
| RESEARCH ARTICLE**Enhancing Energy Efficiency in Locally Developed Steam Boilers: A Response Surface Methodology Approach****Ifeanyichukwu Ugochukwu Onyenanu¹ ✉ John Iorliam Ande² and Vincent Chukwuemeka Ezechukwu³**^{1,2,3}*Department of Mechanical Engineering, Chukwuemeka Odumegwu Ojukwu University, Uli – Nigeria.***Corresponding Author:** Ifeanyichukwu Ugochukwu Onyenanu, **E-mail:** iu.onyenanu@coou.edu.ng

| ABSTRACT

This investigation concentrates on the enhancement of energy efficiency in a locally engineered steam boiler to address considerable energy losses linked to fossil fuel-based power generation. A thorough retrospective examination of boiler technology is offered, highlighting the intrinsic inefficiencies present in earlier designs. Employing Response Surface Methodology (RSM) alongside I-optimal design, this study rigorously evaluates essential operational parameters, such as steam inlet pressure, injection flow rate, and biomass utilization. The optimization procedure delineates the subsequent optimal parameters: a steam inlet pressure of 9.33 bar, a motor speed of 1226.15 rpm, and a biomass utility of 29.989 kg/h (comprising both firewood and rice husk). These configurations yield a peak efficiency of 74.093%, a steam injection flow rate of 246.037 cm³/s, and a steam production rate of 18.451 kg/h. The findings emphasize substantial potential for improving operational efficiency and minimizing emissions, thereby fostering more sustainable energy production methodologies. This research offers significant insights for engineers and scholars seeking to enhance the performance of biomass-based steam systems within the framework of renewable energy endeavours.

| KEYWORDS

Energy Efficiency, Steam Boiler Optimization, Fossil Fuel Power Generation, Response Surface Methodology (RSM), Sustainable Energy.

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1. Introduction

Today, combustion boilers are engineered to utilize fuel energy for raising the thermal energy content of water, serving various power and heating applications across diverse environments, including offices, hotels, hospitals, schools, museums, government buildings, and airports. While boilers can burn a wide array of fuels—both fossil and non-fossil—the most prevalent fuels remain coal, oil, and natural gas. Additionally, alternative fuel sources such as coconut shells, empty fruit bunches, rice husks, and palm kernels have gained recognition. Boilers are produced in various sizes and designs, tailored to fuel characteristics, desired heating output, and required emissions controls. Some are specifically designed for steam generation, while others solely produce hot water [Elie, 2013].

The advent of technological advancements has transformed power plants into highly sophisticated systems capable of operating at supercritical conditions of 28.5 MPa and 600 °C, generating up to 1300 MW of energy with significantly enhanced efficiency [Onyenanu, n.d]. The implementation of energy management systems has empowered organizations to identify potential energy savings through optimized operating procedures. Achieving these efficiencies [Ukwu, 2024] necessitates a comprehensive understanding of the thermodynamic properties of

working fluids involved in the processes, which can require extensive energy simulations, demanding computational resources, and significant training to master relevant software tools [Morakinyo, 2017].

Further enhancing energy savings involves a thorough assessment of emissions. Throughout their operational lifespan, simulators have the potential to yield substantial cost savings on fossil fuel boiler operations, primarily through reductions in operational (fuel, maintenance, and downtime) and capital (extended lifespan of power plant components) costs. Simulators can facilitate the optimization of boiler control parameters, serving as a less risky alternative to direct boiler tuning in operational settings.

The optimal evaluation of steam boiler performance is best achieved through the application of simulation tools and the design of experiments (DOE) for system optimization [Erhimona, 2023, 5 Maddah, 2019]. Efficient management of particulate matter (PM), nitrogen oxides (NO_x), carbon monoxide (CO), and sulfur dioxide (SO₂) emissions at the lowest feasible cost is an essential consideration throughout the design and selection process of boiler and combustion equipment. Therefore, this study focuses on enhancing the energy efficiency and operational efficacy of a locally manufactured steam boiler.

2. Literature Review

Steam generation, a major contributor to industrial energy losses, poses a critical energy efficiency challenge due to locally produced steam boilers' inherent design flaws, poor performance, and substantial energy waste, persisting despite technological advancements. To improve efficiency and boost the steam output rate, the steam boiler's energy efficiency must be optimized by looking at different design characteristics, operational tactics, and technology advancements. RSM and other experimental design techniques have been utilized in several types of research [Onyenanu, 2024, Onyenanu, n.d] to optimize steam boiler designs. [Hechelmann, 2020] focused on steam boiler modelling and efficiency optimization using the Response-Surface Method (RSM) and Neural Networks. The efficiency temperature, or maximum efficiency for nearly all flow rates, was determined by the study to be 196°C. [Mann, 2018] used the Taguchi design method to optimize the operating parameters of a biomass fire-in-tube boiler. Concerning the aspirator orifice area, biomass composite, the volume of cold water, and superheated steam volume, the optimal anticipated independent and dependent processing parameters of the boiler were found to be 2 dm², 483.6 MJ, 100 litres, and 61.22 litres. The temperature of the end tube sections lowers just a few K even after 16 seconds of attemperation, in the intermediate part from 30 to 40 K, and near the intake from 40 to 90 K, according to research by [Erhimona, 2023] on the CFD analysis of the steam superheater, transient state, and observer. [Granda, 2019] sought to look at the decrease of CO₂ emissions while researching the integration of renewable energy for the delivery of steam in industrial food production processes. After developing seven distinct utility models for steam generation, it was discovered that switching to a solid biomass-fueled boiler system might result in the largest CO₂ and e-emissions reduction of up to 63%, albeit at the expense of a 27.8% rise in operating costs. Analysis of the creation of an optimal maintenance program for a steam boiler system using the reliability-centered maintenance (RCM) approach revealed that the system's reliability had increased by 28.15% [Ochoa, 2019].

3. Materials and Methods

3.1 Computer-Aided Design (CAD)

The constituent elements of the steam boiler encompass the boiler shell, inner shell, combustion chamber, insulator, intake/air vent, fire tubes, hopper, cover plate, fire beds, Moberly, pressure valves, drain pump, condensate filter, forced draft (FD) fan, fuel feed motor, gauge glass, pressure relief valve, chimney, husk hopper, screw conveyor, and temperature control sensor. These components were all integral to the architectural design of the steam boiler power generation facility. The external shell of the steam boiler has dimensions of 99 inches in height, 70.98 inches in diameter, and 6 millimetres in thickness; conversely, the internal shell of the steam boiler measures 86.01 inches in height, 57.98 inches in diameter, and 6 millimetres in thickness; the combustion chamber has dimensions of 23.08 inches in height, 35.25 inches in diameter, and a thickness of 6 and 25 millimetres; the concrete insulator is characterized by a height of 86.01 inches, a diameter of 70.5 inches, and a thickness of 12.52 inches. The fire bed exhibits a height of 4.9 inches, a length of 42.87 inches, a width of 42.81 inches, and a thickness of 22 millimetres. The air vent is quantified to have a length of 64.16 inches, a diameter of 2.38 inches, and a thickness of 6

millimetres. The specifications for the fire tube include a height of 58.51 inches, a diameter of 2.18 inches, and a thickness of 0.47 inches. The hopper is measured to be 48 inches in height, 65.75 inches in length, and 28.25 inches in width. A graphical representation of the three-dimensional CAD model constructed utilizing SOLIDWORKS Software version 2023 is presented in Figure 1.



Fig 1: 3D CAD Model of the Steam Boiler

3.2 Steam Boiler Fabrication

Together with NUTABOLTS Technologies Limited, which is based in Enugu State, Nigeria, Hule & Sons Co. Limited, located in Gboko Benue State, Nigeria, built the steam boiler. The several steps of the fabrication process that the steam boiler went through during its construction are depicted in Figures 2a, 2b, and 2c. A thorough explanation of the materials utilized for each component of the steam boiler can be found in Table 1.



Figure 2: (a) Welding of the combustion chamber to the inner shell. (b) The welded assembly part is ready to be lifted. (c) The steam boiler on fabrication

Table 2: Summary of the Design of the Experiment Table

	Factor 1	Factor 2	Factor 3	Response 1	Response 2	Response 3
Run	A: Steam inlet pressure	B: Motor speed levels	C: Biomass utility	Energy Efficiency	Steam Injection rate	Steam Production Rate
	Bar	RPM	kg	%	Cm ³ /s	kg/h
1	7.075	1482.5	25.85	70	200	180
2	7.075	1207.5	20.3	68	180	160
3	10	1000	30	72	250	220
4	5	1500	30	65	180	170
5	6.86516	1500	20	70	190	175
6	7.75993	1275.98	29.8	72	220	200
7	10	1500	26.2721	75	260	230
8	7.5	1025	29.5126	68	210	190
9	10	1185	20	70	220	200
10	10	1185	20	70	220	200
11	5	1000	20	60	160	150
12	5	1000	30	62	180	170
13	9.875	1207.5	25.85	74	240	210
14	5.125	1275	24.49	65	180	170
15	7.75	1007.5	24.5	68	200	180
16	5.25	1250	29.5345	66	190	180
17	6.86516	1500	20	70	190	175
18	7.75993	1275.98	29.8	72	220	200
19	7.75	1007.5	24.5	68	200	180
20	5.125	1275	24.49	65	180	170

4. Results

4.1 ANOVA, or analysis of variance

ANOVA, or analysis of variance, is a statistical model and related estimating technique set. It is used to look at discrepancies inside and between groups, particularly when comparing the means of the groups in a sample. In this investigation, ANOVA was utilized to ascertain whether the experiment's mean values differed noticeably from one another. The ANOVA results for the cooking performance and thermal efficiency based on the experimental data are presented in Tables 3 and 4. These tables include information on the coefficients of the corresponding models as well as the statistical significance of the components that are being considered.

I: The ANVOA for the chosen factorial model's thermal efficiency is displayed below

Table 3: Results of the Analysis of Variance for Thermal Efficiency

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	275.87	9	30.65	97.93	< 0.0001	significant
A-Steam inlet pressure	183.66	1	183.66	586.77	< 0.0001	
B-Motor speed levels	47.47	1	47.47	151.67	< 0.0001	
C-Biomass (firewood and rice husk) utility	13.84	1	13.84	44.22	< 0.0001	
AB	0.0573	1	0.0573	0.1829	0.6779	
AC	3.66	1	3.66	11.70	0.0065	
BC	2.37	1	2.37	7.58	0.0204	
A²	8.08	1	8.08	25.81	0.0005	
B²	5.34	1	5.34	17.05	0.0020	
C²	0.7896	1	0.7896	2.52	0.1433	
Residual	3.13	10	0.3130			
Lack of Fit	3.13	5	0.6260			
Pure Error	0.0000	5	0.0000			
Cor Total	279.00	19				

The significance of the model is indicated by the F-value of 97.93. This kind of huge F-value has a 0.01% probability of being caused by noise. Model terms are considered significant when P-values are less than 0.0500. A, B, C, AC, BC, A², and B² are important model terms in this instance. The model terms are not important if the value is bigger than 0.1000. Model reduction could make your model better if it has a large number of unimportant model terms (apart from those needed to maintain hierarchy).

II: The chosen factorial model's ANVOA for the Steam Injection Flow rate is:

Table 4: Results of the Analysis of Variance for the Flow Rate of Steam Injection

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	12959.66	9	1439.96	151.04	< 0.0001	significant
A-Steam inlet pressure	10432.35	1	10432.35	1094.26	< 0.0001	
B-Motor speed levels	424.62	1	424.62	44.54	< 0.0001	
C-Biomass (firewood and rice husk) utility	1997.05	1	1997.05	209.47	< 0.0001	
AB	94.17	1	94.17	9.88	0.0105	
AC	141.92	1	141.92	14.89	0.0032	
BC	60.62	1	60.62	6.36	0.0303	
A²	172.16	1	172.16	18.06	0.0017	
B²	14.75	1	14.75	1.55	0.2419	
C²	33.32	1	33.32	3.49	0.0911	
Residual	95.34	10	9.53			
Lack of Fit	95.34	5	19.07			
Pure Error	0.0000	5	0.0000			
Cor Total	13055.00	19				

The significance of the model is indicated by the F-value of 151.04. This kind of huge F-value has a 0.01% probability of being caused by noise. Model terms are considered significant when P-values are less than 0.0500. A, B, C, AB, AC, BC, and A² are important model terms in this instance. The model terms are not important if the value

is bigger than 0.1000. Model reduction could make your model better if it has a large number of unimportant model terms (apart from those needed to maintain hierarchy).

III: The chosen factorial model's ANVOA for the Steam Production rate is:

Table 5: Results of the Analysis of Variance for Steam Production Rate

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	7630.88	9	847.88	39.60	< 0.0001	significant
A-Steam inlet pressure	5811.59	1	5811.59	271.42	< 0.0001	
B-Motor speed levels	374.44	1	374.44	17.49	0.0019	
C-Biomass (firewood and rice husk) utility	1460.52	1	1460.52	68.21	< 0.0001	
AB	73.26	1	73.26	3.42	0.0941	
AC	33.87	1	33.87	1.58	0.2371	
BC	67.82	1	67.82	3.17	0.1055	
A²	218.08	1	218.08	10.18	0.0096	
B²	26.20	1	26.20	1.22	0.2945	
C²	7.82	1	7.82	0.3652	0.5591	
Residual	214.12	10	21.41			
Lack of Fit	214.12	5	42.82			
Pure Error	0.0000	5	0.0000			
Cor Total	7845.00	19				

The significance of the model is indicated by the F-value of 39.60. This kind of huge F-value has a 0.01% probability of being caused by noise. Model terms are considered significant when P-values are less than 0.0500. A, B, C, and A² are important model terms in this instance. The model terms are not important if the value is bigger than 0.1000. Model reduction may help your mode if there are a lot of insignificant model terms (apart from those needed to maintain hierarchy).

Results for the three (3) Responses: Predicted and Actual.

4.1.1 Efficiency

Through optimization, the experimental design table was enhanced with the use of the Design Expert program 13. The predicted results of the experiment were then estimated using coded equations developed for each situation. A graph comparing the expected values with the actual experiment findings is shown in Figure 3. The graph, particularly in the instance of the thermal efficiency experiment, validates a strong similarity between the expected and actual values. Table 6 arranges the projected and facts on the thermal efficiency of the steam boiler.

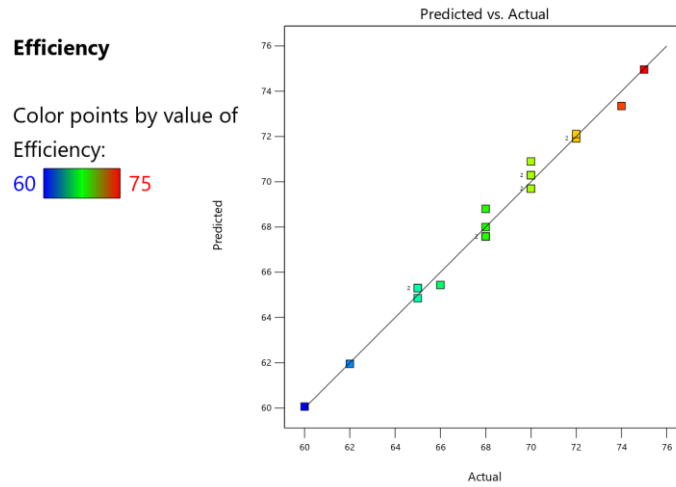


Figure 3: Displaying the actual and predicted thermal efficiency values

Table 6: Displaying the predicted and actual thermal efficiency data sets

Run Order	Actual Value	Predicted Value	Residual	Leverage	Internally Studentized Residuals	Externally Studentized Residuals	Cook's Distance	Influence on Fitted Value DFFITS	Standard Order
1	70.00	70.90	-0.8952	0.313	-1.931	-2.312	0.170	-1.561	12
2	68.00	68.00	0.0032	0.305	0.007	0.006	0.000	0.004	6
3	72.00	72.11	-0.1122	0.874	-0.566	-0.545	0.222	-1.437	19
4	65.00	64.85	0.1458	0.877	0.743	0.726	0.394	1.938	20
5	70.00	69.70	0.3035	0.451	0.732	0.714	0.044	0.646	5
6	72.00	71.92	0.0826	0.388	0.189	0.179	0.002	0.143	17
7	75.00	74.96	0.0404	0.819	0.170	0.161	0.013	0.343	13
8	68.00	68.81	-0.8066	0.288	-1.709	-1.926	0.118	-1.225	14
9	70.00	70.29	-0.2903	0.450	-0.700	-0.681	0.040	-0.616	3
10	70.00	70.29	-0.2903	0.450	-0.700	-0.681	0.040	-0.616	2
11	60.00	60.06	-0.0637	0.912	-0.383	-0.366	0.151	-1.174	1
12	62.00	61.95	0.0461	0.794	0.182	0.173	0.013	0.339	18
13	74.00	73.35	0.6504	0.323	1.413	1.498	0.095	1.035	11
14	65.00	65.30	-0.2999	0.405	-0.695	-0.676	0.033	-0.558	8
15	68.00	67.58	0.4192	0.409	0.975	0.972	0.066	0.808	9
16	66.00	65.44	0.5617	0.290	1.191	1.220	0.058	0.779	15
17	70.00	69.70	0.3035	0.451	0.732	0.714	0.044	0.646	4
18	72.00	71.92	0.0826	0.388	0.189	0.179	0.002	0.143	16
19	68.00	67.58	0.4192	0.409	0.975	0.972	0.066	0.808	10
20	65.00	65.30	-0.2999	0.405	-0.695	-0.676	0.033	-0.558	7

4.1.2 Rate of Steam Injection Flow

The comparison between the predicted and actual results of the experiment measuring the steam injection flow rate is shown graphically in Figure 4. A strong similarity between the projected and observed values is shown by the graph. Table 7 is a well-organized collection of tangible datasets that include both the actual results and the estimated values for the physical tests linked to steam injection flow rate. This table provides a thorough understanding of the experiment's findings and outcomes, making it a useful resource.

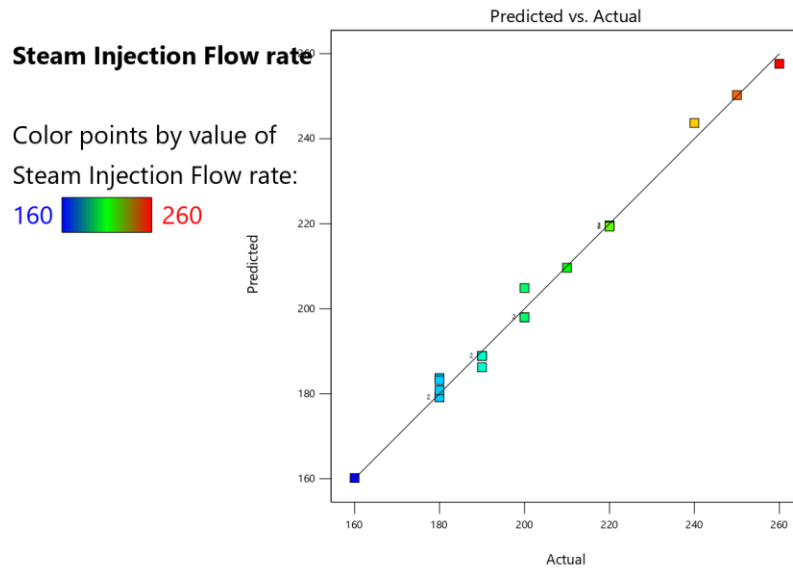


Figure 4: Steam Injection Flow Rate Actual and predicted Values

Table 7: Displaying the steam injection flow rate's actual and projected data sets

Run Order	Actual Value	Predicted Value	Residual	Leverage	Internally Studentized Residuals	Externally Studentized Residuals	Cook's Distance	Influence on Fitted Value DFFITS	Standard Order
1	200.00	204.87	-4.87	0.313	-1.902	-2.258	0.165	-1.524	12
2	180.00	183.70	-3.70	0.305	-1.438	-1.532	0.091	-1.016	6
3	250.00	250.26	-0.2557	0.874	-0.233	-0.222	0.038	-0.585	19
4	180.00	180.79	-0.7854	0.877	-0.725	-0.707	0.375	-1.888	20
5	190.00	188.88	1.12	0.451	0.490	0.470	0.020	0.426	5
6	220.00	219.34	0.6634	0.388	0.275	0.261	0.005	0.208	17
7	260.00	257.62	2.38	0.819	1.809	2.092	1.480 ⁽¹⁾	4.449 ⁽¹⁾	13
8	210.00	209.63	0.3699	0.288	0.142	0.135	0.001	0.086	14
9	220.00	219.59	0.4079	0.450	0.178	0.169	0.003	0.153	3
10	220.00	219.59	0.4079	0.450	0.178	0.169	0.003	0.153	2
11	160.00	160.18	-0.1776	0.912	-0.193	-0.184	0.038	-0.590	1
12	180.00	183.18	-3.18	0.794	-2.270	-3.094	1.991 ⁽¹⁾	-6.081 ⁽¹⁾	18
13	240.00	243.69	-3.69	0.323	-1.452	-1.551	0.101	-1.071	11
14	180.00	179.16	0.8365	0.405	0.351	0.335	0.008	0.277	8
15	200.00	197.97	2.03	0.409	0.854	0.842	0.050	0.700	9
16	190.00	186.21	3.79	0.290	1.458	1.559	0.087	0.995	15
17	190.00	188.88	1.12	0.451	0.490	0.470	0.020	0.426	4
18	220.00	219.34	0.6634	0.388	0.275	0.261	0.005	0.208	16
19	200.00	197.97	2.03	0.409	0.854	0.842	0.050	0.700	10
20	180.00	179.16	0.8365	0.405	0.351	0.335	0.008	0.277	7

4.2 Rate of Steam Production

The comparison between the expected and actual results of the experiment measuring the steam injection flow rate is shown graphically in Figure 5. A strong similarity between the projected and observed values is shown by the graph. Table 8 is a well-organized collection of tangible datasets that include both the actual results and the

estimated values for the physical tests linked to the steam production rate. This table provides a thorough understanding of the experiment's findings and outcomes, making it a useful resource.

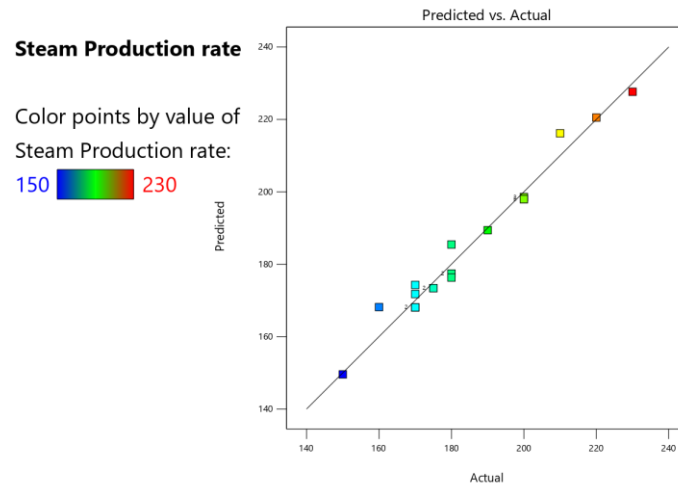


Figure 5: Steam production rate anticipated and actual figures are displayed.

Table 8: Displaying the Steam production rate's actual and projected data sets

Run Order	Actual Value	Predicted Value	Residual	Leverage	Internally Studentized Residuals	Externally Studentized Residuals	Cook's Distance	Influence on Fitted Value DFFITS	Standard Order
1	180.00	185.44	-5.44	0.313	-1.419	-1.507	0.092	-1.017	12
2	160.00	168.16	-8.16	0.305	-2.116	-2.702	0.197	-1.792	6
3	220.00	220.51	-0.5089	0.874	-0.310	-0.296	0.067	-0.779	19
4	170.00	171.76	-1.76	0.877	-1.083	-1.094	0.837	-2.921 ⁽¹⁾	20
5	175.00	173.39	1.61	0.451	0.469	0.450	0.018	0.407	5
6	200.00	197.98	2.02	0.388	0.557	0.537	0.020	0.427	17
7	230.00	227.64	2.36	0.819	1.198	1.228	0.649	2.612 ⁽¹⁾	13
8	190.00	189.40	0.6044	0.288	0.155	0.147	0.001	0.094	14
9	200.00	198.52	1.48	0.450	0.430	0.412	0.015	0.373	3
10	200.00	198.52	1.48	0.450	0.430	0.412	0.015	0.373	2
11	150.00	149.56	0.4361	0.912	0.317	0.302	0.103	0.970	1
12	170.00	174.27	-4.27	0.794	-2.036	-2.525	1.602 ⁽¹⁾	-4.963 ⁽¹⁾	18
13	210.00	216.17	-6.17	0.323	-1.621	-1.791	0.125	-1.236	11
14	170.00	168.08	1.92	0.405	0.539	0.519	0.020	0.429	8
15	180.00	177.41	2.59	0.409	0.729	0.711	0.037	0.591	9
16	180.00	176.32	3.68	0.290	0.943	0.938	0.036	0.599	15
17	175.00	173.39	1.61	0.451	0.469	0.450	0.018	0.407	4
18	200.00	197.98	2.02	0.388	0.557	0.537	0.020	0.427	16
19	180.00	177.41	2.59	0.409	0.729	0.711	0.037	0.591	10
20	170.00	168.08	1.92	0.405	0.539	0.519	0.020	0.429	7

Impact of the examined factors for the steam boiler power plant on the response:

4.2.1 Efficiency

The resulting contour diagram (Figure 6) illustrates the link between the three variables of a steam boiler: thermal efficiency (C), biomass utility (A), motor speed levels (B), and steam inlet pressure (A). The contour plot illustrates an intriguing relationship between thermal efficiency and the steam inlet pressure and motor speed level. The efficiency of the steam boiler also rises when the steam inlet pressure and motor speed level rise at the same time. This indicates that the boiler operates at its most efficient level because there is no blockage to the air inflow. The relationship between three variables and thermal efficiency is depicted in a three-dimensional graphic in Figure 7.

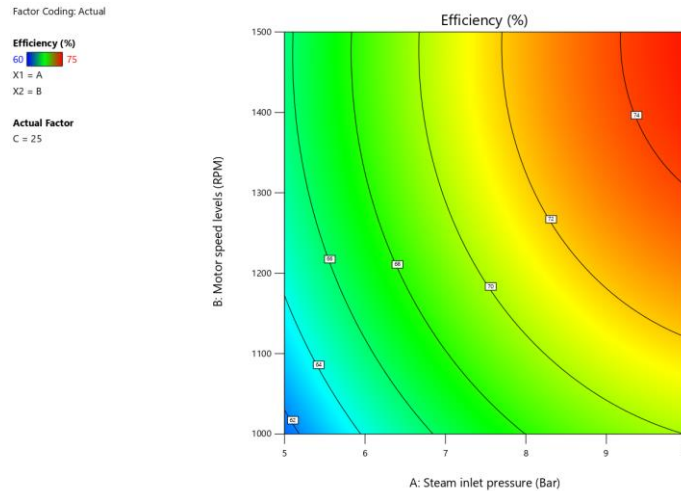


Figure 6. Contour plots of the response (efficiency)

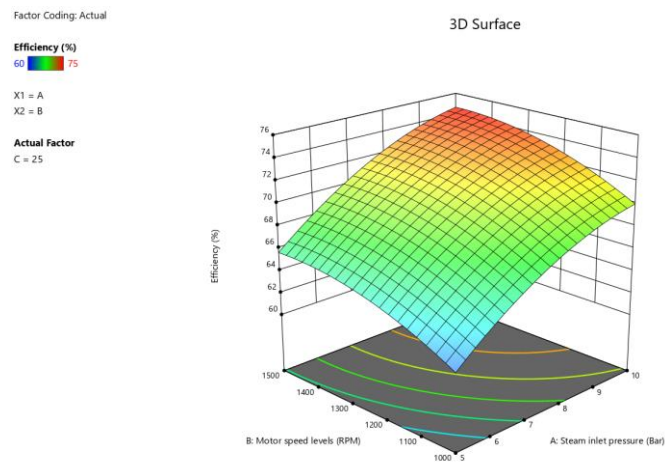


Figure 7 shows a three-dimensional schematic showing how three variables relate to thermal efficiency.

4.3 Rate of Steam Injection Flow

A similar study is shown in Figure 8, but it concentrates on the steam injection flow rate this time. Figure 8 presents a contour diagram that illustrates the correlation between three variables in a steam boiler: steam inlet pressure (A), motor speed levels (B), biomass utility (C), and thermal efficiency. The findings demonstrate that the steam injection flow rate is significantly influenced by the steam inlet pressures and motor speed levels. The observed trend suggests that the efficient steam injection flow rate is a result of steady increases in both steam input pressures and motor speed levels occurring at the same time. In contrast, Figure 9 shows a three-dimensional figure that shows how these three variables relate to the steam injection flow rate.

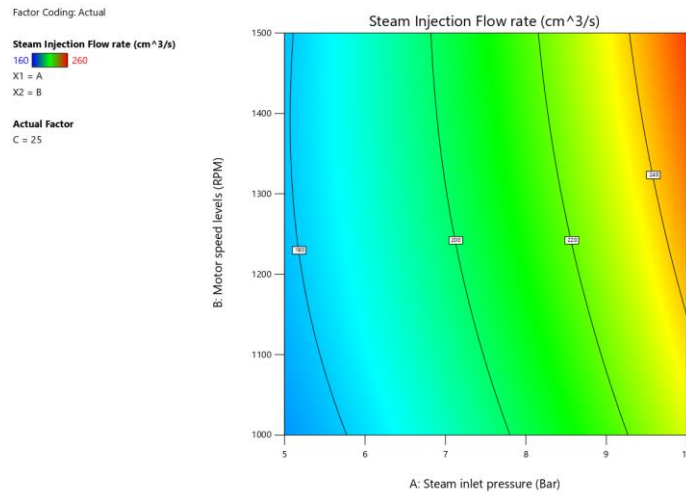


Figure 8: Contour plots of the Steam Injection flow rate (cm³)

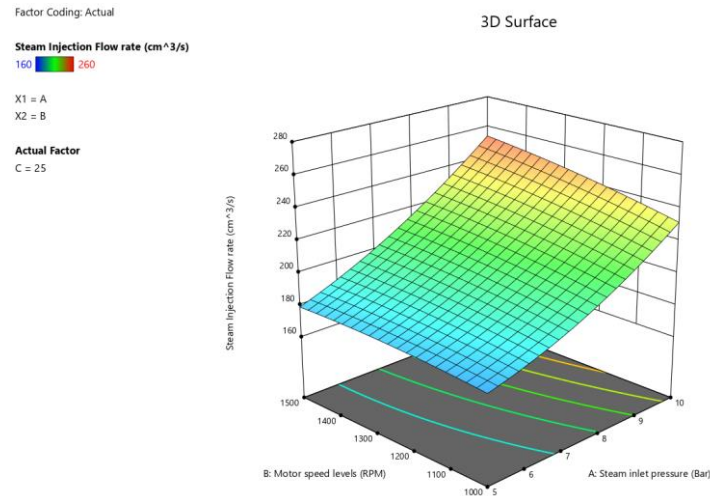


Figure 9: Three-dimensional diagram showing the link between the steam injection flow rate and three variables

4.4 Rate of Steam Production

Similar to Figure 9, Figure 10 presents an analysis that is centered on the pace of steam production. Figure 9 presents a contour diagram that illustrates the correlation between three factors related to steam boilers: steam inlet pressure (A), motor speed levels (B), biomass utility (C), and thermal efficiency. As the motor speed levels and steam inlet pressures gradually rise, the pattern shows that the steam generation rate grows efficiently at the same time. A three-dimensional figure showing the link between these three variables and the rate of steam production is shown in Figure 11.

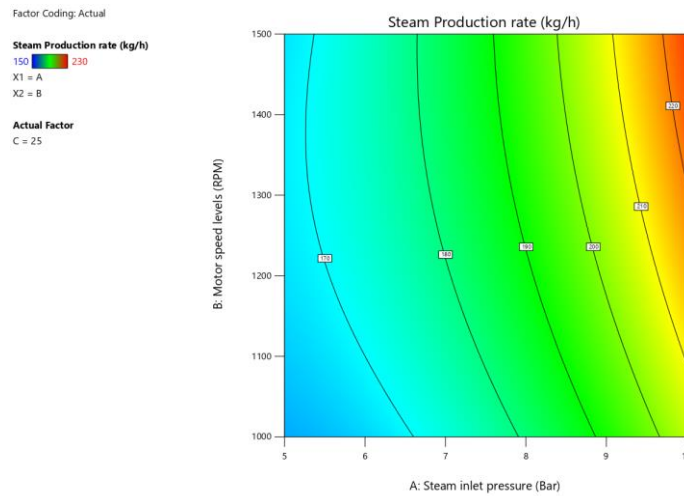


Figure 10: Contour plots of the Steam production rate (kg/h)

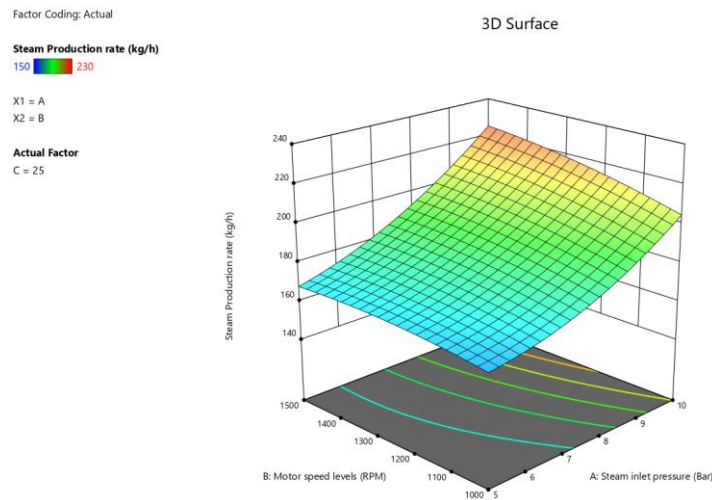


Figure 11: Three-dimensional graphic showing the correlation between three variables and the desirable rate of steam production.

4.5 Desirability Plot

Steam inlet pressure (9.33), motor speed levels (1226.15), and biomass (firewood and rice husk) utility (29.989) were found to be the selected or optimal values from the solution of the combination of the three categoric factor levels. This will result in an efficiency of 74.093%, a steam injection flow rate of 246.037cm³/s, and a steam production rate of 218.451kg/h. Figure 12 illustrates the plot of optimal desirability.

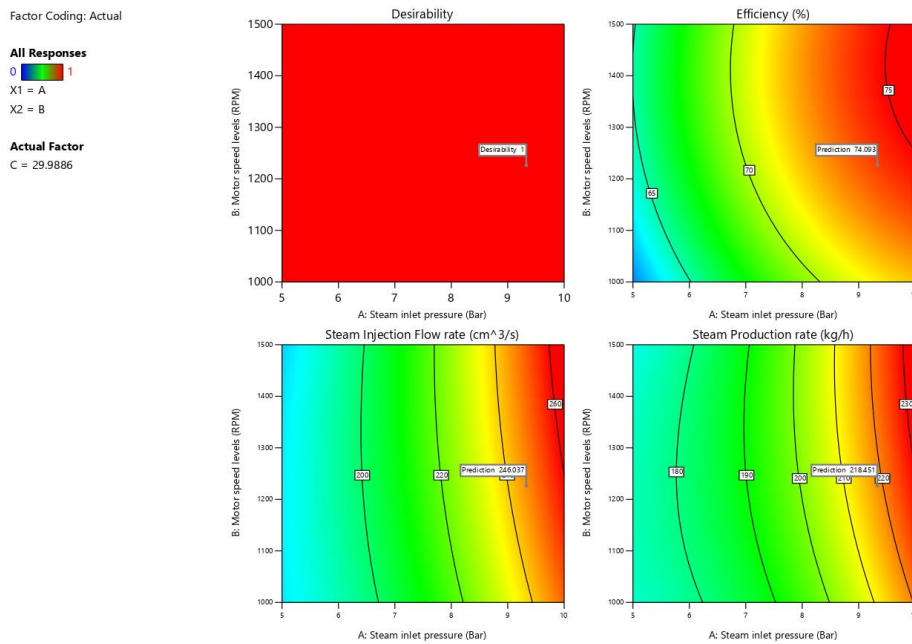


Figure 12: Plot of Optimal Desirability

5. Conclusion

This research aimed to maximize the energy efficiency of a steam boiler that was developed locally. A mixture of data analysis, numerical modelling, and experimental measurements were used to examine the impact of important design parameters on energy efficiency, steam injection flow rate, and steam generation rate. The experimental samples were optimized using the I-Optimal design (RSM) technique. Furthermore, there was a strong similarity between the actual and projected values in both replies, especially in light of this particular experiment. There was a substantial agreement between the experimental and predicted values for the optimization, as indicated by the regression coefficient (R2) values. The following settings were tuned using numerical optimization techniques: steam inlet pressure (9.330), biomass (firewood and rice husk) utility (29.989), and motor speed levels (1226.145).

6. Recommendation

To improve the optimization of the energy efficiency and steam production rate of the steam boiler, more research and development in this field are encouraged to investigate further opportunities of finding better materials for parts like the insulator and combustion chamber. To maximize combustion efficiency in real-time, an advanced combustion control system that can continually monitor and modify the primary and secondary air distribution should also be included.

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