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The Optimization of Operational Parameters of a Biomass Fire-in-tube Boiler Using Taguchi Design Method

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Abstract This paper presented the optimization of the operational parameters of a biomass fire-in-tube boiler using Taguchi design method to enhance boiler thermal efficiency and throughput. Taguchi's experimental design of orthogonal array L9 (3^4) was employed to generate nine runs of experiment. Response surface method was used to optimize processing parameters and validated using Taguchi's table. Experimental results were analyzed and dependent operation parameters were predicted using linear multiple regression modeling. Hence, coefficients of correlations were established using Karl Persons's formula. The optimum operational parameters for boiler were 2 dm^2, 483.6 MJ, 100 L and 280 mm for aspirator orifice area, biomass composite, volume of cold water and vertical distance of fire grate to the kettle respectively. The coefficient of correlations between experimental and predicted values of super heated steam for temperature, pressure and volume were: 0.84, 0.96 and 0.89 respectively.

Keywords: *Taguchi design, optimization, biomass composite, vertical boiler, operation parameters*

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1. Introduction

1.1. Background

Boiler is a closed pressurized vessel, a fired heat exchanger in which heat is transferred continuously from a combustion chamber, converting cold water in the kettle into hot water, saturated and supersaturated steam above the atmospheric pressure [1,2,3]. There are eight types of steam boilers namely: fire-in-tube, water-in-tube, combine fire-in-tube and water-in-tube, packaged, fluidized bed combustion, stoker fired, pulverized fuel, waste heat and thermal fluid heater boilers [3,4]. The most common commercial and modern types of boiler are fire-in-tube and water-in-tube heat exchanger [5,6]. Generally, modern boiler system comprises of three compartments namely: a feed water system, steam system and fuel system. All boilers consist of a separate compartment where fuel is burned and a compartment where water can be evaporated into steam [7]. Boiler as a fired heat exchanger, transfer heat from hot region to cold region conventionally by the virtue of a temperature gradient, and it always flows in the direction of higher temperature to lower temperature. The three phenomenon of heat transfer (conduction, convection, and radiation) takes place complementarily during boiling nucleation inside the kettle of the boiler [7,8,9]. The feed water system regulates the feeding of cold water into the heat exchanger of the boiler automatically to meet steam demand. The steam system, which is referred as kettle, is made of shell and tube heat exchanger that convert the thermal energy from the combustion chamber into steam, while the fuel system includes all equipments assembled for effective combustion and conversion of fuel into thermal energy.

There are many types of heat exchangers, but the most applicable type is shell-and-tube heat exchanger which was adapted into fire-in-tube boiler [10]. This type of boiler has been broadly utilized in various industrial fields such as petrochemical engineering, food processing and agro-allied industries, breweries, canning confectionaries and energy generation plants, due to their structural simplicity, design flexibility and low cost [5,6]. It was reported to account for more than 35–40% of the heat exchangers used in global heat transfer processes. Therefore, it is of great importance to improve the thermal efficiency, throughput at lower economic cost of operation by optimizing operational parameters of newly developed fire-in-tube boiler using Taguchi's method. Previous researchers investigated the effective of shell and tube design variables on number of tubes, shell and baffles using mixed integer programming approach for optimization [11]. Chaudhari et al. [12] also adopted simulated annealing algorithm to minimize shell and tube heat exchanger surface area to maximize heat transfer coefficient. UNEP [13] considered nine independent variables to optimize shell and tube heat exchanger such as tube layout pattern, number of tubes, tube length, tube-to-baffle diameter clearance, tube outer diameter, tube wall thickness, and shell-to-baffle clearance, baffle spacing and baffle cut. These nine variables were optimized using non-dominated sorting genetic algorithm (NSGA II). Hadidi et al. [14] reported the designing of shell-tube fired heat exchanger using multi-objectives optimization approach to minimize the cost of running shell and tube heat exchanger. Turgut et al. [15] investigated the optimum design process for shell and tube heat exchanger using improved intelligent tuned harmony search algorithm. They adopted appropriate geometric configuration of working components and material selection based on allowable pressure and maximum temperature for the optimization of heat transfer coefficient.

The experimental design adopted in this study was Taguchi's orthogonal arrays developed by Dr. Genichi Taguchi in 1986 for quality engineering approach. It is a set of methodologies by which the independent variables or parameters are grouped using orthogonal arrays to generate few experimental runs instead of factorial design of several runs [16,17,18,19]. The application of this experimental design had become widespread in many United State of America and European industries after the 1980s. The advantage of Taguchi design over factorial design is that, multiple factors can be considered at once. In this study orthogonal arrays significantly reduced factorial design of 3^4 (eighty one runs) into nine experimental runs.

1.2. Objective

The main objective of this study was to investigate the optimum combination of operational parameters values for biomass fire-in-tube boiler using Taguchi's experimental design method.

2. Materials and methods

2.1. Description of the Boiler

A biomass fired fire-in-tube boiler was developed and installed as one of the unit operations of medium-scale oil palm processing mill located at Department of Agricultural and Environmental Engineering, Faculty of Technology, University of Ibadan. This biomass fire-in-tube boiler consists of these major working components namely: combustion chamber, kettle (shell and tube), and hot gas chamber, aspirator, and steam tank (Figure 1 and Figure 2). In Figure 1, (A) represented kettle, (B) represented cold water inlet duct, (C) represented super-heated steam flow direction, (D) represented outlet duct for the super-heated steam from the boiler. The combustion chamber is a fire-box that can accommodate 20 to 25 kg of biomass. The combustion chamber is of cylindrical shape made of mild steel material of $\theta\,600\times400\times3(mm)$ thickness. One third of its circumference was used as a door for the loading of biomass. The interior was reinforced with iron rod and casted with clay soil as an insulated wall of 35 mm thickness. The bottom was sealed with perforated collapsible fire grate of mild steel material for ash separation. The collapsible fire grate enhances regulation of this unit into three vertical levels (180, 280, and 380 mm) which vary the flame distance to the bottom of the kettle as shown in Table 1. Kettle is of shell and tube type of heat exchanger (Figure 1 and Figure 2). The shell was made of mild steel material of $\theta\,600\times500\times6\left(mm\right)$, internally arranged with 20 numbers of tubes of $\theta\,50\times500\times3mm$, welded together with the help of two suspended perforated plates. The holes were arranged in squared pattern with uniform point to center distance [10]. The total capacity of the kettle is about 150 litres. During the experiment design, the volumes of cold water were varied according to Table 1. The hot gas chamber of vertical height of 300 mm was welded to the upper part of the kettle, having the same diameter with the kettle. It has an external rectangular chute (150×120×250mm) that connected the aspirator which enhances random motion of the thermal energy along the internal walls of the tubes. In between aspirator and the chute, there was a shutter which regulates suction rate of hot gas, varied the surface area of the aspirator orifice and resisting counter current hot gas flow rate out of the aspirator. The three levels of aspirator orifice surface area observed were; 1, 2, 3 (dm^3). The steam storage tank is a pressure vessel of draw steel material, having a spherical shape, two half disc-end of $\theta\,600\times175mm$, joined together and suspended on the hot gas chamber. Both kettle and steam chamber were joined together with seamless pipe. This un-insulated fire-in-tube boiler has vertical height of 2.10 m. The calibrated transducers such as thermometer of 0 - 200°C, pressure gauge of 0- 8 bar and pressure relief valve of 10 bar were installed on steam chamber tank for measurement and control (Figure 2). All these working components were suspended on tripod stand made of angle iron 75 × 75 × 6 mm at vertical height of 750 mm.

2.2. Experimental Run

The operational parameters selected were design dimensions of these major working components of the developed boiler namely: orifice surface area of the aspirator, vertical distance of fire grate to the bottom of the kettle, volume of cold water inside the kettle likewise the biomass composite fed into the combustion chamber. They were varied at three levels as shown in Table 1. The heat content of biomasses of different composites of palm kernel shell, fibre and wood were measured using 2ke bulb-calorimeter. The biomasses composite of 20 kg were mixed together in ratio 1:2:3, 2:3:1 and 3:2:1 combinations (palm kernel shell, fibre, wood (*Dogonyaro tree*)) before they were loaded inside combustion chamber. Nine runs of experiment were observed by filling the kettle with known volume of cold water as depicted in Table 1. 20 kg of biomass composite was ignited during each run of experiment with corresponding orifice surface area of the aspirator. The inlet and outlet gate valve and blown down valve were close. The loading of biomass composite of a particular ratio continue until all were combusted. The maximum superheated steam pressure and temperature were recorded against each run. The steam generated for each run was discharged through non-return valve via gate valve into the sterilizer.

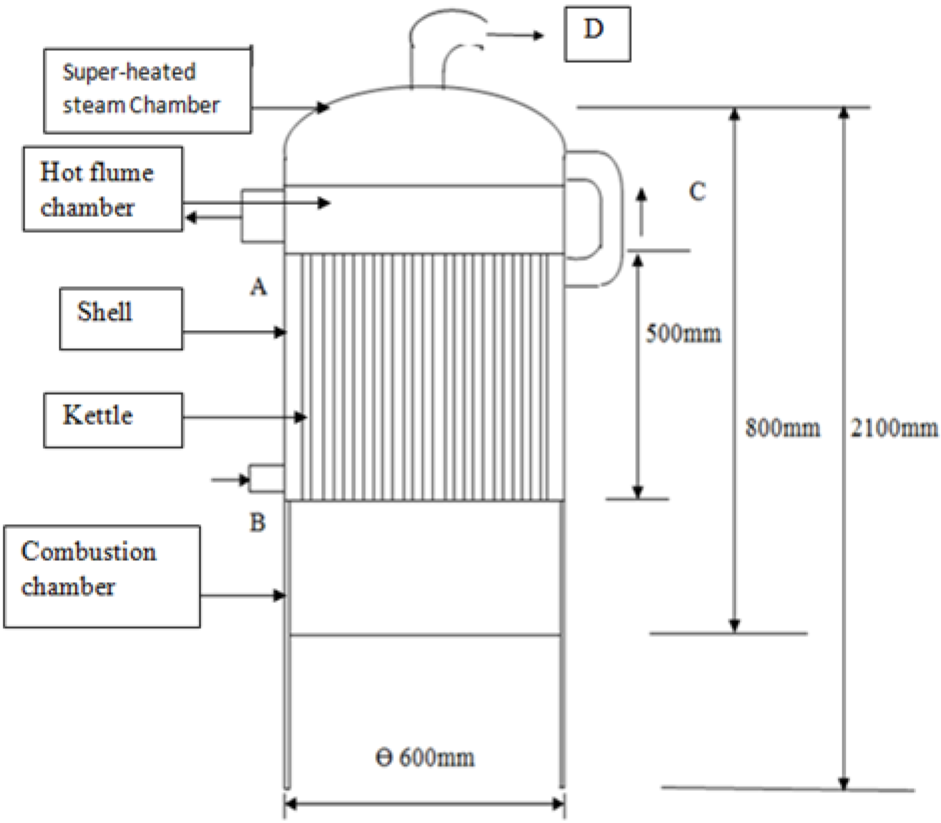


Figure 1. Schematic diagram of biomass fire-in-tube boiler

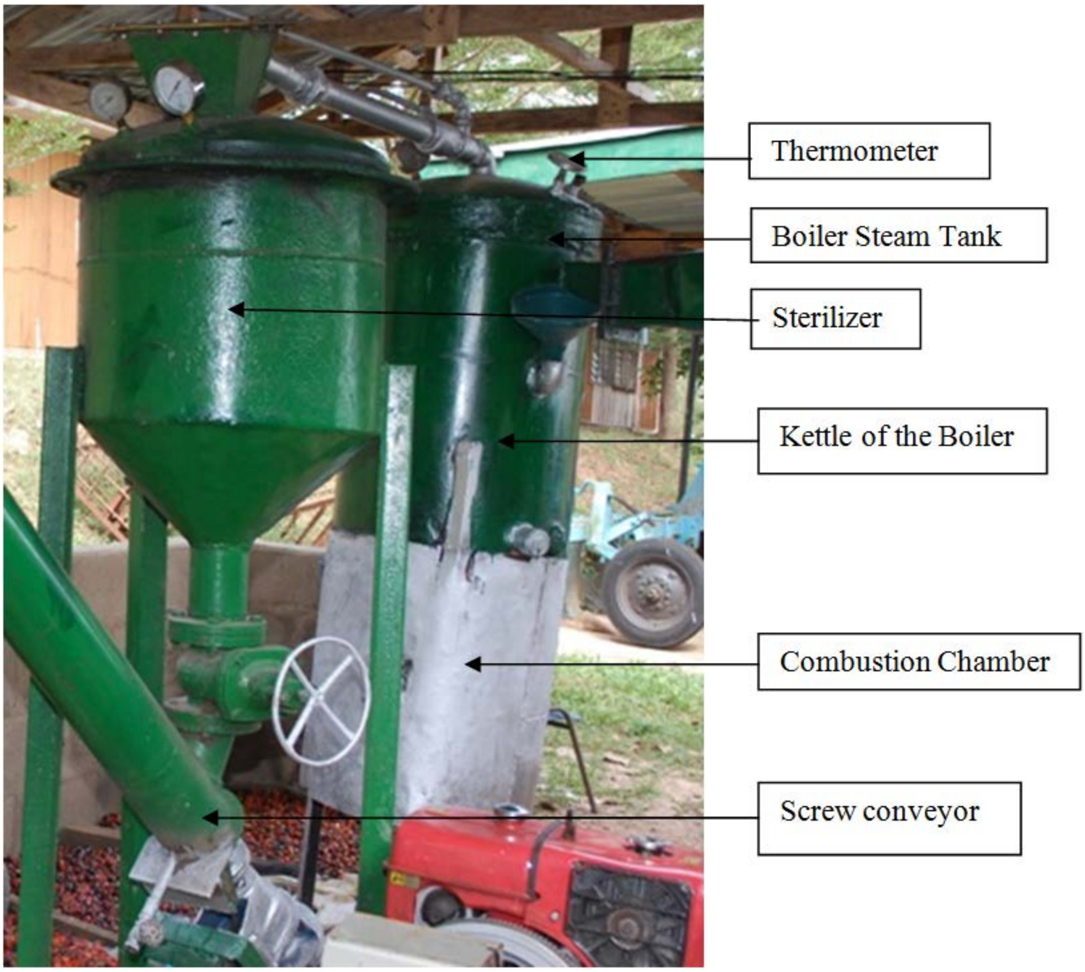


Figure 2. Vertical Sterilizer synchronized with Biomass boiler

Table 1. The operating parameters for experimental design of boiler operation

Operation Parameters	Level 1	Level 2	Level 3
A. Orifice Area of Aspirator (dm^2)	1	2	3
B. Vertical Distance of Fire Grate to the Kettle (mm)	180	280	380
C. Biomass Composite (MJ kg^{-1})	447.90	497.28	504.60
D. Volume of Cold Water (Litres)	80	100	120

Table 2. Experimental design of L9 orthogonal array (coded) for boiler evaluation

Runs of Experiments	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	3	2	3
5	2	1	3	1
6	2	2	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Table 3. Taguchi's experimental design for independent operation parameters of vertical boiler

	Operating Parameters			
Experiments	Orifice Area of Aspirator (dm^2)	Vertical distance from fire grate to kettle (mm)	Biomass composite (MJ kg^{-1})	Vol. of cold water (Litres)
1	1	180	447.90	80
2	1	280	497.28	100
3	1	380	504.60	120
4	2	380	497.28	120
5	2	180	504.60	80
6	2	280	447.90	100
7	3	180	504.60	100
8	3	280	447.90	120
9	3	380	497.28	80

2.3. Experimental Design

Orifice surface area of the aspirator, vertical distance of the fire grate to the bottom of the kettle, biomass composite and volume of cold water inside the kettle were optimized. These selected operational parameters were varied in three levels as depicted in Table 1. Taguchi's experimental design of orthogonal array L9 (3^4) was employed to generates nine experimental runs of independent operation parameters and were coded numerically (1,2,3 and 4) to generate matrix table of nine Orthogonal Array L9(3^4) shown as Taguchi's (Table 2), while their empirical values were shown as Table 3. The dependent variables used to characterize the thermal efficiency and throughput is superheated steam temperature, pressure and volume. The boiler was operated using experimental design Table 3 of Taguchi's experimental design of Orthogonal Array L9(3^4) and corresponding experimental results of each run which generated experimental dependent operational parameters were obtained. However, both independent and dependent experimental data were optimized using STATISTICA SIX SIGMA. This arrangement enhances the thorough investigation of the effect of each operation parameter independently and their level of interaction during operation of the boiler [19,20,21,22].

Desirability profiles of surface response were adopted to predict optimum independent operation parameters that generated corresponding optimum dependent operation parameters out of nine runs. These predicted optimum operational parameters were used to validate the optimal experimental run on Taguchi's tables. However, experimental results were analyzed using SAS system, windows 9.00 (2002) software packages and dependent operation parameters were predicted through linear multiple regression modeling with corresponding coefficients of determinations (R^2) for degree of reliability test. Furthermore, coefficient of correlations between independent and dependent variables were also calculated using Karl Persons formula (r^2) as depicted below.

Karl Persons coefficient of correlations formula r^2

$$= \frac{\sum\left(X-\bar{X}\right)\left(Y-\bar{Y}\right)}{\sqrt{\sum\left(X-\bar{X}\right)^2\sum\left(Y-\bar{Y}\right)^2}}. \quad [23]$$

3. Result and Discussion

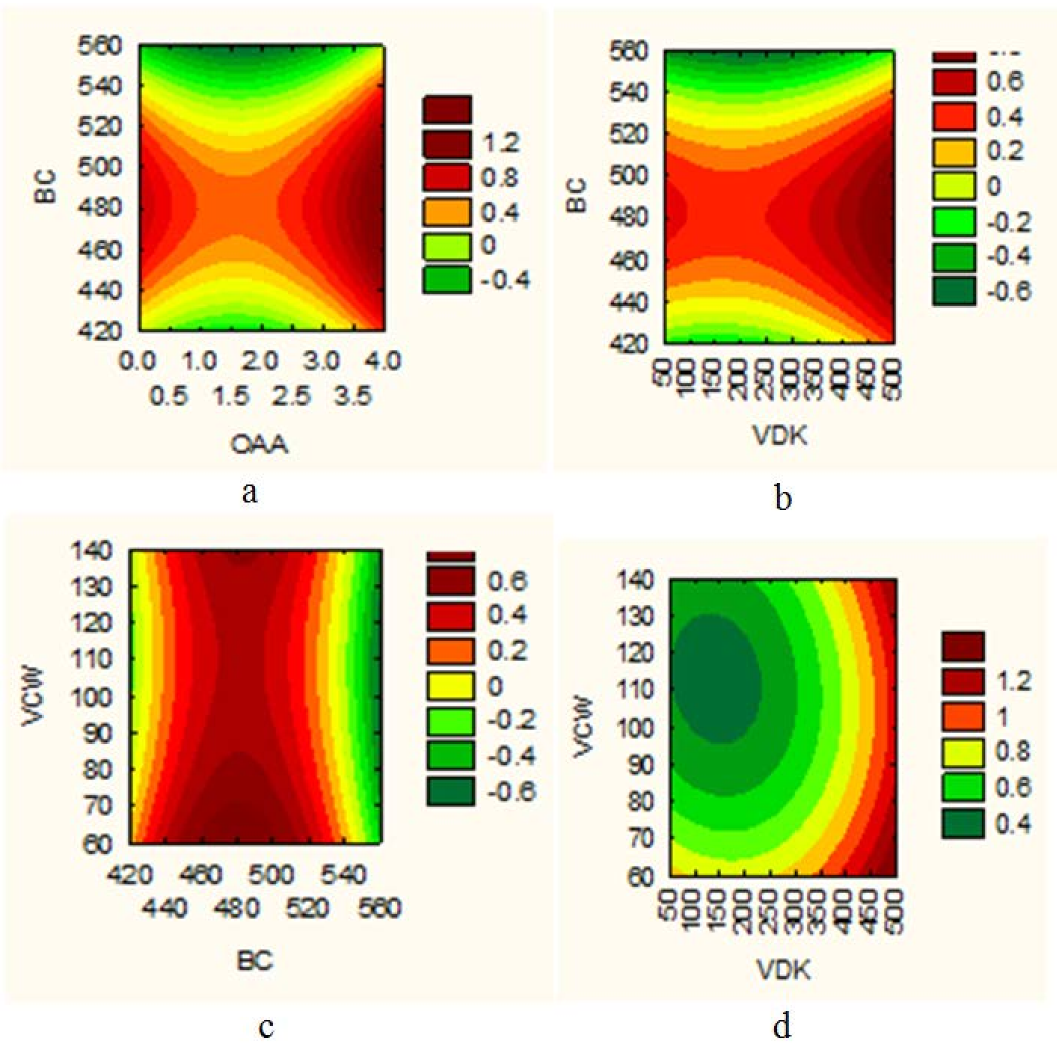
3.1. Optimization of Operation Parameters Using Response Surface Method (Desirability Contours and Profile)

Figure 3 and Figure 4 show desirability surface contour plot and desiribility profiles of surface response methods which were used for predicting the optimum independent processing parameters of biomass fire-tube boiler respectively. The graphical representation of contours in Figure 3 are distictively shown emperically in Figure 4. Hence, the vertical middle red dotted lines in Figure 4, clearly indicated the optimum desirable independent operation parameter values of 2 dm^2 , 280 mm, 483.26 MJ kg^{-1} and 100 litres for orifice area of aspirator, vertical distance of fire-grate to the bottom of kettle, biomass composite and volume of cold water respectively. These optimum desirable independent operation parameters generated optimum desirable dependent operation parameters as resultant values, showed as Figure 5 (a, b and c) having corresponding values of 151.36°C, 5.01 bar and 61.22 litres for super-heated temperature, steam pressure and super-heated steam volume, respectively.

3.2. Validation of Optimum Operation Parameters Using Taguchi's Method

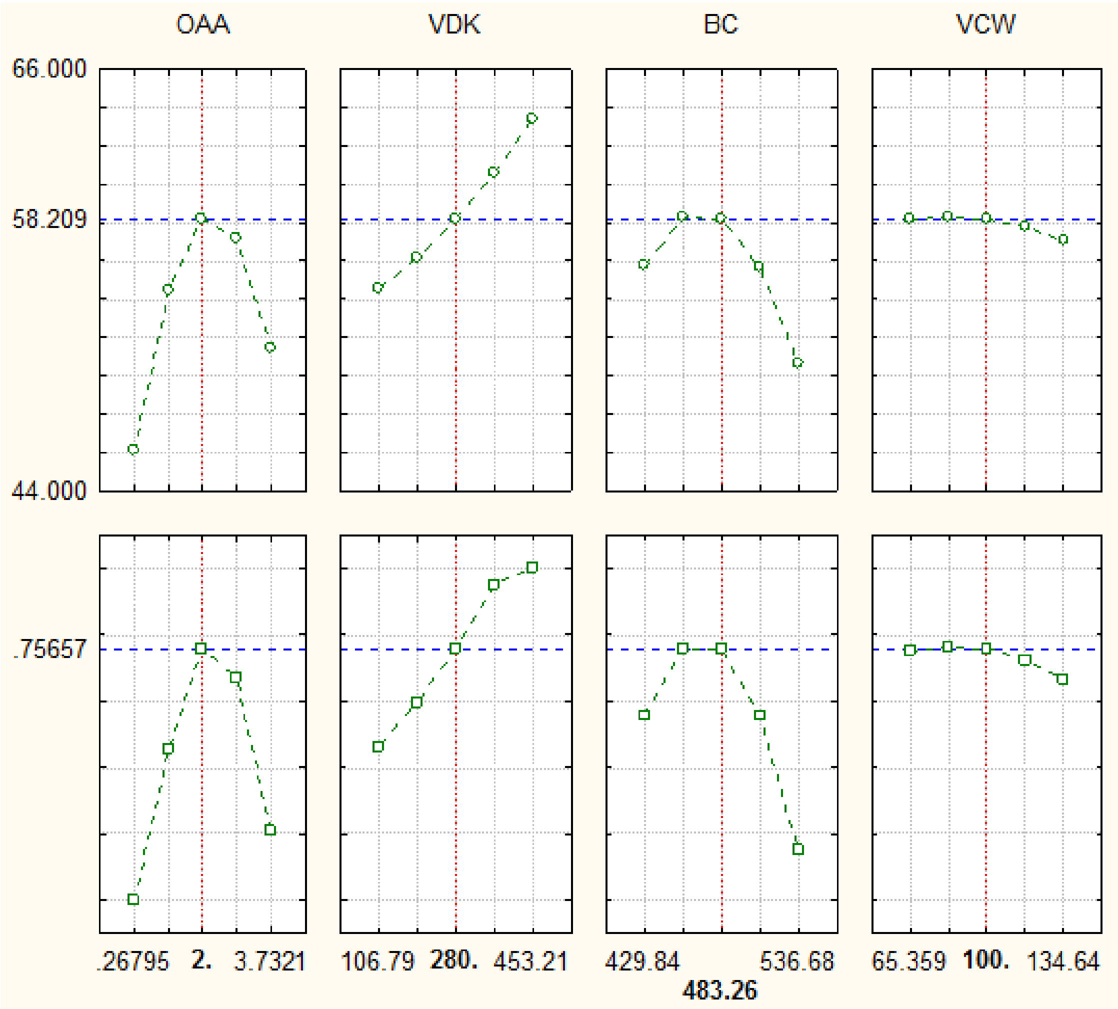
The optimum super-heated steam temperature and pressure that generated the maximum volume of super-heated steam of 60.5 litres in Table 4, occurs at experimental 6 of Taguchi's method. However, in comparison of both desirability profile (Figure 5c) and experimental Table 4 of Taguchi's method, the maximum volumes of super-heated steam were 61.22 litres and 60.5 litres, respectively. In Table 4, this optimum superheated steam of 60.5 litres was found to occur at experimental run number 6. Hence, optimum super-heated steam volumes in both desirable profile and Taguchi's method experimental result of Table 4 occurred at the same optimum independent operation parameters of experimental run number 6 of Table 3. Furthermore, this maximum volume occurred at maximum temperature and pressure of 155°C and of 5.5 bar respectively as depicted in Table 4 and was found to be the experimental run number 6.

Consequently, the experimental run number 6 in Table 3 of independent processing parameters that produced this highest volume of super-heated steam of 60.5 litres were at the values of 2 dm^2, 280 mm, 447.90 MJ kg^{-1} and 100 litres for orifice area of aspirator, vertical distance of fire-grate to the bottom of the kettle, biomass composite and cold water fed initially into the boiler kettle respectively. Hence, this experimental run number 6 could be seen as optimum experimental independent processing parameters for effective running of the newly developed biomass fire-tube boiler.



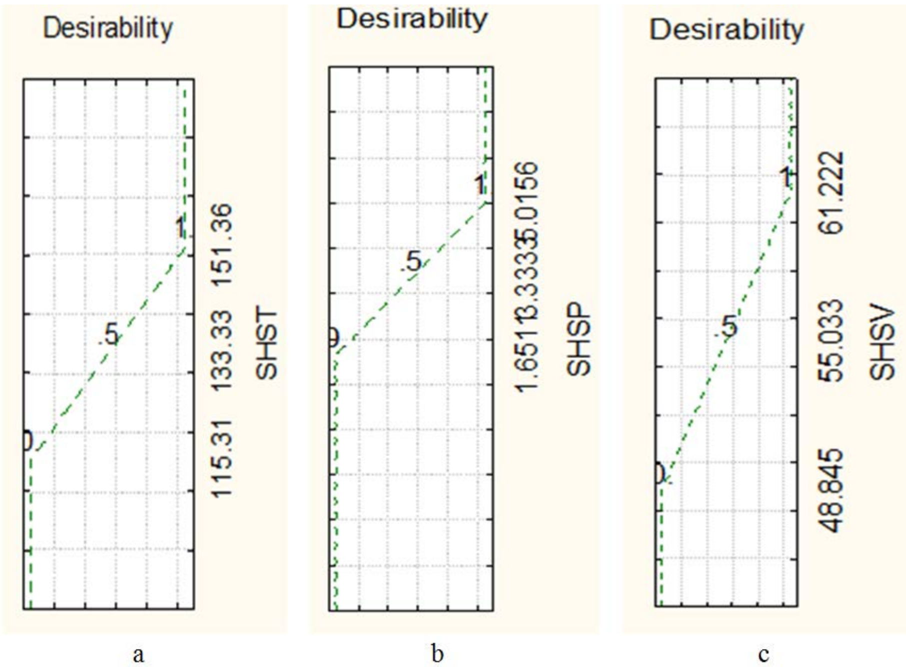
Key: OAA – Orifice Area of Aspirator, VDK – Vertical Distance of Fire-grate to the bottom of kettle, BC – Biomass Composite, VCD- Volume of cold water inside kettle.

Figure 3. Response Surface Contour Plots for predicting optimum desirable independent operation parameters using Quadratic Fit Method (a: Biomass composite against Orifice area of aspirator, b: Biomass composite against Vertical distance of fire grate to kettle, c: Volume of cold water against Biomass composite, d: Volume of cold water against Vertical distance of fire grate to kettle)



Key: OAA – Orifice Area of Aspirator, VDK – Vertical Distance of Fire-grate to the bottom of kettle, BC – Biomass Composite, VCW – Volume of cold water inside kettle.

Figure 4. Response surface desirability profiles for predicting independent operation parameters for vertical fire-tube boiler



Key: OAA –Orifice Area of Aspirator VCW – Volume of Cold Water, SHSV- Volume of Super Heated Steam

Figure 5. Response surface desirability profiles for predicting optimum dependent operation parameters (a: optimum superheated steam temperature (SHST) b: optimum superheated steam pressure (SHSP) c: optimum superheated steam volume (SHSV)

3.3. Degree of Relibility Test Using Regression Model

The results of linear multiple regression model equations was used for testing the degree of reliability between the predicting and experimental dependent operational parameters of the boiler. These parameters are: super heated steam temperature, pressure and volume as expressed in Equations 1, 2 and 3 respectively, with their corresponding coefficient of determinations R^2 as degree of reliability test.

$$\text{Superheated steam temperature} = 95.36 + 2.86X_1 + 0.03X_2 + 0.04X_3 + 0.03X_4 + \varepsilon, R^2 = 0.67 \tag{1}$$

$$\text{Superheated steam pressure} = 1.7748 + 0.23Y_1 + 0.0017Y_2 + 0.0005Y_3 + 0.0015Y_4 + \varepsilon, R^2 = 0.75 \tag{2}$$

$$\text{Superheated steam volume} = 52.101 + 1.50Z_1 + 0.025Z_2 - 0.0013Z_3 - 0.009Z_4 + \varepsilon, R^2 = 0.71 \tag{3}$$

Where: X_1, X_2, X_3, X_4; Y_1, Y_2, Y_3, Y_4; Z_1, Z_2, Z_3, Z_4, were independent processing parameters such as: orifice area of aspirator, vertical distance of fire grate to the bottom of kettle, biomass composite and volume of cold water for each predicted dependent operation parameters respectively. The coefficient of determinations R^2 as degree of reliability test of modeling Equations. 1, 2 and 3 between experimental and predicted dependent operation parameters are: 0.67, 0.75 and 0.71 for superheated steam temperature, pressure and volume respectively. Parameter test Table 5 was generated showing interrelationship between experimental dependent operation parameters to that of predicted dependent operation parameters of the vertical fire-in-tube boiler. Hence, coefficients of correlations (r^2) between experimental and predicted dependent processing parameters were established also using Karl Persons formula are: 0.80, 0.96 and 0.89 for superheated steam temperature, pressure and volume respectively [23]. These values were closer to 100%, indicating close relationship between the experimental and predicted values. Therefore to achieve optimum and desirable thermal efficiency and throughput of the newly developed biomass fire-tube boiler, it must be operated using independent operation parameters number 6 of Taguchi Table 3. In Table 5, the predicted dependent operational parameters values for temperaure, pressure and volume of super-heated steam were found to be higher than that of experimental independent operation parameters values. However, experimental and predicted dependent optimum processing parameters were significant different ($p<0.05$) to each other in terms of temperature, pressure and volume of super heated steam generated.

Pietila [24] used Taguchi method in optimizing combustion parameters of wood in biomass stove. The combustion parameters such as temperature of the fire chamber, quality of the biomass in terms of heat content, initial moisture content of biomass, sizes of the biomass in terms of their surface area and air feed rate which is related with vertical distance of fire grate to the roof of the stove was reported. Pietila [24] reported that optimal thermal efficiency depend on the vertical distance of the fire grate to the roof of the stove, while intensive combustion was observed with 3 kg biomass, 1100 litre min^{-1}. air feed rate, biomass of initial moisture content of 10% and large wood size of 30% higher surface area than small size. This finding is similar to what was observed in this work, as the vertical distance of fire grate to the bottom of kettle increased from 180 to 280 mm, the volume of super-heated steam generated increased from 50.8 to 60.5 litres as optimum throughput value that generated optimum thermal efficiency (Table 3 and Table 4). Furthermore, it was observed that at a constant speed of aspirator via the hot air orifice, the optimum desirable orifice surface area that enhances optimum thermal efficiency and throughput of boiler was 2 dm^2. At 1 dm^2, the maximum super-heated steam generated was 54.0 litres, with the vertical distance of fire grate to the kettle of 380 mm as shown in Table 3. This means that the rate of heat and mass transfers in the kettle has gradually reduced. However, at vertical distance of 180 mm, minimum super-heated steam was generated. At this point, it was observed that, the flame propagation at this vertical distance of 180 mm does not enhance complete combustion of biomass. It was also observed that at the orifice area of 3 dm^2, heat lost to the environment through the chimney was enormous and it does not conserve thermal energy that could have transferred quantum thermal energy to the steam chamber of the boiler.

Table 4. Experimental Result for Optimum dependent Processing Parameters of Vertical Boiler

Experiments	Super Heated Temperature (°C)	Steam Pressure (Bar)	Volume of Super Heated Steam Generated (Litres)
1	125	2.8	50.80
2	130	3.0	52.50
3	135	3.2	54.00
4	125	2.8	54.40
5	130	3.0	56.50
6	155	5.5	60.50
7	135	3.2	52.50
8	135	3.5	55.60
9	130	3.3	58.50

Table 5. Experimental and Predicted Values of Dependent Operation Parameters for Boiler

Exp.	ESHST (°C) X_T	PSHST (°C) Y_T	ESHSP (Bar) X_P	PSHSP (Bar) Y_P	ESHSV (litre) X_V	PSHSV (litre) Y_V
1	124.8	123.57	2.8	2.66	50.8	51.61
	125	123.57	2.75	2.66	50.75	51.61
	125.2	123.57	2.8	2.66	50.85	51.61
2	130.5	128.85	2.95	2.89	52.5	53.29
	130	128.85	3.2	2.89	52.5	53.29
	129.5	128.85	2.95	2.89	52.4	53.29
3	135	132.43	3.2	3.09	54	55.50
	135	132.43	3.25	3.09	54.2	55.50
	134	132.43	3.15	3.09	54	55.50
4	125	129.60	2.8	2.97	54.4	52.10
	124.8	129.60	2.75	2.97	54.6	52.10
	125.2	129.60	2.85	2.97	54.3	52.10
5	130.5	131.45	3	3.09	56.5	54.88
	131	131.45	3.05	3.09	56.5.3	54.88
	128.5	131.45	2.95	3.09	56.2	54.88
6	130	132.42	5.05	4.27	60	57.91
	130.5	132.42	5	4.27	60.7	57.91
	129.5	132.42	4.95	4.27	60.8	57.91
7	135	132.16	3.2	3.18	52.5	53.69
	135.5	132.16	3.25	3.18	52.75	53.69
	134.6	132.16	3.15	3.18	52.35	53.69
8	135.7	133.12	3.55	3.35	56.3	56.72
	135	133.12	3.5	3.35	55.6	56.72
	134.3	133.12	3.45	3.35	54.85	56.72
9	130	130.0	3.3	3.49	58.5	58.96
	130.5	130.50	3.25	3.49	58.65	58.96
	130	130.20	3.35	3.49	58.3	58.96
r^2		0.80		0.96		0.89
R^2		0.67		0.75		0.71

Coefficient of correlation $(X_T,Y_T) = r_T^2 = 0.80$, Coefficient of correlation $(X_P,Y_P) = r_P^2 = 0.96$ Coefficient of correlation $(X_V,Y_V) = r_V^2 = 0.89$.

Key: ESHST- Experimental Super Heated Steam Temperature, PSHST- Predicted Super Heated Steam Temperature, ESHSP- Experimental Super Heated Steam Pressure, ESHSP- Experimental Super Heated Steam Pressure, ESHSV- Experimental Super Heated Steam Volume, ESHSV- Experimental Super Heated Steam Volume.

Previous researchers reported similar observation using biomass boiler. Johanssona et al. [25] reported that the amount of emission during biomass combustion depend on the quantum of air supply into the furnace. Hansen et al. [26] reported the same observation, that regulated conditions must be observed specifically in the pellet boiler furnace to reduced amount of emission. While many other researchers posed that emission rate must be minimal in biomass fired boiler to enhance optimum combustion parameters for maximum thermal efficiency [27,28,29]. The experimental run number 5 could have been the likely optimum experimental run by considering Fourier law principle of heat transfer, having lesser volume of cold water of 80 litres, while the maximum heat content of biomass composite of 504.60 MJ kg^{-1} were combusted. However, it was not so, due to its insufficient vertical distance of fire grate to the kettle of 180 mm instead of 280 mm. Therefore pyrolysis stage of incomplete combustion characterized the burning pattern of biomass for a longer period during this experimental run number 5 which resulted to lower super-heated steam volume generated of 56.50 litres. The same trend was observed during experimental number 7, in Table 3, as the vertical distance to the kettle decreased to 180 mm, the combustion of 504.60 MJ kg^{-1} of biomass composite resulted into incomplete combustion with enormous emissions of carbon mono-oxide. The resultant effect of this could be seen in Table 4 which shown almost the lowest volume of superheated steam generated. Tseng et al. [30] also reported the application of Taguchi's method for optimizing experimental runs of biomass material pretreatment on microwave to enhance combustion. It was reported that the optimal pretreatment parameters combination are 150 ml, 0.05 kW and 5 g of vessel capacity, heating power and mass of biomass material respectively. They reported that application of Taguchi method coupled with microwave-based heating for pretreatment of the cellulosic biomass reduce the parameter combination variations. More importantly, a specific vessel capacity of water enhances optimum and adequate heat and mass transfer related to weight and heat content of biomass utilized coupled with heating power in forced convection. Kirsanvos et al. [29] optimized the combustion process of biomass inside a small scale pellet boiler and the importance of adequate air supply was reported that it enhances complete combustion, optimum thermal efficiency, and emission density and boiler capacity.

4. Conclusion

The optimum predicted independent and dependent processing parameters of the boiler were 2 dm^2, 483.6 MJ, 100 litres and 280 mm, 151°C, 5.01 bar and 61.22 litres for aspirator orifice area, biomass composite, volume of cold water and vertical distance of fire grate to the kettle, super heated steam temperature, pressure, and super heated steam volume respectively. This result comfirmed the suitability of Taguchi method to generate minimum experimental runs that enhances effective operation of this boiler for maximum thermal efficiency and throughput. This investigation has corrected un-scientific loading of biomass composite into the boiler.

Acknowledgements

Department of Agriculture and Environment Engineering, University of Ibadan, Nigeria and Department of Food Science and Technology, Obafemi Awolowo University, Ile-Ife, Nigeria.

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