Nigerian Journal of Engineering Science Research (NIJESR).
Vol. 4, Issue 4, pp.01-11, December, 2021
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ISSN: 2636-7114
Journal Homepage: https://nijesr.iuokada.edu.ng/

Performance Evaluation of Industrial Pumps using Design Experts Analysis

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Manuscript History
Received: 09/05/2025
Revised: 17/06/2025
Accepted: 25/06/2025
Published: 20/07/2025
https://doi.org/10.5281/zenodo.16339816

Abstract: *Industrial Centrifugal pumps play a critical role in oil and gas industries by ensuring efficient fluid transport under varying operational conditions. Optimizing the volume, temperature, and pressure of these pumps enhances performance, reduces energy consumption, and minimizes wear and tear, leading to improved reliability and cost-effectiveness. This study explores optimization strategies using design experts analysis to achieve optimal operating conditions. Key parameters such as hourly flow rate, operating temperature and pressure are analyzed. The results demonstrate that precise control of these variables enhances pump lifespan, reduces maintenance costs, and improves overall system efficiency. The analysis result suggested 250 psi (inlet pressure), 260psi (delivery pressure), 245.1* m^3/h *(hourly rate) and 201.36 ℃ (temperature) as the optimized working parameters of the pump. Adopting this finding can significantly optimize pump performance in oil and gas applications.*

Keywords: Centrifugal Pump, Optimization, Hourly Rate, Volume, Temperature

INTRODUCTION

Centrifugal pumps are widely used in industries such as water treatment, Oil and Gas, chemical processing, and power generation due to their efficiency in fluid transportation. Their performance is governed by key parameters, including flow rate (volume), operating temperature, and pressure, all of which influence efficiency, reliability, and energy consumption (Gjetaj *et al.,* 2025). Optimizing these parameters is essential for improving operational efficiency, minimizing energy losses, and extending pump lifespan. Temperature variations affect fluid viscosity and pump material expansion, influencing overall efficiency (SAE, 2022). Similarly, pressure fluctuations can lead to cavitation, reducing pump performance and causing mechanical wear (IJCRT, 2018). Flow rate optimization ensures that the pump operates within its best efficiency point (BEP), reducing unnecessary energy consumption (JSTAGE, 2022). This research analysed the interdependencies between volumes, temperature, and pressure to develop optimization strategies for centrifugal pump performance. Robertson, M. (2013) carried out the thermodynamic method of pump testing, which measures temperature rise, power consumption, and differential pressure to determine pump efficiency.

Developed in the early 1960s, this method is capable of achieving results with uncertainties of less than 1% in pump efficiency and less than 1.5% in flow, making it applicable in various industrial settings. Zhang, *et al*., (2022) applied entropy generation theory to analyse energy losses in centrifugal pumps. By utilizing a particle swarm optimization algorithm, the research identifies optimal impeller designs that reduce entropy generation by 5.41% and increase efficiency by 3.89%. Almasi, (2023) investigated the impact of decentralized systems and variable-speed drives on centrifugal pump pressure optimization. He highlighted the benefits of variable-speed drives in managing pressure zones and reducing power consumption in pump systems. Liu *et al*. (2023) used a combination of Detached Eddy Simulation (DES) and cavitation models to optimize the performance of centrifugal pumps and understand the unsteady cavitation flow fields in pumps. Their research explores how cavitation interacts with turbulence and how energy loss concentrates in key areas like the impeller and volute, leading to performance deterioration under cavitating conditions. Chen & Yan (2023) scrutinised the impact of labyrinth seals on wear-ring clearance in centrifugal pumps (https://link.springer.com). They explored how different wear-ring structures, such as labyrinth seals, enhanced overall efficiency and reduced hydraulic losses. Nguyen & Vo (2023) carried out works on optimization strategies in centrifugal pump design using AI and CFD analysis. They examined AI-integrated CFD analysis for pump optimization, revealing enhanced designs that improve flow rate, temperature control, and pressure stability. Popela, (2023) did an optimization of pumping system design and performance using stochastic modelling. He addressed the integration of optimization techniques for managing pressure and flow variability in high-demand settings. Shi, *et al*. (2023) analysed centrifugal pump energy performance under fluctuating flow rates. The authors proposed methods to minimize energy losses during variable flow conditions, with a focus on temperature rise management. Zheng & Li (2023) carried out an interesting work on efficiency improvements through optimized impeller design in multistage pumps. They examined the influence of impeller design on pump performance, focusing on flow rate stabilization and reduced temperature rise. This study aims at optimizing the volume, temperature, and pressure of centrifugal pumps in a bid to enhance performance, reduces energy consumption and minimizes wear and tear, leading to improved reliability and cost-effectiveness. More so, the approach has not been adopted by the existing researchers in the Oil and Gas Industry.

MATERIALS AND METHODS

The method employed in this research is the utilization and comparison of simulation results of expert design model with field readings recorded from a particular pump in operation in order to predict failures and suggest maintenance routine for the pump while in operations.

2.1 Description of the Centrifugal Pump

This is a mechanical device that transports fluids by the conversion of rotational kinetic energy to the hydrodynamic energy of the fluid flow. In the Oil and Gas Industry, centrifugal pumps are used in three (3) major areas as follows:

Upstream (Exploration & Production)

i. Drilling operations: Mud pumps circulate drilling fluids Well stimulation: High-pressure pumps inject water, steam, or chemicals.
ii. Artificial lift systems: ESPs or gas lift pumps increase oil flow from reservoirs.
iii. Produced water handling: Pumps transfer water separated from crude oil.

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Midstream (Transportation & Storage)

i. Pipeline boosting stations: Maintain pressure and flow over long distances.
ii. Storage facilities: Loading and unloading crude or refined products.
iii. Liquefied Natural Gas (LNG) operations: Cryogenic pumps handle liquefied natural gas.

Downstream (Refining & Distribution)

i. Process pumps: Handle chemicals and hydrocarbons in refining units.
ii. Utility pumps: Circulate steam, cooling water, etc.
iii. Fuel transfer pumps: In terminals and gas stations.

Fig. 1 Installed Centrifugal pumps (in series) in the wastewater treatment plant (WRPC, 2025)

Industry Standards and Certifications of Centrifugal Pumps are listed hereunder;

1. API 610 – Centrifugal Pumps for Petroleum, Petrochemical, and Natural Gas Industries
2. API 674 – Reciprocating Pumps
3. API 676 – Rotary Pumps (Karassik, et al. 2001)

2.2 Data Collection

In the refinery's wastewater treatment plant, pressure, temperature, and flow rate data from centrifugal pumps were collected using the following precision instruments:

Pressure Sensors: Pressure gauges were installed at the pump suction and discharge lines to monitor inlet and outlet pressures.

Temperature Sensors: Infrared pyrometers were placed on the pump casing or bearings to detect fluid and equipment temperatures.

Flow Meters: Flow meters were installed on the discharge line to measure the volume or mass of fluid being pumped.

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The field operational data were recorded between 1st June, 2022 and 12th July, 2022.

Table-1 Field Recorded Data

S/N	Temp. (Celsius)	Pump Head Pressure (PSI)	Export Delivery Line Pressure (PSI)	PUMP 1	PUMP 2	Hourly Rate (m^3/h)
1	230	230	250	ON		295.4
2	232	230	250	ON		290.0
3	299	230	250	ON		294.6
4	230	230	250		ON	298.4
5	231	230	253		ON	239.0
6	232	230	258		ON	289.0
7	235	250	260	ON		298.8
8	233.5	250	260	ON		299.2
9	237	240	250	ON		290.2
10	235	220	250		ON	288.9
11	231	230	230		ON	290.0
12	231	220	225		ON	289.1
13	233	230	250	ON		286.5
14	234	230	240	ON		297.5
15	290	230	240	ON		287.4
16	231	235	250		ON	295.0
17	232	230	255		ON	292.8
18	231	240	245		ON	289.0
19	233	230	250	ON		287.7
20	230	225	245	ON		290.8
21	231	230	253	ON		280.5
22	240	241	255		ON	286.4
23	233	239	257		ON	290.8
24	235	240	250		ON	295.5
25	233	235	250	ON		289.9
25	236	240	245	ON		295.0
27	237	235	260	ON		290.8
28	233	220	230		ON	270.0
29	232	230	240		ON	288.9
30	231	240	260		ON	295.0

2.3 Design Expert Software Application

Design-Expert software is a powerful tool for design of experiments (DOE) and process optimization, and it was effectively used to optimize pressure, temperature, and flow rate of the centrifugal pumps. Expert Software package used in this study was Response Surface Methodology (RSM) to optimize pump operating conditions. Set response goals were as follows:

i. Optimize flow rate for treatment throughput.
ii. Control temperature to prevent overheating and equipment wear
iii. Maintain pressure within safe operational limits.

Responses Factors (Inputs): Pump speed (RPM), suction head and export delivery temperature. Responses Factors (Outputs): Delivery and Discharge pressures, Pump fluid temperature and Flow rate.

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Table-2 Experimental Variables

		Factor 1	Factor 2	Response 1	Response 2
Std	Run	A: Pump head pressure (Psi)	B: Export delivery pressure (Psi)	Hourly Rate (m^3/h)	Pump Temperature(◦c)
3	1	230	260	297.6	202.5
13	2	240	250	280.6	202.3
5	3	225.858	250	294	200.5
7	4	240	235.858	0	198.6
4	5	250	260	281.5	204
11	6	240	250	280.6	200
8	7	240	264.142	285.9	204.2
12	8	240	250	280.6	205.1
2	9	250	240	0	200
9	10	240	250	280.6	199
1	11	230	240	282.5	199.8
6	12	254.142	250	0	201.5
10	13	240	250	280.6	198.6

The Table-2 result shows that the eleventh run has the least standard deviation (Std) of 1.0 which suggested 282.5 m^3/h and 199.8 ℃ as responses of hourly rate and operational temperature of factor 1 and 2 (230psi and 240psi). On the other hand, the second run has the highest standard deviation of 13 (by ranking). Despite the high pressures recorded but low flow rate (i.e 280.6m^3/h) was experienced. Table-3 below indicates the minimum and maximum pump head as well as delivery pressures with their averages of 240psi and 250psi respectively.

Table-3 Information about input variable

Factor	Name	Units	Type	Minimum	Maximum	Coded Low	Coded High	Mean	Std. Dev.
A	Pump head pressure	psi	Numeric	225.86	254.14	-1 ⟺ 230.00	+1 ⟺ 250.00	240.00	8.16
B	Export delivery pressure	psi	Numeric	235.86	264.14	-1 ⟺ 240	+1 ⟺ 260	250.00	8.16

Table -4 Information about Responses

Response	Name	Observations	Analysis	Min.	Max.	Mean	Std. Dev.	Transform	Model
R1	Hourly rate	13	Polynomial	0	297.6	218.81	124.86	None	Quadratic
R2	Pump temp.	13	Polynomial	198.6	205.1	201.24	2.21	None	Linear

Table-5 Model Summary Statistics for hourly flow rate

Source	Std. Dev.	R^2	Adjusted R^2	Predicted R^2	PRESS	
Linear	78.66	0.6693	0.6031	0.3755	1.168E+05	
2FI	70.02	0.7641	s0.6855	0.5554	83174.62	
Quadratic	43.24	0.9300	0.8801	0.5026	93057.91	Suggested
Cubic	44.54	0.9470	0.8727	-2.3935	6.348E+05	Aliased

Focus on the model maximizing the Adjusted R^2 and the Predicted R^2. There are series of models that can be used to optimize the operating parameters of the pump such as linear, 2FI, Quadratic and Cubic. In order to achieve robust solutions/results, we focused on the model maximizing the Adjusted R^2 and the Predicted R^2. It shows that the quadratic model has the highest values, hence suggested to be chosen.

ANOVA for Quadratic Model

Response 1: hourly flow rate

Table-6 ANOVA table for hourly flow rate

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	1.740E+05	5	34797.22	18.61	0.0006	significant
A-pump head pressure	63792.13	1	63792.13	34.12	0.0006	
B-export delivery pressure	61411.75	1	61411.75	32.85	0.0007	
AB	17742.24	1	17742.24	9.49	0.0178	
A^2	16834.96	1	16834.96	9.01	0.0199	
B^2	18249.46	1	18249.46	9.76	0.0167	
Residual	13086.27	7	1869.47			
Lack of Fit	13086.27	3	4362.09			
Pure Error	0.0000	4	0.0000			
Core Total	1.871E+05	12				

The Model F-value of 18.61 implies the model is significant. There is only a 0.06% chance that an F-value is large and errors could occur due to noise. P-values less than 0.0500 indicate model terms are significant. In this case A, B, AB, A^2, B^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

Fit Statistics

Table-7 Fit statistics for hourly flow rate

Std. Dev.	43.24	R^2	0.9300
Mean	218.81	Adjusted R^2	0.8801
C.V. %	19.76	Predicted R^2	0.5026
		Adeq. Precision	12.6583

Predicted Equation for Hourly Flow Rate

$$\text{Hourly flow rate} = 280.6 - 89.297A + 87.615B + 66.6AB - 49.19375A^2 - 51.21875B^2$$

The equation in terms of coded factors can be used to make predictions about the response for given levels of each factor. By default, the high levels of the factors are coded as +1 and the low levels are coded as -1. The coded equation is useful for identifying the relative impact of the factors by comparing the factor coefficients.

Table-8 Model Summary Statistics of Response pump temperature

Source	Std. Dev.	R^2	Adjusted R^2	Predicted R^2	PRESS	
Linear	1.75	0.4757	0.3708	0.3629	37.41	Suggested
2FI	1.84	0.4829	0.3105	0.3471	38.34	
Quadratic	2.06	0.4935	0.1317	0.1635	49.11	
Cubic	2.43	0.4968	-0.2076	-0.0853	63.72	Aliased

ANOVA for Linear Model

Response 2: pump temperature

Table-8 ANOVA table for temperature

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	27.93	2	13.96	4.54	0.0396	significant
A-pump head pressure	1.21	1	1.21	0.3938	0.5444	
B-export delivery pressure	26.72	1	26.72	8.68	0.0146	
Residual	30.78	10	3.08			
Lack of Fit	1.52	6	0.2537	0.0347	0.9995	not significant
Pure Error	29.26	4	7.31			
Total	58.71	12				

The Model F-value of 4.54 implies the model is significant. There is only a 3.96% chance that an F-value this large could occur *due to noise*. P-values less than 0.0500 indicate model terms are significant. In this case B is a significant model term. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model. The Lack of Fit F-value of 0.03 implies the Lack of Fit is not significant relative to the pure error. There is a 99.95% chance that a Lack of Fit F-value this large could occur due to noise. Non-significant lack of fit is good -- we want the model to fit.

Fit Statistics

Table-9 Fit statistics for temperature

Std. Dev.	1.75	R^2	0.4757
Mean	201.24	Adjusted R^2	0.3708
C.V. %	0.8718	Predicted R^2	0.3629
		Adeq Precision	6.1327

The Predicted R^2 of 0.3629 is in reasonable agreement with the Adjusted R^2 of 0.3708; i.e. the difference is less than 0.2. Adeq. Precision measures the signal to noise ratio. A ratio greater than 4 is *desirable*. The ratio of *6.133* indicates an adequate signal. This model can be used to navigate the design space.

Model Equation to predict pump temperature

Pump temp. = 201.24 + 0.3893A + 1.827B

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The equation in terms of coded factors can be used to make predictions about the response for given levels of each factor. By default, the high levels of the factors are coded as +1 and the low levels are coded as -1. The coded equation is useful for identifying the relative impact of the factors by comparing the factor coefficients.

RESULTS AND DISCUSSION

Design Experts Analysis

File Version	11.1.2.0		
Study Type	Response Surface	Subtype	Randomized
Design Type	Central Composite	Runs	13
Design Model	Quadratic	Blocks	No Blocks
	Build Time (ms) 1.0000		

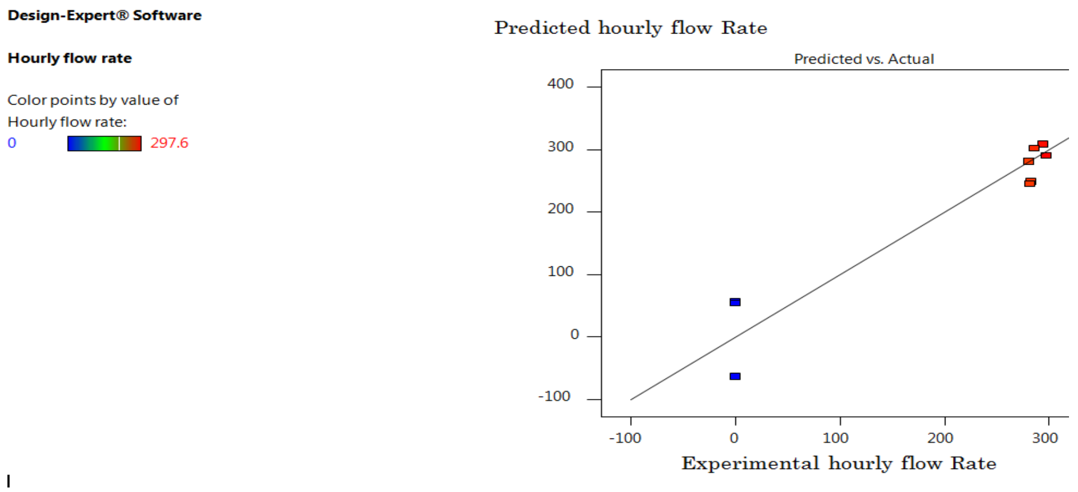

Fig. 2 Graph of predicted hourly against experimental flow rate

From the figure above, there is a correlation between the predicted and actual hourly rate. Out of eight results, six are closely correlated while the remaining two more scattered. More so, Adequate precision measures signal to noise ratio.

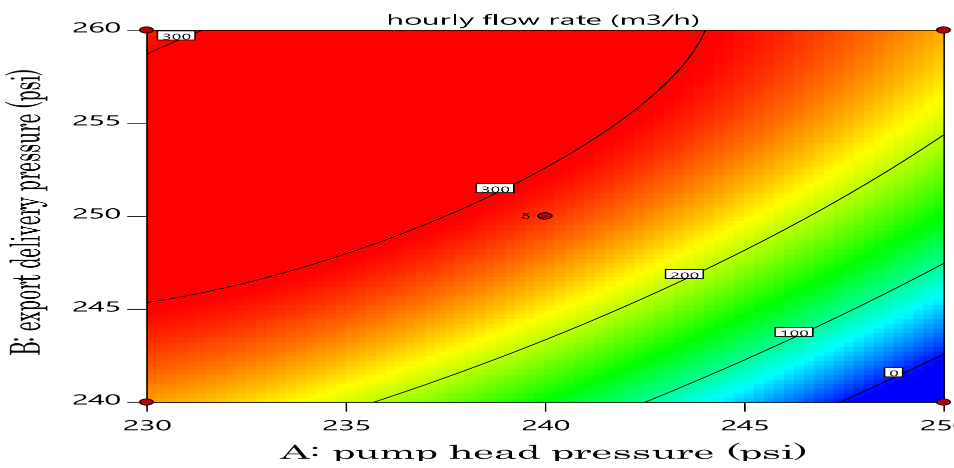

Fig. 3 Contour diagram of hourly flow rate

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From the above graph, the blue and green color regions indicate safest operating pressures. As the head pressure exceeds 250psi, the operating head pressure becomes unsafe. All red regions are considered unsafe as shown in the graph.

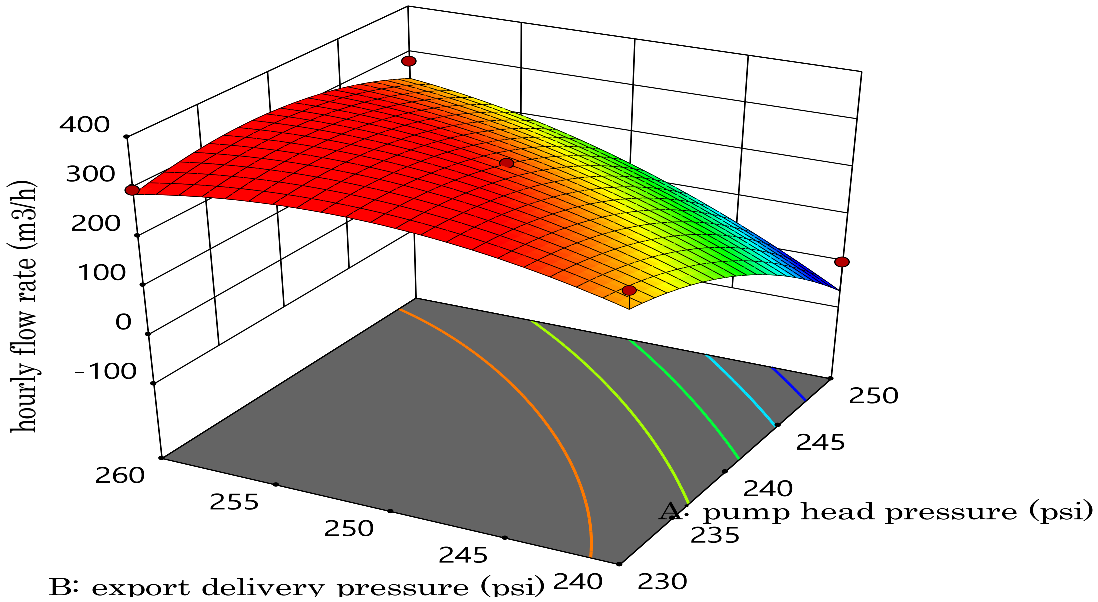

Fig. 4 3-D surface diagram of hourly flow rate

The above 3D surface diagram represents a clearer picture of the contour diagram in a multi-dimensional form. Red dots are border points between safe and unsafe regions.

Pump Temperature Analysis

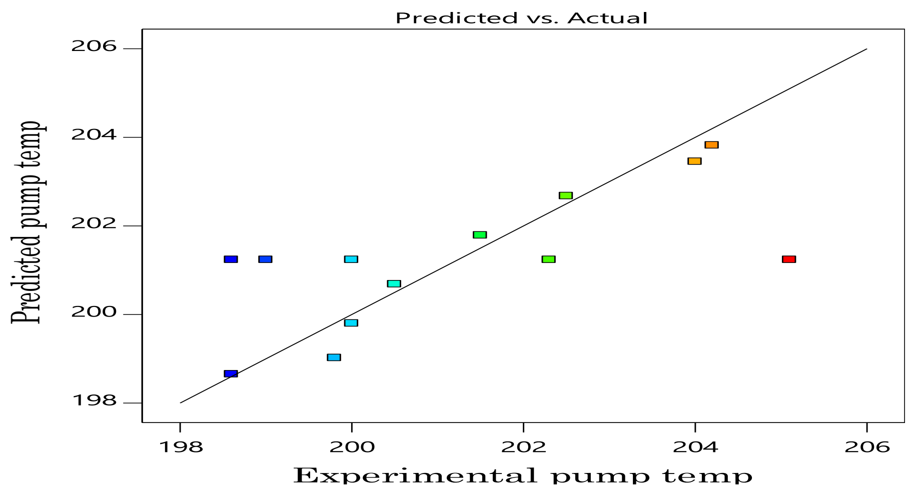

Fig. 5 Graph of Predicted versus Actual operating temperatures

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The above scattered diagram above shows the correlation between predicted and experimental pump temperature in which whenever exceeds 202℃ the pump is liable to experience overheating. It is strongly advised that the operating temperature should be less than or equal 200℃.

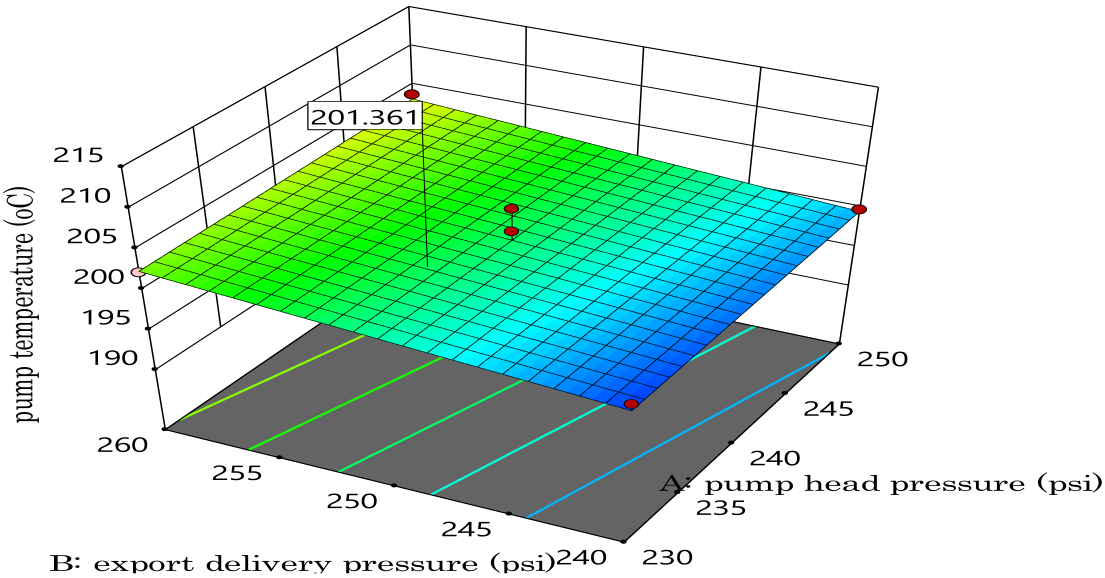

Fig. 6 3D Surface diagrams

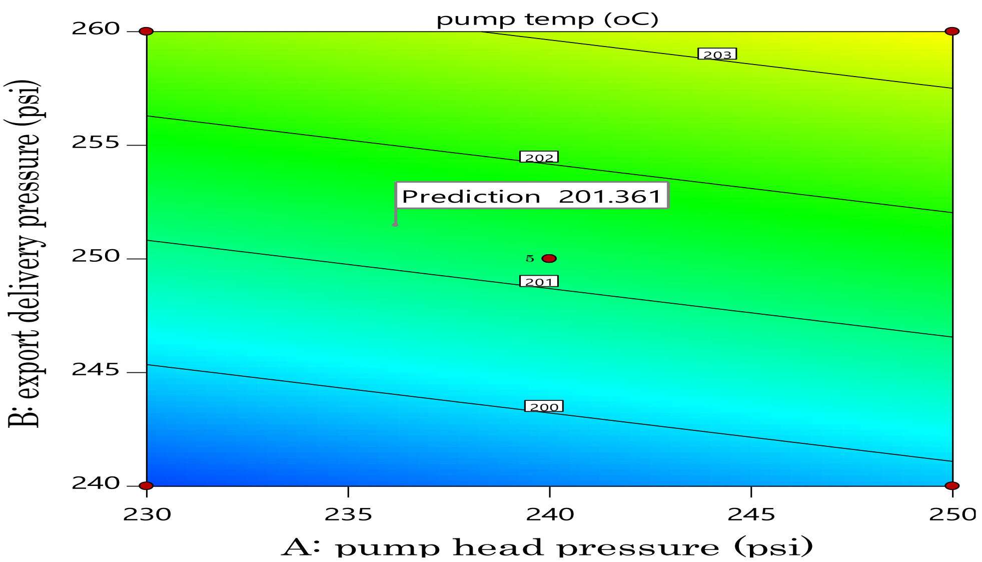

Fig. 7 Contour diagram of pump temperature

Above contour diagrams represent 3D which predicted the safest operating temperature of the pump (i.e 201.361℃). This result is quite lower than the operational temperature levels recorded in the WRPC waste water treatment plant.

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Optimization Result

Table-10 Constraints

Name	Goal	Lower Limit	Upper Limit
A: pump head pressure	maximize	230	250
B: export delivery pressure	maximize	240	260
hourly flow rate	maximize	0	297.6
pump temp	is in range	198.6	205.1

Table-11 Optimization and selected solution

Number	pump head pressure	export delivery pressure	hourly flow rate	pump temp	Desirability	
1	250.000	260.000	245.106	201.361	0.937	Selected
2	249.911	260.000	246.182	203.452	0.935	
3	249.823	260.000	247.233	203.448	0.935	
4	249.680	260.000	248.936	203.443	0.933	
5	249.568	260.000	250.241	203.438	0.931	
6	250.000	259.873	244.442	203.432	0.930	
7	249.999	259.640	243.184	203.389	0.929	

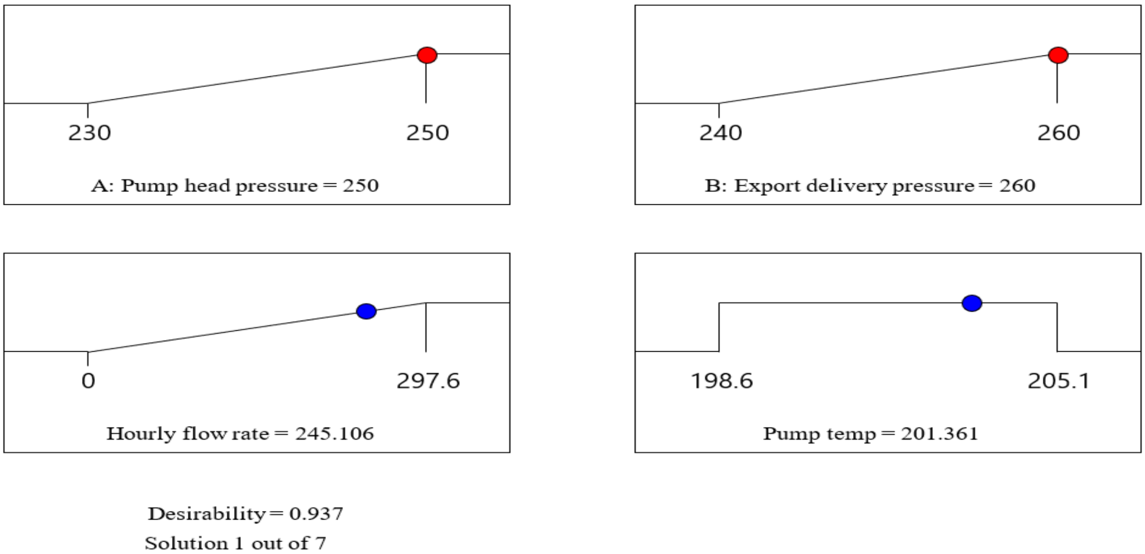

Fig. 8 Ram Diagram

When the suction pressure is high, the hourly rate becomes high and the pump delivery increases. A number of solutions were generated. The first solution indicates the highest desirability up to 93.5% which is considered the best optimized solution. Operation of the pump should be halted should the greater values of 250 psi (inlet), 260psi (delivery), 245.1 m^3/h (hourly rate) and 201.36 ℃ (temperature) be registered on the pump. An immediate maintenance routine to rectify the effect of the excessive vibration should be carried out to avoid damage to the pump and downtime. Even while operating under safe conditions, due to the tendency of fatigue, the pump components should be critically examined after reasonable working cycles.

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CONCLUSION

The integrated optimization of pressure, temperature and hourly rate in centrifugal pumps not only ensures optimal pump operations but also contributes significantly to the overall performance and sustainability of industrial processes. Based on the findings, operation of the pump should be halted should higher readings be registered on the pump. An immediate maintenance routine to rectify the effect of the excessive vibration should be carried out to avoid damage to the pump and downtime.

CONTRIBUTION TO KNOWLEDGE

This research establishes benchmarks for monitoring the operation of centrifugal pumps used in Oil and Gas and allied industries. The findings could significantly improve reliability, reduce maintenance costs and support sustainability goals across industries reliant on pump systems.

CONFLICT OF INTEREST

There is no conflict of interest for this research work.

ACKNOWLEDGEMENT

We acknowledge authors whose works were consulted in the course of conducting this research work. We equally acknowledge the moral supports given to us by our noble families throughout the period of executing this magnanimous work.

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