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OPTIMIZATION OF NOZZLE INLET ANGLE AND WHEEL DIAMETER OF A PORTABLE MINI-STEAM IMPULSE TURBINE FOR DOMESTIC ELECTRICITY GENERATION USING TAGUCHI DESIGN AND RSM APPROACH

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ABSTRACT

This study seeks to determine a portable mini stream turbine's optimum nozzle angle and wheel diameter at a constant loss velocity. Taguchi Design and Response Surface methodology (RSM) was utilized for the optimization. A theoretical computational value obtained for a steam generator (boiler) output to the turbine, at a steam of pressure 15bar, velocity of 115m/s, outlet temperature of 250℃ and mass flow rate of 0.25kg/s, within a range of 120-200rpm to generate electric power output. The results predicted a power output optimum value of 125.58 watts at a turbine wheel diameter of 0.24 m and nozzle inlet angle of 15° with a constant loss velocity of 0.85 using Taguchi design and RSM. It was observed that the optimum power output could depend on the efficiency of the jet of steam impinging on the turbine blades and turbine wheel diameter.

KEYWORDS: Nozzle Inlet angle, Turbine Wheel Diameter, mini-turbine, Taguchi Design, RSM.

1.0 INTRODUCTION

In turbines, rotary motion is obtained from the gradual change in the steam jet's momentum, which is referred to as prime movers. The rotary motion of the turbine depends on the impact velocity and pressure of the steam jet from the boiler. Utilizing the rotary motion (Mechanical work), electricity could be generated by connecting the turbine to a generator (Alternator) through a shaft.[1] The velocity of the steam jet from the nozzle of the boiler determines the force exerted on the turbine blades and the turbine wheel's rotary motion.[2-3] Attempts has been made by several researchers on the development of Impulse turbine. For instance,[4] studied a 1.5 kW single-stage partial-admission impulse turbine designed for waste heat recovery of internal combustion engines and analyzed the aerodynamic characteristics of the designed supersonic impulse turbine using a 3D CFD simulation and they found that the mean velocity and the Mach number at the nozzle outlet were 1082.87 m/s and 2.645, respectively and a high load could be generated on the blades.[5–9] studied the design and optimization of small-scale subsonic radial inflow and axial turbines with a power output of 5–10 kW. They observed that the maximum efficiency could exceeded 85%. Relatedly, Steam turbine analysis, development and optimization have been studied by.[10-24] In this work attempt is made to optimize a miniature Impulse stream turbine nozzle inlet angle and wheel diameter for maximum power generation.

2.0 METHODOLOGY

2.1 Design considerations for the Impulse Turbine Runner and Blades

The following assumption was made;

i. The turbine blade is symmetrical, that is, the inlet angle and outline angle are equal.
ii. There is a loss of velocity of 0.85 (Khurmi and Gupta, 2000).
iii. Revolution per minute (rpm) of the alternator and turbine are equal.

Minitab software was utilized for the Taguchi method and response surface method (RSM) for the design of the experiment (DOE);

2.2 Optimization of turbine wheel blade design

This work considered two design optimization methods, Taguchi Design and Response Surface Methodology (RSM) to determine the optimum power output for a mini-steam turbine capable to generate electricity for domestic consumption. The factors considered in the design and optimization of the turbine power output are the nozzle inlet angle, diameter of the turbine wheels and the loss velocity.

2.2.1 Taguchi design method

i. Identification of the main factors

The controllable input factors are nozzle inlet angle and diameter of turbine wheel and uncontrollable factor- the noise factors is the loss velocity.

ii. Identification of the objective factors

The response factor, that is the factor to be optimized is power and the objective function is given as "larger the better", the signal to noise ratio for this function is given as

$$S/N = -10 log \sum \frac{1/y^2}{n} \qquad (1)$$

where Y= responses for the given factor level which represents the power output in that run and *n* represents the sample size.

iii. Identification of the control factors levels

The levels of the factors are shown in table 1.

Table 1: Selected Factors (Controllable factors) and Levels.

Factors	**Levels**				
	1	**2**	**3**	**4**	**5**
Nozzle inlet angle(°)	15.00	18.75	22.50	26.25	30.00
Diameter of turbine wheel (m)	0.20	0.21	0.22	0.23	0.24

For the steam turbine wheel design, frictional factor or loss velocity k, is assumed to be 0.85. Taguchi design and orthogonal array is generated in tables 2 and 3.

Table 2: Shows the orthogonal array.

Experiment No.	**Diameter of wheel (m)**	**Nozzle Inlet angle (°)**	**Loss of velocity (k)**
1	1	1	1
2	1	2	1
3	1	3	1
4	1	4	1
5	1	5	1
6	2	1	1
7	2	2	1
8	2	3	1
9	2	4	1
10	2	5	1
11	3	1	1
12	3	2	1
13	3	3	1

14	3	4	1
15	3	5	1
16	4	1	1
17	4	2	1
18	4	3	1
19	4	4	1
20	4	5	1
21	5	1	1
22	5	2	1
23	5	3	1
24	5	4	1
25	5	5	1

Table 3: Showing the orthogonal array with levels replaced by actual values.

Experiment No.	Diameter of wheel	Nozzle inlet angle (°)	Loss of velocity
1	0.200	15.00	0.850
2	0.200	18.75	0.850
3	0.200	22.50	0.850
4	0.200	26.25	0.850
5	0.200	30.00	0.850
6	0.210	15.00	0.850
7	0.210	18.75	0.850
8	0.210	22.50	0.850
9	0.210	26.25	0.850
10	0.210	30.00	0.850
11	0.220	15.00	0.850
12	0.220	18.75	0.850
13	0.220	22.50	0.850
14	0.220	26.25	0.850
15	0.220	30.00	0.850
16	0.230	15.00	0.850
17	0.230	18.75	0.850
18	0.230	22.50	0.850
19	0.230	26.25	0.850
20	0.230	30.00	0.850
21	0.240	15.00	0.850
22	0.240	18.75	0.850
23	0.240	22.50	0.850
24	0.240	26.25	0.850
25	0.240	30.00	0.850

Experimental method in[1] was obtained the value of power output for the Taguchi design and RSM, as shown in table 4.

Table 4: Shows the orthogonal Array and Result of power for each experiment.

Diameter of wheel(m)	Nozzle inlet angle(°)	loss velocity	Power(Watts)
1	1	0.85	105.5712
1	2	0.85	103.4551
1	3	0.85	100.8874
1	4	0.85	97.87896
1	5	0.85	94.4427
2	1	0.85	110.7432
2	2	0.85	108.5214
2	3	0.85	105.8253
2	4	0.85	102.6664
2	5	0.85	99.05833
3	1	0.85	115.9051
3	2	0.85	113.5775
3	3	0.85	119.7329
3	4	0.85	107.4437
3	5	0.85	103.6638
4	1	0.85	121.0569
4	2	0.85	118.6234
4	3	0.85	115.6705
4	4	0.85	112.2108
4	5	0.85	108.2591
5	1	0.85	126.1985
5	2	0.85	123.6593
5	3	0.85	120.578
5	4	0.85	116.9679
5	5	0.85	112.8443

2.2.2. Response surface method (RSM)

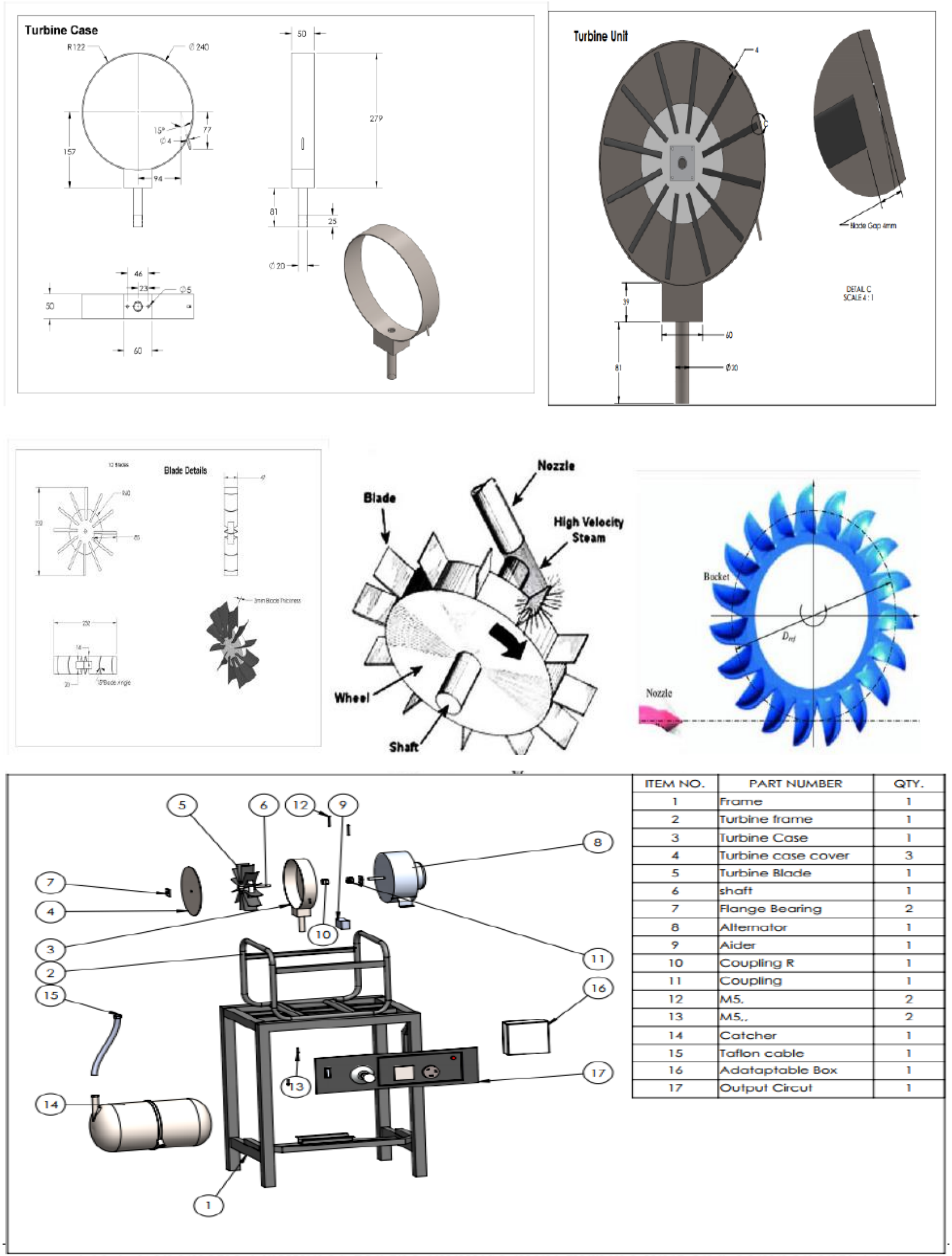
Response Surface Methodology (RSM) is useful for the modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response.[25] and could be expressed in this form;

$y = f(x_1, x_2) + \varepsilon$

The variables x_1 and x_2 are independent variables where the response y depends on them and the experimental error term, denoted as ε. The error term ε represents any measurement error on the response, as well as other type of variations not counted in f. The response is assumed to be a linear function of independent variables, hence, the approximating function as a first-order model. A first-order model with 2 independent variables can be expressed as;

$Y = aX_1 + bX_2 + c\, X_1, X_2 \ldots\ldots + \varepsilon.$

Where a, b, c are coefficients and X_1, X_2 are nozzle inlet angle and diameter of turbine wheel, respectively; and the response variable Y is the power output. The schematic drawings for the impulse mini-turbine components are shown in figure 1.



ITEM NO.	PART NUMBER	QTY.
1	Frame	1
2	Turbine frame	1
3	Turbine Case	1
4	Turbine case cover	3
5	Turbine Blade	1
6	shaft	1
7	Flange Bearing	2
8	Alternator	1
9	Aider	1
10	Coupling R	1
11	Coupling	1
12	M5.	2
13	M5,,	2
14	Catcher	1
15	Taflon cable	1
16	Adatptable Box	1
17	Output Circut	1

Fig: Schematic Drawings for the impulse mini turbine unit and components.[1]

3.0 RESULTS AND DISCUSSION

3.1 Results of taguchi method

To optimize the power output condition, the factors with the highest signal to noise ratio were chosen. The linear graphs in Figures 2 and 3 show the optimum values for the nozzle angle and diameter of wheel as given in table 5;

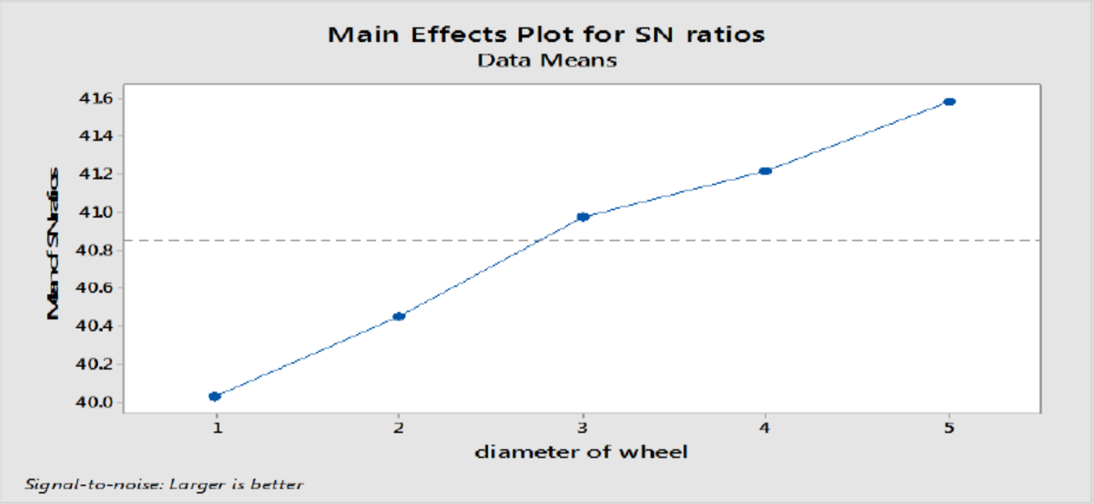


Fig. 2: Plot showing the parameter level for diameter of wheel versus S/N ratio.

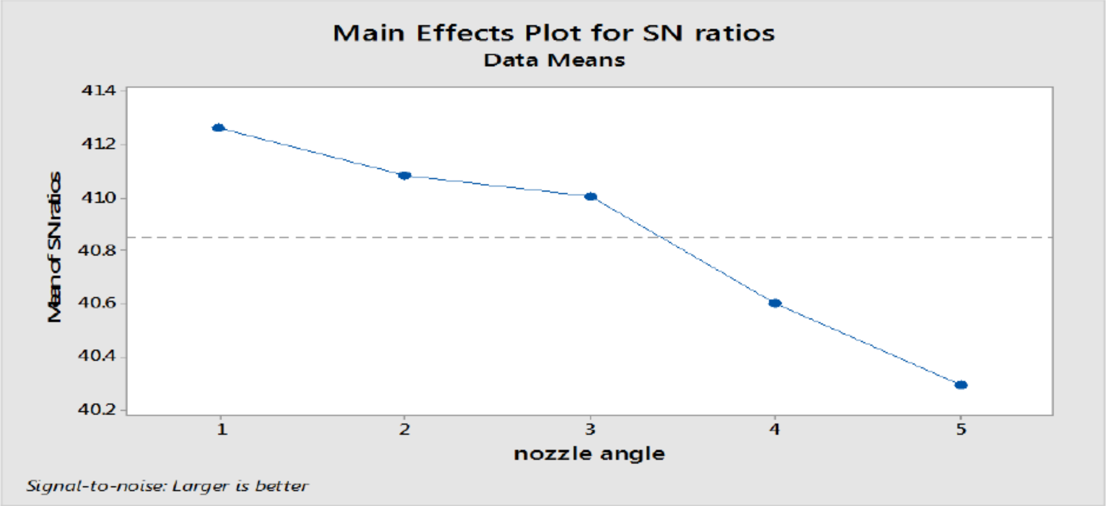


Fig. 3: Plot showing the parameter levels for nozzle angle versus S/N ratio.

To optimize the power output condition, the factors with the highest signal-to-noise ratio were chosen. The linear graphs in figures 2 and 3 show the optimum values of the factors and their levels as given in tables 5 and 6.

Table 5: Response table for signal to noise ratios larger is better.

Experiment levels	Signal-noise (S/N) ratio for power versus nozzle angle	Signal-noise (S/N) ratio for power versus diameter of turbine wheel
1	41.26	40.03
2	41.09	40.45
3	41.00	40.98
4	40.61	41.22
5	40.29	41.58

Table 6: Shows Optimum values of factors and their levels.

Parameter	Optimum values
Nozzle angle (°)	15.00
Wheel diameter (m)	24.00

Results of Response surface method (RSM)

From the RSM optimization response as shown in figure 4 and table 7, the optimum power output is 125.58 watts, at a nozzle angle and turbine wheel diameter of 15° and 0.24m, respectively, with a constant loss velocity of 0.85. The regression expression is;

Power = 114 + + $0.82X_1 + 0.51X_2 - 0.12X_1X_2$

Where, x_1= nozzle inlet angle, x_2 = diameter of wheel

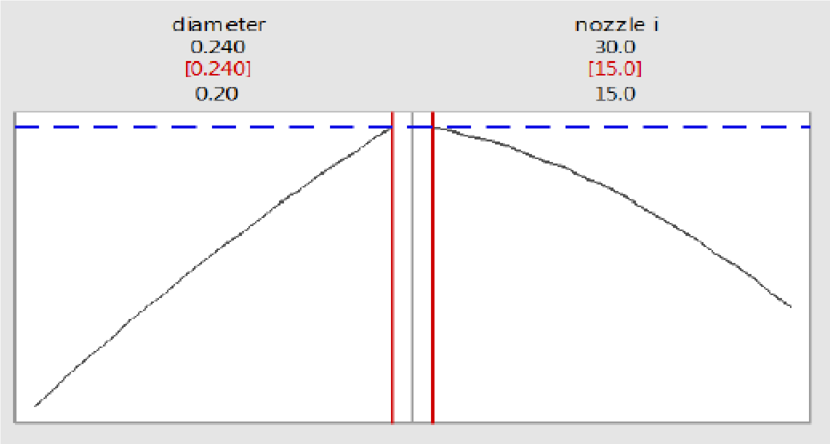


Fig. 4: Shows the optimization plot.

Table 7: Response (Power) optimization.

Parameters
Response goal lower target upper weight importance
Power (watt) Maximum 94.4427 126.199 1 1

Solution
Nozzle
Solution diameter of wheel inlet angle power fit composite desirability
1 0.24 15 125.578 0.980469
Multiple response prediction
Variable Setting
Diameter of wheel 0.24
Nozzle inlet angle 15

Response Fit SE Fit 95% CI 95% PI
Power(watt) 125.58 1.30 (122.85, 128.31) (120.76, 130.39)

Where; PI = prediction interval CI = confidence interval

The Contour plot in Figure 5 is the simple view of the input variables and response surface in two-dimensional graphs. From the top left side of the contour plot is the movement from a dark blue colour to a dark green colour and from the key at the right top corner of the chart, for a power output above 125 watts, the region indicated by the dark green should be used for design; this region from the chart shows that nozzle inlet angle should be 15° and turbine wheel diameter should be 0.24m.

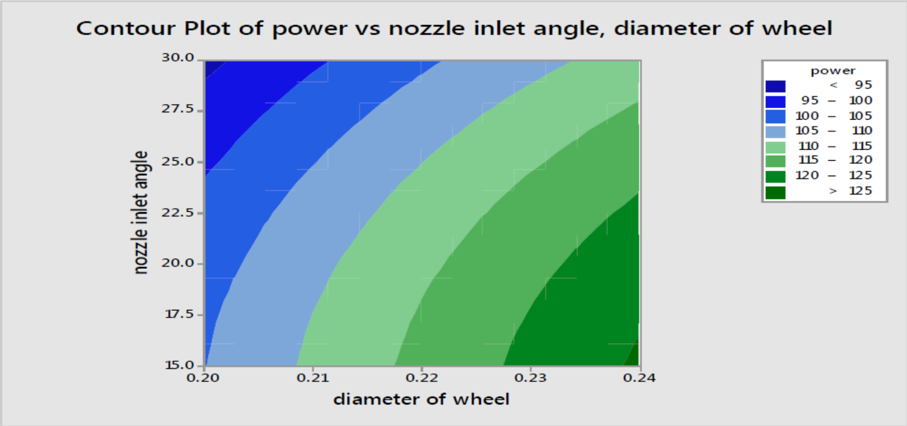


Fig. 5: Shows the contour plot for power versus nozzle inlet Angle and Diameter of wheel.

With the theoretical design parameters and conditions obtained in,[1] in the modelling of a mini steam turbine system for a steam pressure of 15 bar, steam velocity of 115 m/s, steam mass flowrate of 0.25kg/s, steam inlet temperature of 250℃, and rpm of the alternator in range of 120 to 200rpm, the Taguchi design and RSM predicted that power output would be 125.58 at an optimal Nozzle inlet angle of 15° and turbine wheel diameter of 0.24m with a constant loss velocity of 0.85.

CONCLUSION

This study optimized a portable single-stage De Laval Impulse steam turbine with an AC generator (alternator) capable of generating electricity[1] using Taguchi Design and Response Surface Methodology RSM for efficient power output. It was observed that a steam pressure of 15 bar, steam velocity of 115 m/s, steam mass flowrate of 0.25kg/s, steam inlet temperature of 250℃, and rpm of alternator of range 120-200rpm, the results from the Taguchi design and RSM could predict a power output optimum value of 125.58 at a Nozzle inlet angle of 15° and turbine wheel diameter of 0.24m with a constant loss of velocity k of 0.85.

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