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A VERTICAL AXIS HINGED BLADE KINETIC TURBINE PERFORMANCE USING RESPONSE SURFACE METHODOLOGY

BOEDI, S. D.[1,*], SOENOKO, R.[2], WAHYUDI, S.[2], CHOIRON, M.A.[2]

[1]The Manado State Polytechnic, 95254, Manado, Indonesia
[2]Brawijaya University, Mechanical Engineering Department, 65145, Malang, Indonesia
*Corresponding Author: silvyboedi@gmail.com

Abstract

Untapped water potential was found across Indonesia. Major rivers in Kalimantan and Sumatra, as well as smaller rivers elsewhere in the country contain rich potentials. Generally, there are opportunities to develop kinetic turbines, especially for areas not yet reached by electricity. Response Surface Methodology is a set of mathematical and statistical methods employed to see between one or more variable treatments. This research seeks to examine the performance of vertical axis kinetic turbines used as hinged blade type with Response Surface Methodology. It is expected that from the Response Surface Methodology design, optimisation and equation would be obtained for the kinetic turbine. Using the desirability function analysis approach as the variable combination result, the process produces a minimal response. The optimisation value for the turbine power includes, Maximum Power = 33.9922 Watt, steering angle of = 33.41°, Number of blades = 15.36, X_3, Water flow rate = 48.41 m^3/hours. The optimisation value for turbine efficiency: Maximum efficiency = 68.2998%, the steering angle= 33.41°, Number of blades = 15.36, Water Flow Rate = 48.41 m^3/hour.

Keywords: Kinetic turbines, Hinged blades, Response surface methodology.

1. Introduction

In 2013, the Indonesian population reached about 249.8 million, amounting to around 1.51 % increase per year since 2000. Some 80% of the population live on the Java Island, whereas 54% of them live in urban areas. In 2012, the gross domestic product (GDP) reached 2.619 trillion rupiah (constant 2000 prices), while the rate of GDP growth on average over the last 12 years reached 5.4%. During the same year, the national economic growth reached 6.3% per year, somewhat lower than the growth in 2011 which amounted to 6.5% [1].

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

Most micro power hydro projects in Indonesia are always on the look-out for water with a high potential water fall, and rarely look at low height rivers with a big enough flow speed.

The river water flow has a kinetic energy that can be harnessed to drive water turbines. The water flow turbine often used is the one with horizontal axisas well as those with vertical axis. Turbine with a vertical axis is typically used for small-scale power plants and for power generation applications in remote locations.

Vertical axis turbines can receive the water flow from all directions, but in practice the turbine efficiency is still low.

Kaprawi et al. [2] conducted a research with a turbine configuration combined with two savonius rotor.The observation was conducted on a water flow with constant water speed of 0.8 m/s. The deflector angle was used to direct the water flow. The optimal deflector angle is at 30°, which provide a better performance than the Darrieus-Savonius turbine type. Research conducted to improve the kinetic turbine efficiency is done using a deflector plate to overcome the negative torque to the turbine [3]. The result showed that two deflector plates placed on the optimal upstream position would increase the power coefficient which is 0.35. This is significantly higher than the power coefficient without a plate deflector, which 0.14.

Gorban et al. [4] demonstrated that the three-dimensional helical turbine is more efficient than the two-dimensional propeller turbine, at least in the application of water turbines. In addition, well-documented test has shown that helical turbine has an efficiency of 35 %. Thus, it is better utilised in the free water flow. Studies generally indicate that helical turbine is still in a research development phase, especially kinetic water turbine studies.

A research was recently conducted by Lempoy et al. [5] exploring new sources of renewable energy from a small flow rate water flow (1.7 m^3/hour). From these results the power produced is about 5.55 Watt,with the efficiency of 10.53%. Sornes K. [6] also examines small-scale hydro turbines for applications in the rivers. According to him, small-scale turbines at the moment are highly reliable, as they are environmentally friendly, cost effective, last long and supply electricity in remote areas otherwise not reached.

Also, Soenoko et al [7] has conducted a research by making a two wheel kinetic turbine prototype for the purpose of generating a simple turbine to support the procurement of electrical energy in remote areas. The study reveals that the torque produced by the turbine is much larger than the torque produced by a waterwheel turbine.

Currently, turbine kinetics now uses amoving kinetic turbine blade or hinged blade, some of which have been extensively studied by scholars including Bo Yang et al. [8]. These scholars are conductinga research about the vertical axis kinetic turbine performance with a hinged blade called Hunter. The experiment was conducted by flow visualisation on a small model to provide some basic movements of each blade in every position of the drum. The 2-dimensional CFD simulations are then used to obtain detailed information about the flow field, including pressure and velocity contours and the pressure distribution on the blade surface. Bo Yang and Chris Lawn utilised a semi-circularblade made of steel plate.

Each blade is attached to the shaft using a hinge. Another research is done analysing the zero head cross flow turbine performance with variations in the blade numbers of (12, 6 and 4) and the movement of the blade (hinged blade and fixed blade) [9]. The results showed that the best performance is obtained when the turbine blade is 12, with a number of fixed blade movement. The optimum efficiency of 0.47% was obtained at 89.9 rpm generator rotational speed and generator energy output of 29.25 Watt. Silvy et al. [10] conducted a kinetic turbine with hinged bladeresearch. It can be concluded that the turbine with a hinged blade type has a better efficiency than turbines with fixed blade.In this study, the optimum water turbine efficiency is around 38.15% and generates electricity about 19.92 watts.

Hyosung [11] wrote that RSM allows us to easily modify the function during the optimisation process; it also helps determine the effect of various functions. Although the number of RSM design variables are limited, this method can be a viable tool to optimise the aerodynamic characteristics of wind turbine airfoils. The Response Surface Method is applied to obtain optimum result from the function. Nita et al. [12] examined the performance of the vertical shaft kinetic turbine optimisation by using Response Surface Methodology, and could find that values predicted and observed values for water flow rate, have a similar power input and power output. The predictive efficiency value of 29.46% andthe experimental efficiency of 29.52% were also part of the findings.

This study generally examines the vertical axis kinetic turbine performance using the hinged blade, by implementing the Response Surface Methodology. It is expected that from the Response Surface Methodology draft design optimisation, a more optimum equation could be obtained for the hinged blade kinetic turbine blade performance.

2. Literature Review

According to Montgomery [13], Response Surface Methodology is a set of mathematical and statisticalmethods used to see between one or more variable treatment form with a variable in an experiment.

The relationship between the response Y and the independent variable X is:

$$Y = f(X_1, X_2, ..., X_k) + \varepsilon \quad (1)$$

where: Y = the dependent variable (response), X_i = independent variables / factors (i = 1, 2, 3, ..., k), and ε = error, residual components that are random and identically distributed and independent with normal distribution.

The relationship between the response and the independent variables are generally unknown. The first step in the response surface method is to find a suitable approach to the relationship. If the response can be well modelled in a linear function of the independent variables, then the function approach is the first-order model, and formulated as follows:

$$Y = \beta_0 \sum_{i=1}^{k} \beta_i X_i \quad (2)$$

The first-order experimental design that is appropriate for the factor filter stages are the factorial design 2^k (Two Level Factorial Design). For the second-order model, there is usually a curvature, and a second order polynomial quadratic function is used:

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum\sum_{i<j} \beta_{ij} X_i X_j + \varepsilon \quad (3)$$

The order II experimental design used is a factorial design 3 k (Three Level Factorial Design), which corresponds to an optimisation problem. From the second-order model, a stationary point is then specified, through the response surface characteristic and optimisation model.

3. Research Methods

Kinetic Turbine

Kinetic turbine is a form of turbine which relies on the water flow velocity. This kind of turbine does not require a high water fall. The turbine is more appropriate for flat areas with a river flow, especially rural areas. Currently, there are three types of kinetic turbines, including the flat kinetic turbine, the upright kinetic turbine, and the horizontal kinetic turbine, which is the turbine placed horizontally with the axis placed vertically.

The equipment used in this study is as follows:

1. The Kinetic Turbine Runner

   Three main parts of the runner arethe ST 37 steel shaft with a 30 mm diameter, an acrylic material disc with a diameter of 355 mm and 8 bladesof 4 mm thickness and 10 cm height, which is mounted around the disc and move on hinges mounted on the outer diameter of the disc.

2. Flow steering angle blade, where the water flow rate is arranged. The dependent variable observed in this study is turbine power and the turbine efficiency.

In this study, there are three different kinetic turbines with a blade number variation of 10 blades turbine, 12 blades turbine and 14 blades turbine. Every turbine was tested under three kinds of steering angle variations, which are the 20, 25 and 30 steering angles. Every steering angle variation was also tested with three kinds of water flow rate variation, which is the 35, 40, 45 m^3/h, such that for every turbine type there could be nine data available. This indicates that, the whole research with three types of turbines would give 27 data. Every data was repeated three times, amounting to about 81 data for the whole research carried out. The kinetic turbine with a 10 blade number variation turbine is seen in Fig. 1

The objective of this research, by measuring every type of turbine, is to get the turbine specification with the best performance. The turbine blade number, the water steering angle, and the water flow rate are generally the main parameters which should appear in designing every kind of turbine. Thus, if a turbine designer desires to get an optimal kinetic turbine, these three parameters should be minimally considered first. The challenge is how to solve an optimisation problem with three variables,as these three respective variables are somewhat complicated. Therefore, the Response Surface Methodology (RSM) is relied upon as the optimisation measure for this research. This RSM could help the 9 variables to get the best turbine blade number, the best steering angle, and the optimal water flow rate.

To obtain the relevant data to be processed in the RSM system, the turbine was run under the variables mentioned above.

The turbine research installation for the observation is seen in Fig. 2.

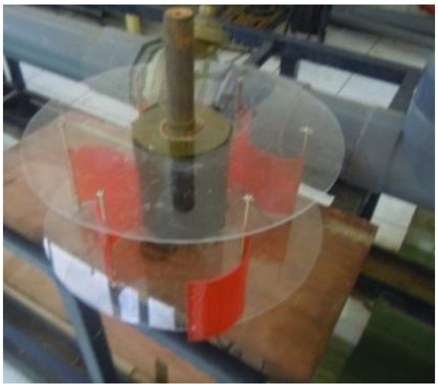


Fig. 1. Hinged blade kinetic turbine.

Fig. 2. Research installation.

Kinetic Turbine Power

The energy amount produced by a stream is determined by the water head and the water flow rate.

$$E_a = \frac{1}{2} . \dot{m} . x^2 \quad (4)$$

where E_a = Water energy (N.m) or (Joule), $\dot{m}$ = Water mass flowrate (kg/s), and V = Water flow velocity (m/s)

Water power flowing in a certain cross section could be calculated by utilising the following formulas:

$$P_a = \frac{1}{2} . \rho . A . V^2 \quad (5)$$

where P_a = Water power (watt), and ρ= Water density (kg/m^3).

To calculate the turbine generated power due to the kinetic energy used

$$P_t = T . \omega \quad (6)$$

$$T = F . l \quad (7)$$

$$\omega = \frac{2.\pi.n}{60} \quad (8)$$

where P_t = Turbine power (watt), T = Torque (Nm), l = arm length (m), n = Turbine shaft rotation (rpm), and F = Force (N).

Kinetic Turbine Efficiency

Kinetic turbine efficiency is determined by the ratio between theincoming water turbine powers to the amount of power generated by the kinetic turbine, as shown in:

$$\eta = \frac{P_t}{P_a} \text{ x } 100 \ \% \quad (9)$$

where η = Turbine efficiency (%).

4. Experimental Design

To obtain a first-order and second-order empirical model, firstly, a 2^k factorial experimental design coupled with several observations at the central point and the points in the axial axis with α = 2k/4 in the form of Central Composite Design (CCD) was performed.

The 2^k factorial design of the CCD was used for the experiments consisting of k factorials, while each factor has a low level, coded as -1, +1 coded for the high level, 0 coded for the middle level, and the middle level is coded as -α and + α. For k = 3, with α value = 1.682 [14]. Table 1 shows the second order experimental design for k = 3 with CCD.

Based on Table 1, an experimental CCD was designed with parameters used for the study variables. In this study, there are two kinds of variables, namely the independent variable and the response variable. The turbine performance parameters of independent variables used in this study are:

- Steering angle steering : 20°, 25° and 30°
- Blade number : 10 blades, 12 blades and 14 blades
- Water flow rate : 35 m^3/h, 40 m^3/h and 45 m^3/h

In accordance with the independent variables used, the specified independent variable level was chosen, as shown in Table 2.

Table 1.Second order experimental design for k = 3 with CCD.

No.	X_1	X_2	X_3	No.	X_1	X_2	X_3
1	-1	-1	-1	11	0	-1.682	0
2	1	-1	-1	12	0	1.682	0
3	-1	1	-1	13	0	0	-1.682
4	1	1	-1	14	0	0	1.682
5	-1	-1	1	15	0	0	0
6	1	-1	1	16	0	0	0
7	-1	1	1	17	0	0	0
8	1	1	1	18	0	0	0
9	-1.682	0	0	19	0	0	0
10	1.682	0	0	20	0	0	0

Table 2. Independent variable level.

Variable Name	Steering Angle (°)	Blade Number	Water Flow rate (m^3/hour)
Low Level (-1)	20	10	35
Middle Level (0)	25	12	40
High Level (+1)	30	14	45

The response variable is the dependent variable. This variable is influenced by the factor level or the factors combination. The response variable in this study is the turbine power and the turbine efficiency.

5. Results and Discussion

The research variables are specified, while the resulting experimental design is shown in Table 3.

The study design in Table 3 was analysed by using MINITAB 16 and obtained the following results:

Normality test is done to demonstrate the model adequacy. Three main steps were undertaken in the residual analysis, namely checking the residuals normality, making the plot reflect estimated residual response, and making a plot between the residual and the other. The data residual normality test value of the turbine power is shown in Fig. 3.

Figure 3 gives the output information, including the average and the residual standard deviation respectively -1.37945x10 -15 and 0.2255. The average residual is very small because it is close to zero.

Table 3. Experimental research design.

No.	Independent variable			Response variable	
	Steering Angle (°)	Blade Number	Flow rate (m^3/hour)	Turbine Power (Watt)	Turbine Efficiency (%)
1	20	10	35	9.54	29.08
2	30	10	35	12.69	38.69
3	20	14	35	11.77	35.86
4	30	14	35	16.46	48.39
5	20	10	45	11.29	17.13
6	30	10	45	17.52	26.59
7	20	14	45	14.25	21.62
8	30	14	45	22.28	33.82
9	16.59	12	40	8.52	18.78
10	33.41	12	40	18.08	39.86
11	25	8.64	40	10.29	22.69
12	25	15.36	40	15.00	33.08
13	25	12	31.59	12.78	38.95
14	25	12	48.4	20.32	24.49
15	25	12	40	11.72	25.84
16	25	12	40	11.84	26.10
17	25	12	40	11.78	25.97
18	25	12	40	11.95	26.36
19	25	12	40	11.84	26.10
20	25	12	40	11.72	25.84

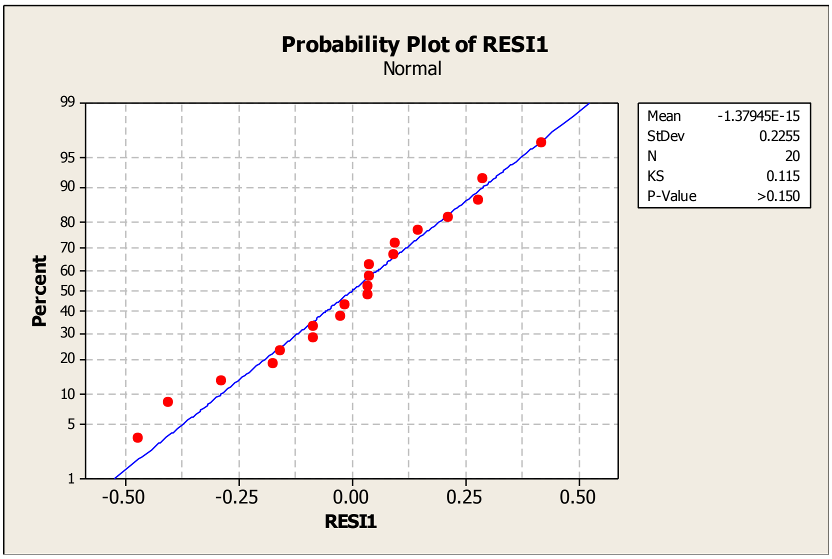


Fig. 3. Residual normality test response surface models.

Determination coefficient test (R^2)

Based on Tables 4 and 5, the total variation percentage can be explained by the R^2 model of 99.61% for the turbine power, and 97.64% for the turbine efficiency. This value is quite large, which means that the predicted second-order polynomial models are predicted fulfilled.

Table 4. Turbine power regression.

Turbine Power Estimated Regression Coefficients				
Term	**Coefficient**	**SE Coefficient**	**T**	**P**
Constant	11.8030	0.12678	93.094	0.000
Steering Angle	2.7955	0.08412	33.233	0.000
Blade Number	1.5849	0.08412	18.841	0.000
Water Flow Rate	2.0181	0.08412	23.991	0.000
Steering Angle*Steering Angle	0.5626	0.08189	6.870	0.000
Blade Number *Blade Number	0.3313	0.08189	4.046	0.002
Water Flow Rate*Water Flow Rate	1.7116	0.08189	20.902	0.000
Steering Angle*Blade Number	0.4175	0.10991	3.799	0.003
Steering Angle*Water Flow Rate	0.8025	0.10991	7.302	0.000
Blade Number*Water Flow Rate	0.2150	0.10991	1.956	0.079
S = 0,310863	PRESS = 7,11316			
R^2 = 99,61%	R^2 (pred) = 97,15%	R^2 (adj) = 99,26%		

Table 5. Turbine efficiency regression.

Turbine Efficiency Estimated Regression Coefficients				
Term	**Coefficient**	**SE Coefficient**	**T**	**P**
Constant	25.9854	0.6838	38.000	0.000
Steering Angle	5.8031	0.4537	12.790	0.000
Blade Number	3.3444	0.4537	7.371	0.000
Water Flow Rate	-5.6513	0.4537	-12.456	0.000
Steering Angle*Steering Angle	1.4838	0.4417	3.364	0.007
Blade Number *Blade Number	0.9784	0.4417	2.215	0.051
Water Flow Rate*Water Flow Rate	2.3343	0.4417	5.285	0.000
Steering Angle*Blade Number	0.7075	0.5928	1.193	0.260
Steering Angle*Water Flow Rate	-0.0600	0.5928	-0.101	0.921
Blade Number*Water Flow Rate	-0.5950	0.5928	-1.004	0.339
S = 1,67668	PRESS = 211,998			
R^2 = 97,64%	R^2 (pred) = 82,20%	R^2 (adj) = 95,52%		

Empirical model of the power turbine's average value and the turbine efficiency based on the response analysis method can be formulated as follows:

Turbine power:

$$Y = 11,803 + 2,796(X_1) + 1,585(X_2) + 2,018(X_3) + 0,563(X_1)^2 + 0,331(X_2)^2 + 1,712(X_3)^2 + 0,418(X_1)(X_2) + 0,803 (X_1)(X_3) + 0,215(X_2)(X_3)$$

Turbine efficiency:

$$Y = 25,985 + 5,803(X_1) + 3,344(X_2) – 5,651(X_3) + 1,486(X_1)^2 +0,978(X_2)^2 + 2,334(X_3)^2 + 0,708(X_1)(X_2) - 0,060 (X_1)(X_3) - 0,595(X_2)(X_3)$$

Based on the mathematical model obtained, it can be seen that the third independent variable is the steering angle, the blade number, and the water flow rate, creating an effect on the turbine power and turbine efficiency value.

Contour plots and surface plots

The response surface analysis results would demonstrate the turbine power and turbine efficiency contour in Figs. 4 and 5, and the surface plot of the power turbine and turbine efficiency value is shown in Figs. 6 and 7.

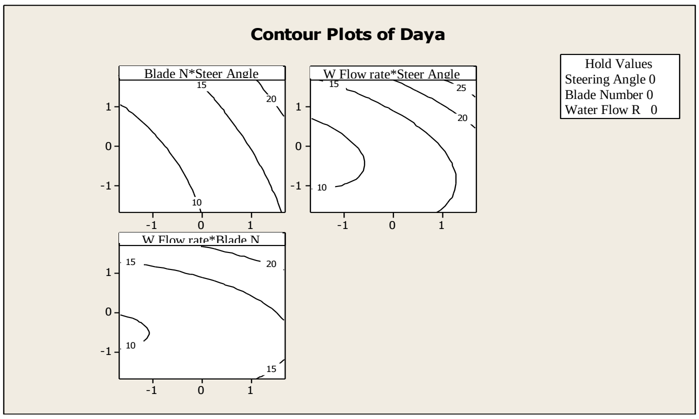


Fig. 4. Turbine power contour plot.

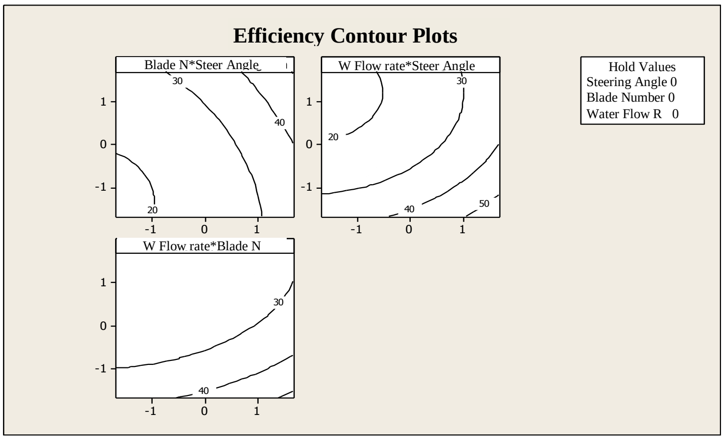
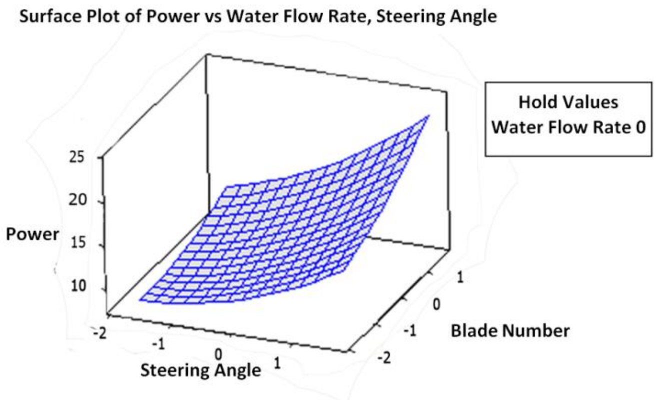
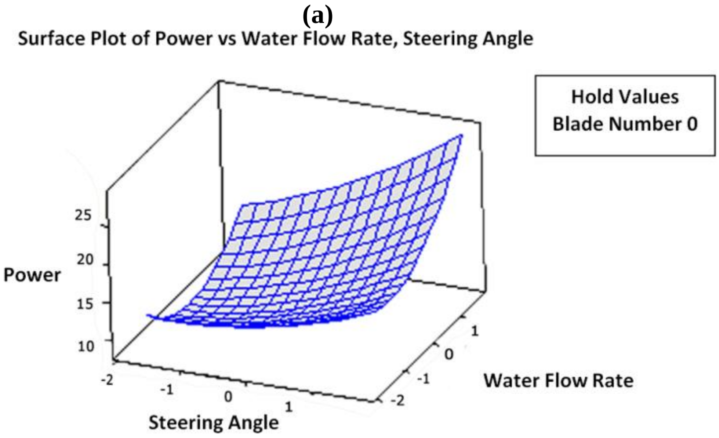


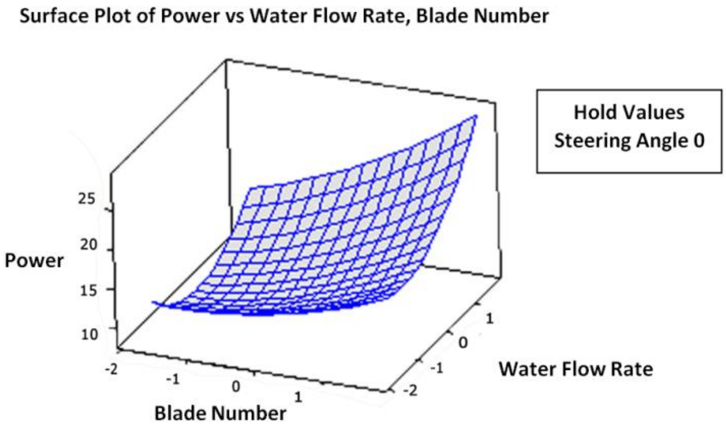
Fig. 5. Turbine efficiency contour plot.



(a)

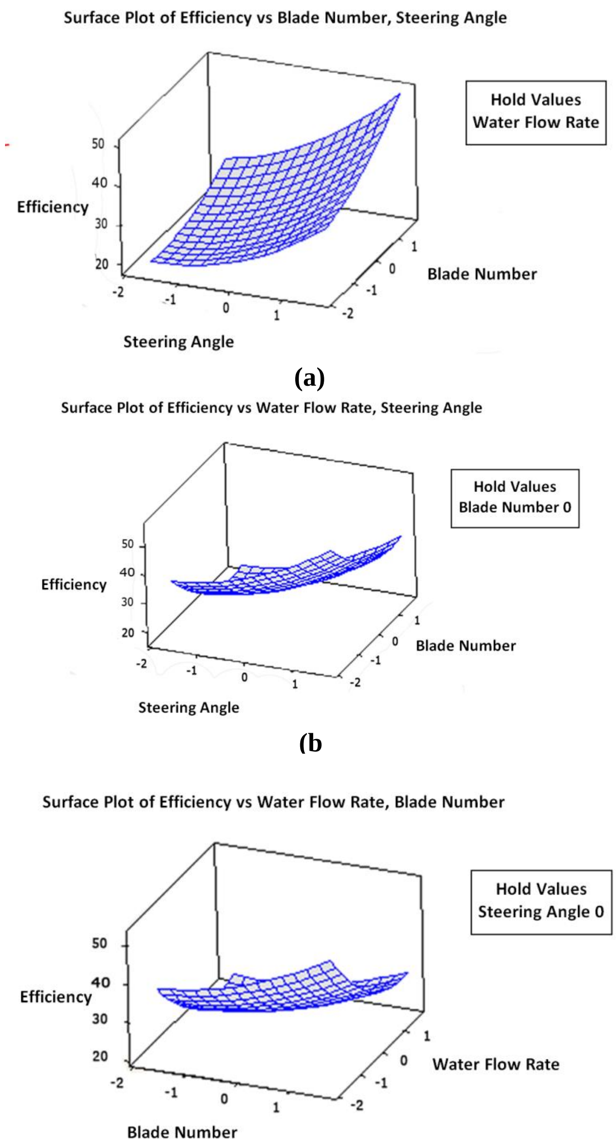


(b)



(c)

Fig. 6. Turbine power surface plot.



(c)

Fig. 7. Turbine efficiency surface plot.

The desirability function approach analysis

To analyse the desirability function approach, the first step was to enter the response limit value. The criteria used are ‘the smaller the better’. The target to be achieved is that, the power turbine and turbine efficiency value is almost the same. Analysis desirability function as a result of process variables combination which produce minimal responses are shown in Table 6 and Table 8, the desirability function approach analysis is seen in Table 7, while Table 9 presents the response optimisation level.

Table 6. The turbine power desirability function approach analysis.

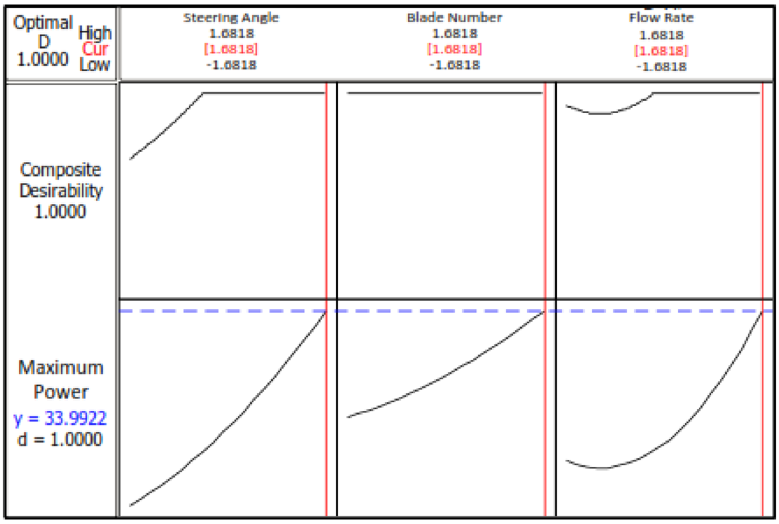


Table 7. Turbine power response optimization.

Response Optimization					
Parameters					
Goal	Lower	Target	Upper	Weight	Import
Max. Eff.	8.52	22.28	22.28	1	1
Global Solution					
Steering Angle	= 1.68179				
Blade number	= 1.68179				
Water Flow Rate	= 1.68179				
Prediction Responses					
Efficiency	= 33.9922				
Desirability	1				

Table 8. Turbine efficiency desirability function approach analysis.

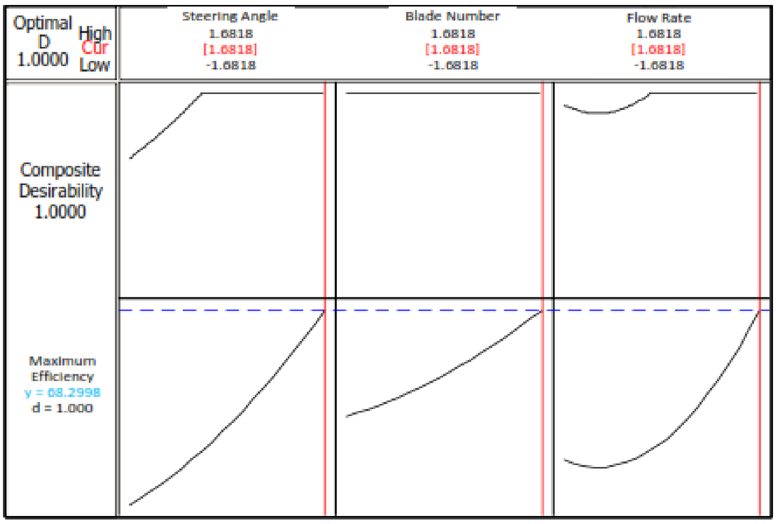


Table 9. Turbine efficiency response optimization.

Response Optimization					
Parameters					
Goal	Lower	Target	Upper	Weight	Import
Max. Eff.	17.31	48.39	48.39	1	1
Global Solution					
Steering Angle	= 1.68179				
Blade number	= 1.68179				
Water Flow Rate	= -1.68179				
Prediction Responses					
Efficiency	= 68.2998				
Desirability	1				

As mentioned above, this study sets out to test three different kinetic turbines with 10, 12 and 14 turbine blade numbers. Every turbine type was tested under three kind of steering angle variations, including 20°, 25° and 30° steering angle. Every steering angle variation was also tested with three kind of water flow rate variation, at 35, 40, 45 m^3/h.

Based on tables 6 and table 7, the desirability function value of 1.000 suggests that the lowest desired value has been reached. From Tables 8 and 9, a maximum turbine power represented by Y on the first RSM equation was obtained. The steering angle was represented by X_1, turbine blade number was represented by X_2, and water flow rate was represented by X_3.On the second RSM equation, Y represents the turbine efficiency.

6. Conclusion

Results from the response surface optimisation approach and mathematical models obtained from the turbine power and turbine efficiency prediction value are as follows:

Turbine power:

$$Y = 11{,}803 + 2{,}796(X_1) + 1{,}585(X_2) + 2{,}018(X_3) + 0{,}563(X_1)^2 + 0{,}331(X_2)^2 + 1{,}712(X_3)^2 + 0{,}418(X_1)(X_2) + 0{,}803\,(X_1)(X_3) + 0{,}215(X_2)(X_3)$$

The turbine efficiency:

$$Y = 25{,}985 + 5{,}803(X_1) + 3{,}344(X_2) - 5{,}651(X_3) + 1{,}486(X_1)^2 + 0{,}978(X_2)^2 + 2{,}334(X_3)^2 + 0{,}708(X_1)(X_2) - 0{,}060\,(X_1)(X_3) - 0{,}595(X_2)(X_3)$$

Based on the desirability function approach, and giventhat the combination of the variable process resulted in minimal responses, it is found that the maximum turbine power is 33,9922 Watt; the best steering angle is 33,41°; while the turbine efficiency is 68,2998 %. The best water flow rate is estimated to be 48,41 m^3/jam, and the blade number is 15.36. From the RSM result, to verify the real turbine specification, a blade number of 15, a water flow rate of 50 m^3/hour, and finally steering angle of 30° should be utilised.

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