23,18	1,359	28,18
Low Level (-1)	30	1,7	35
Middle Level (0)	40	2,2	45
High Level (+1)	50	2,7	55
Level $+\alpha$	56,82	3,041	61,82

Based on Table 1, CCD experimental was designed. In Table 2 it is shown the second order experimental design for $k = 3$ using the CCD.

Response Surface Methodology (RSM) is a set of mathematical and statistical methods which was used to examine the relationship between one or more variable treatment in a form of response. The relationship between treatment response and modelled linearly resulted a factorial design with a first-order regression model approach [14, 15], namely:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_m x_m + \varepsilon \tag{5}$$

If the relationship between the response and treatment in the first-order model does not meet the requirements, then an approach is done to a second-order regression model, namely:

$$y = \beta_0 + \sum_{i=1}^{m} \beta_i x_i + \sum_{i=1}^{m} \beta_{ii} x_i^2 + \varepsilon \quad (6)$$

Central Composite Design (CCD) is an experimental design which consists of 2k factorial design with added a couple of centre runs and axial runs. Parts of the CCD are the 2k factorial design (runs / cube) = nc, where k is the factors number, namely the experiment at point (≠ 1 ≠ 1, ..., ≠ 1). Centre runs (nc), which is the experiment at the central point (0.0, ..., 0). Axial runs, the experiment at the points (a, 0, ..., 0), (-α, 0, ..., 0), (0, α, ..., 0), (0, - α, ..., 0), (0,0, ..., α), and (0,0, ..., -α) using axial runs or star point α whose value is determined by a number of variable factors and CCD typed is used [15, 16].

Points on the 2k factorial design which is used to establish a model of first order. While the addition of runs and axial centre runs are used to form the second order models. In the Central Composite Design, in order to get a good predictive quality, the design besides having orthogonal nature must also be routable. A draft is said routable if the variance of the estimated response variables, variety of g, is a function of $x1$, $x2$, ..., $x3$ which was only depends on the distance from the centre of the design and is not dependent on the direction [14].

Table 2. Experimental results.

No.	Steering angle (α)	Flow Speed m/sec	Turbine Rotation rpm	Turbine Power Watt	Turbine Efficiency %
1	30	1.7	35	3.08	7.34
2	50	1.7	35	2.79	11.52
3	30	2.7	35	3.46	1.85
4	50	2.7	35	2.83	2.46
5	30	1.7	55	4.58	10.91
6	50	1.7	55	3.19	13.16
7	30	2.7	55	4.71	2.52
8	50	2.7	55	4.61	4.01
9	23,18	2.2	45	3.67	4.01
10	56,82	2.2	45	3.81	6.9
11	40	1.359	45	2.19	15.61
12	40	3.041	45	4.45	2.26
13	40	2.2	28,18	3.05	4.83
14	40	2.2	61,82	5.97	9.44
15	40	2.2	45	4.24	6.7
16	40	2.2	45	4.24	6.7
17	40	2.2	45	4.24	6.7
18	40	2.2	45	4.24	6.7
19	40	2.2	45	4.24	6.7
20	40	2.2	45	4.24	6.7

4. Results and Discussion

The data result from the turbine testing are the flow steering angle, flow speed and turbine rotation.

The turbine power residual normality is shown in Fig. 3 below.

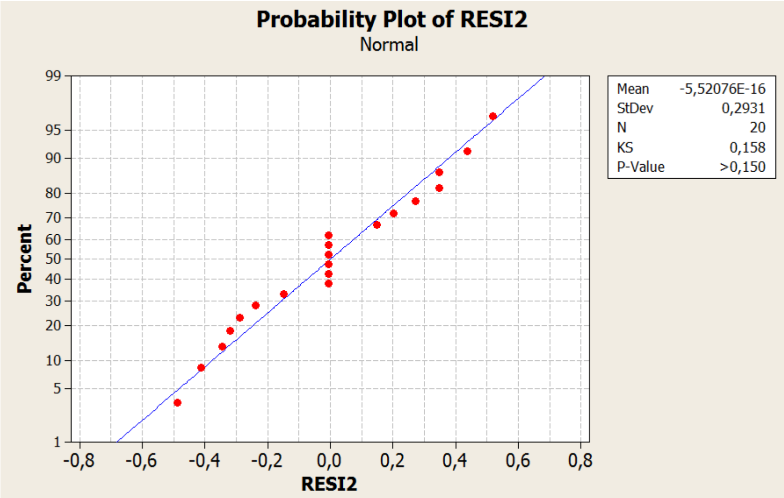

Fig. 3. The Residual normality test of the turbine power.

From the turbine power residual normality test result in Fig. 3, it could be seen that the *P-Value* is greater than 0.15 means that the residual is already normally distributed. The residual normality assumption in the regression model has been met by a regression model that has been made so that it can be used.

Based on the turbine power ANOVA, the percentage of the total variation indicated by the model (R^2), wherein R^2 is 88.63%. The R^2 value is quite large, meaning that the second-order polynomial prediction model is fulfilled. The determination coefficient of the full quadratic regression models are shown in Table 3.

Table 3. The full quadratic regression test for the turbine power.

Estimated Regression Coefficients for Turbine Power				
Term	**Coefficient**	**SE Coefficient**	**T**	**P**
Constant	4.24572	0.1648	25.765	0.000
Steering Angle	-0.15923	0.1093	-1.456	0.176
Flow Speed	0.42256	0.1093	3.865	0.003
Turbine Rotation	0.72058	0.1093	6.591	0.000
Steering Angle*Steering Angle	-0.21416	0.1064	-2.012	0.072
Flow Speed*Flow Speed	-0.36265	0.1064	-3.407	0.007
Turbine Rot.*Turbine Rot.	0.05807	0.1064	0.546	0.597
Steering Angle*Flow Speed	0.11875	0.1429	0.831	0.425
Steering Angle*Turbine Rot.	-0.07125	0.1429	-0.499	0.629
Flow speed*Turbine Rot.	0.14125	0.1429	0.989	0.346
S = 0,404044	PRESS = 12,9194			
R^2 = 88,63%	R^2 (pred) = 10,01%		R^2 (adj) = 78,40%	

From the Full Quadratic Empirical Testing Model, the turbine power based on the surface response analysis model result a mathematical model as follows.

$Y = 4.24 - 0.159X1 + 0.422\mathrm{X}2 + 0.720X3 - 0.21X12 - 0.36X22 + 0.058X12 + 0.118X1.X2 - 0.071X1.X3 + 0.141X2.X3$.

Based on the analysis of full quadratic response surface models the contour plot and the surface plot turbine could be seen in Fig. 4 and 5.

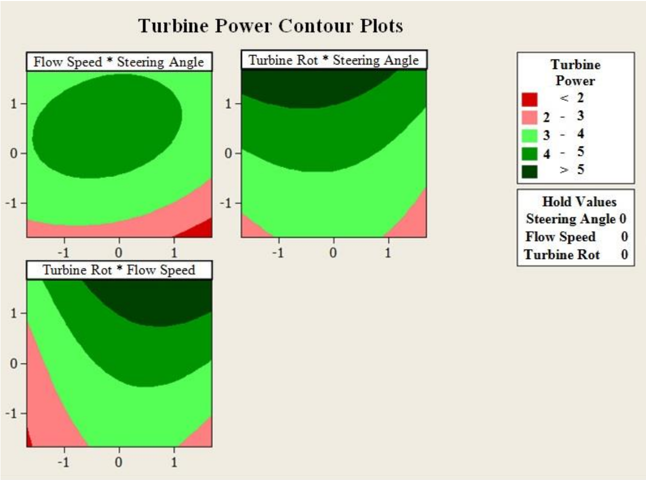

Fig. 4. Turbine power contour plot.

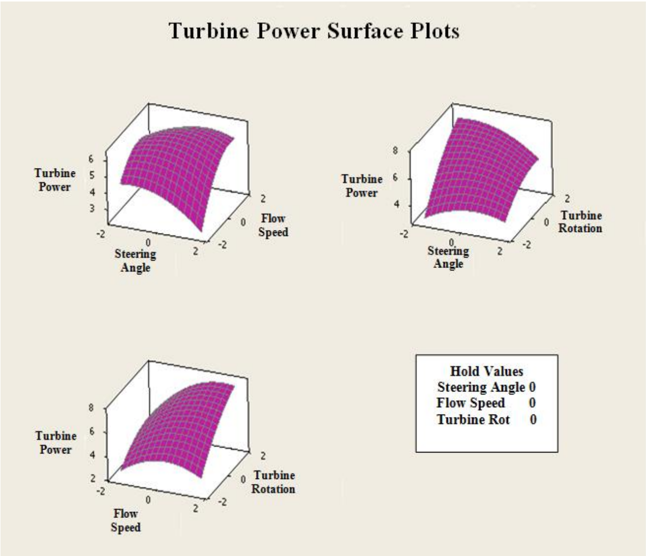

Fig. 5. Turbine power surface plot.

The mathematical model for the turbine power generation from the full quadratic test model is plotted on the response surface plot on Fig 4 and projected on the contour plot in Fig. 5.

The response surface in Fig 4 and contour plots in Fig. 5 show the effects of interaction between flow speed and steering angle on the turbine power under a 61.82 rpm turbine rotation. This figure suggests that the best flow speed in order to achieve the maximum turbine power generation is 2.78 m/sec and the best steering angle is 35.75°. Further increase in flow speed caused turbine power generation to decrease.

Turbine Efficiency normality test from the residual for turbine efficiency is shown in Fig. 6.

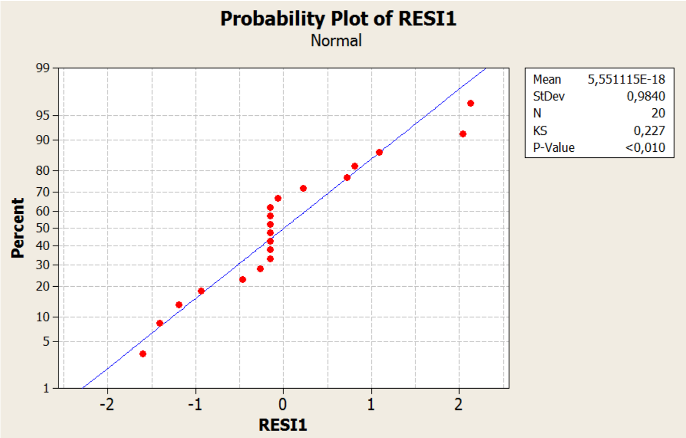

Fig. 6. Probability Plot of Residual turbine efficiency.

From the turbine efficiency residual normality test result in Fig. 6, it could be seen that the *P-Value* is less than 0.010 means that the residuals are already distributed normally. The residuals normality assumption on the regression model has been fulfilled so that it can be used.

Based the turbine efficiency ANOVA, the total variance percentage indicated by the model (R^2), wherein R^2 is 99.05%. The R^2 value is large; it means that the second-order polynomial models estimation is valid. The determination coefficient of full quadratic regression models is shown in Table 4.

Table 4. Full quadratic regression model for turbine efficiency.

Estimated Regression Coefficients for Turbine Efficiency				
Term	**Coefficient**	**SE Coefficient**	**T**	**P**
Constant	6.71558	0.2050	32.765	0.000
Steering Angle	0.98049	0.1360	7.210	0.000
Flow Speed	-3.99374	0.1360	-29.368	0.000
Turbine Rotation	1.11175	0.1360	8.175	0.000
Steering Angle*Steering Angle	-0.54201	0.1324	-4.094	0.002
Flow Speed*Flow Speed	0.68836	0.1324	5.200	0.000
Turbine Rot.*Turbine Rot.	0.05196	0.1324	0.393	0.70
Steering Angle*Flow Speed	-0.54125	0.1777	-3.046	0.012
Steering Angle*Turbine Rot.	-0.13125	0.1777	-0.739	0.477
Flow speed*Turbine Rot.	-0.37375	0.1777	-2.104	0.062

S = 0,502547 PRESS = 20,7014
R^2 = 99,05% R^2 (pred) = 92,22% R^2 (adj) = 98,20%

Empirical Model of a Testing Full Quadratic Test Model; the turbine efficiency based on the surface analysis model resulted a mathematical model as follows.

$Y = 6.71 + 0.98X1 - 3.99X2 + 1.11X3 - 0.54X12 + 0.68X22 + 0.05X32 - 0.54X1.X2 - 0.13X1.X3 - 0.37X2.X3$. Y is the RSM result for turbine efficiency.

Based on the analysis of full quadratic response surface models the contour plot and the surface plot turbine could be seen in Figs. 7 and 8.

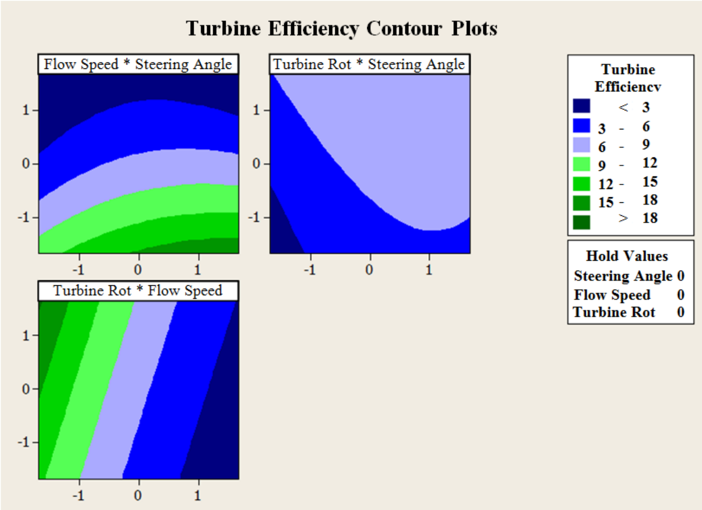

Fig. 7. Turbine efficiency contour plot.

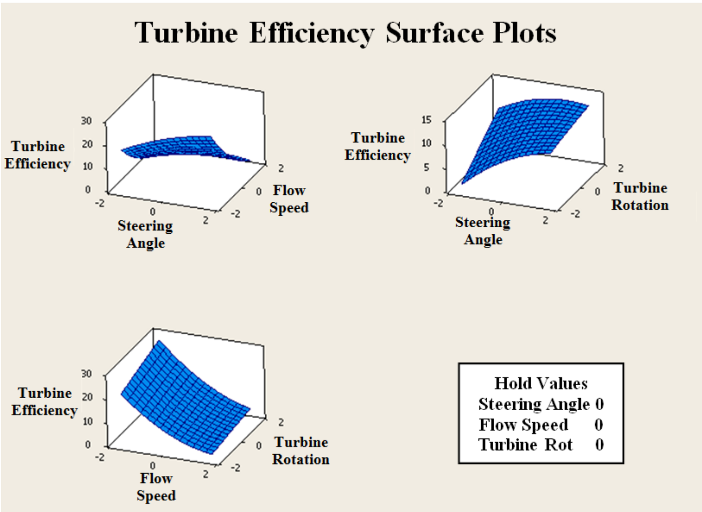

Fig. 8. Turbine efficiency surface plot.

The mathematical model for the turbine efficiency from the full quadratic test model is plotted on the response surface plot on Fig 7 and projected on the contour plot in Fig. 8. The response surface in Fig 7 and contour plots in Fig. 8 for the turbine efficiency show the effects of interaction between flow speed and steering angle on the turbine efficiency under a 61.82 rpm turbine rotation. This figure suggests that the best flow speed in order to achieve the maximum turbine power generation is 1.36 m/sec and the best steering angle is 55.46°. Further increase in flow speed caused turbine power generation to decrease.

The turbine on this research is a turbine model that was observed to get the optimum design. The parameters used in this study are a turbine with a specification as follows:

- Turbine Disc diameter = 11.5 cm.
- Turbine blade number = 8
- With a flow speed variation = 1.7 – 2.2 m/sec
- Steering angle = 30° - 50°
- Turbine rotation = 35rpm – 55rpm.

From the RSM result it is found that the turbine parameters for an optimum turbine power are:

- Optimum turbine power of 5.97 Watts
- With a flow speed = 2.78 m/sec
- Steering angle = 35.75°
- Turbine rotation = 61.82 rpm.

While for the turbine Efficiency; from the RSM result it is found that the turbine parameters for the optimum turbine efficiency are:

- Optimum turbine efficiency of 19.74 %
- With a flow speed = 1.36 m/sec
- Steering angle = 55.46°
- Turbine rotation = 61.82 rpm.

5. Conclusion

Based on the response surface optimization approach then it can be concluded as follows:

- Power turbines; based on three variables, namely: a 35,75º steering angle, the flow speed of 2.78 m/sec and a turbine rotation of 61.82 rpm; the turbine power gained was 5.97 Watts. For the Full Quadratic Model Testing; the turbine power based on the response surface analysis obtained a mathematical model as follows:

  $Y = 4.24 - 0.159X1 + 0.422X2 + 0.720X3 - 0.21X12 - 0.36X22 + 0.058X12 + 0.118X1.X2 - 0.071X1.X3 + 0.141X2.X3.$

- The turbine efficiency; based on three variables, namely: 55,46º steering angle, the flow speed of 1.36 m/sec and a turbine rotation of 61.82 rpm, obtained a turbine efficiency of 19.74%. For the Full Quadratic Model Test; the turbine efficiency based on the response surface analysis obtained a mathematical model as follows:

  $Y = 6.71 + 0.98X1 - 3.99X2 + 1.11X3 - 0.54X12 + 0.68X22 + 0.05X32 - 0.54X1.X2 - 0.13X1.X3 - 0.37X2.X3$

These result values are an ideal result, the values were obtained from a statistical model. So for verifying the optimum turbine parameter any value could be chosen that is not far from the observation result. For example what the team has done is by verifying the result value on another verifying test. The verification turbine test is by running the turbine with a steering angle α of 60°, a turbine rotation of 60 rpm and a water flow speed of 1.4 m/sec.

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