American Journal of Mechanical Engineering, 2018, Vol. 6, No. 3, 114-126
Available online at http://pubs.sciepub.com/ajme/6/3/4
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DOI:10.12691/ajme-6-3-4

Performance Evaluation of a Forward Curved Blower for Thermal Applications

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Received August 17, 2018; Revised October 02, 2018; Accepted November 23, 2018

Abstract This paper presents the performance evaluation of a forward curved blower, for air supply at high temperature thermal applications such as incineration and biomass gasification. For such an application to be successful, and work as intended, the blower and system must be compatible both structurally as well as from a performance standpoint. Tests were carried out in order to determine the performance of the designed blower under actual working conditions. Agricultural wastes such as: groundnut shell, rice husk and bagasse were used to carry out these tests in an existing incinerator. A constant mass of 20 kg each was measured for the variables and fed into the incinerator. The blower was operated at rotational speeds and air velocities of 3203 rpm, 3111rpm, 3078 rpm and 24.4m/s, 23.8m/s, 21.3m/s as measured using a tachometer and anemometer respectively. Temperatures were recorded using two digital thermocouples at 300 seconds intervals. The obtained data were varied at nine levels and laid in randomized complete design (RCD) which was replicated three times for a total of 243 experimental treatments. The Design Expert software version 7.0 was used to analyze and interpret the experimental data. A peak temperature of 891°C was recorded at 3111 rpm and an air velocity of 23.8 m/s. Major characteristics of the blower such as the power output and mechanical efficiency were obtained as 0.56 kW and 62% respectively. The designed blower is suitable for gasification operations which require temperatures of about 750°C.

Keywords: *forward curved, power output, volumetric flow rate, mechanical efficiency, gas velocity*

Cite This Article: Abubakar A. Bukar, M. Ben Oumarou, Fasiu A Oluwole, and Sahabo Abubakar, "**P**erformance Evaluation of a Forward Curved Blower for Thermal Applications." *American Journal of Mechanical Engineering*, vol. 6, no. 3 (2018): 124-126. doi: 10.12691/ajme-6-3-4.

1. Introduction

A blower is considered to be a particular type of fan specifically a motor – driven centrifugal fan that delivers air or gases to the conditioned space under pressure. Blowers have many applications in which they can be used. For such an application to be successful, and work as intended, the blower and system must be compatible both structurally as well as from a performance standpoint. Major considerations; relating to blower type and performance are: the type, design and rating parameters. Application characteristics are usually reduced to clean or dirty air, normal or high temperature, fume or gas control, low or high erosion, etc. [1].

Several researches have gone into systematic design of centrifugal blowers. Over the years, various authors have suggested different procedures, although each has a slightly different method but the broad underlying principles are similar [2-18].

Dhande *et al.* [19] carried out a performance evaluation of a centrifugal blower of air assisted sprayer for orchard pesticide application by designing a forward curved blade and blower casing to deliver the air of 3m^3/s for 35hp tractor . The blade shape, blade inlet and outlet angle and blade inclination angle which have the best performance were considered. Jayapragasan *et al.* [20] analyzed the importance of centrifugal fans role in the proper functioning of a travelling cleaner. The blades of the fan were fixed between the inner and outer diameters. Jayapragasan and Janardhan [21] presented a CFD modeling and experimental investigation of waste collection blower by comparing the analytical and experimental results for forward and radial fan blower with same volute to standardize for both applications. They concluded that the radial blower appeared to be better in centralized waste collection system for higher performance and functionality.

Ehsan *et al.* [22] discussed the Effect of Number of Blades on the Performance of Ceiling Fans by carrying out a parametric study and observed that increasing number of blades while Muna *et al.* [23] discussed and presented an Experimental and Numerical Investigation to study the effect of adding slots to the blades on rotating stall phenomenon and pressure fluctuations in centrifugal blower.

This paper focuses on the testing and performance evaluation of a previously constructed forward curved blower [24], for air supply at high temperature thermal applications such as incineration and biomass gasification. Performance characteristics such as the: air density, gas velocity, volumetric flow rate and the mechanical efficiency of the blower will be determined through several tests.

2. Materials and Methods

2.1. Materials/Equipment

The materials used for this performance evaluation are: Rice husk, groundnut shell and bagasse, while the equipment used for these tests were: a blower [24], an existing incinerator, one (1) digital tachometer DT-2234 B photo type, 0.1 rpm-5-999 rpm, 1 rpm-1,000-99,999 rpm; one (1) Digital Anemometer CT LUTRON SP-8001, one (1) digital stop watch SUNWAY S1-1025, two (2) RKC Rex- C700 digital thermocouples with ranges of 0-1100^{o}C. The blower has a 0.75 hp ATLAS motor mounted and being powered by a 950 Tiger generator. The Design Expert software version 7.0 was used to analyze and interpret the experimental results.

2.2. Methods

Several tests were carried out in the faculty of engineering, University of Maiduguri in order to determine the performance of the designed blower [24] under actual working conditions. Agricultural wastes such as: groundnut shell, rice husk and bagasse were used to carry out these tests in an existing incinerator. A constant mass of 20kg each was measured for the variables and fed into the incinerator. The blower was operated with rotational speeds and air velocities of 3203 rpm, 3111rpm, 3078 rpm and 24.5 m/s, 23.8m/s, 21.3m/s using a tachometer and anemometer respectively. The ambient temperature was ranging from 29°C to 33°C while the temperatures at points 1 and 2 were recorded using thermocouples at intervals of 300 seconds using a digital stop watch.

The experimental factor considered in this work were agricultural feedstock at three levels (3) rice husk, bagasse, and groundnut shell and operated at different blower speed with an air velocity varied at three levels each (3203 rpm, 3111 rpm, and 3078 rpm) and (24.5m/s, 23.8m/s and 21.3m/s) respectively. A time interval of 300 seconds was considered while the experimental factor was varied at nine (9) levels. The obtained data were laid in Randomized Complete Design (RCD) and was replicated three times making a total of (3×3×3×9 = 243) experimental treatments.

2.3. Analysis of Blower Technical Characteristics

The blower technical characteristics are determined using formulas as suggested by Vibhakar and Chaniwala [2].

1.) Air density (ρ):

$$1.325\times\left(\frac{P_b}{T_a}\right) \qquad (1)$$

2.) Air velocity (V $_{(i.o)}$):

$$1.096.2\times\sqrt{\frac{P_{v(i,o)}}{\rho}} \qquad (2)$$

3.) Duct cross sectional Area (A $_{(i,o)}$):

$$\frac{\pi\times d_{(i,0)}^2}{4} \qquad (3)$$

4.) Volumetric flow rate (Q $_{(i,o)}$):

$$V_{(i,o)}\times A_{(i,o)} \qquad (4)$$

5.) Avg. Volumetric Flow Rate (Q_{avg})

$$\frac{Q_i+Q_0}{2} \qquad (5)$$

6.) Power Output of Fan (W_o)

$$\frac{Q_{avg}x\Delta P_s xK_p}{6362}x\frac{0.746kw}{1hp} \qquad (6)$$

7.) Mechanical Efficiency of Fan (η_f)

$$\frac{W_o}{W_i} \qquad (7)$$

Where:
P_b = Barometric pressure, Pa
T_a= Absolute temperature, °C
$P_{v\,=}$ inlet and outlet dynamic pressure, P
ρ = Density, kg/m^3
d= Duct diameter, m
V $_{(i.o)}$ =inlet and outlet velocity, m/
A $_{(i,\,o)}$ = Duct cross sectional Area, m^3
Q_i = inlet volumetric flow rate, m^3/s
Q_o = outlet volumetric flow rate, m^3/s
ΔP_s= static differential pressure, Pa
K_p=Air compressibility factor
W_o = power output of blower, kW
W_i= power input to blower driver shaft, kW.

3. Results and Discussion

3.1. Effects of Air Velocity and Operating Time on Specific Feed Stock Using Thermocouple T1.

The Model F-value of 205.48 in Table 1, implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, C, BC, A^2, B^2, A^2B, A^2C, B^2C, A^3 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. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 56.489 indicates an adequate signal. This model can be used to navigate the design space.

Table 1. ANOVA Response Surface Cubic Model for T1

Analysis of variance table [Classical sum of squares - Type II]						
Source	Sum of Squares	df	Mean Square	F Value	p-value Prob> F	
Model	3395424	21	161686.9	205.482	< 0.0001	significant
A-Air velocity	7726.401	1	7726.401	9.819203	0.0025	
B-Time	1652742	1	1652742	2100.409	< 0.0001	
C-Feed stock	747494.2	2	373747.1	474.9816	< 0.0001	
AB	26.72812	1	26.72812	0.033968	0.8543	
AC	942.8785	2	471.4392	0.599135	0.5522	
BC	647364.9	2	323682.4	411.3562	< 0.0001	
A^2	36162.56	1	36162.56	45.95768	< 0.0001	
B^2	156898.5	1	156898.5	199.3966	< 0.0001	
A^2B	8456.484	1	8456.484	10.74704	0.0016	
A^2C	28326.26	2	14163.13	17.99941	< 0.0001	
AB^2	803.6967	1	803.6967	1.021389	0.3158	
B^2C	26521.15	2	13260.58	16.85239	< 0.0001	
A^3	3239.884	1	3239.884	4.117451	0.0464	
Residual	53506.92	68	786.8665			
Cor Total	3448931	89				

The final Equation in Terms of Coded Factors for Thermocouple 1 could be written as

$$\begin{aligned} T1 = & -313.31+1605.44A+186.14B+153C_1 \\ & -16.27C_2+122.83BC_1+59.64BC_2+831.69A^2 \\ & -115.49B^2+50.83A^2B-78.78A^2C_1+19.83A^2C_2 \\ & +29.70B^2C_1+38.81B^2C_2-1599.53A^3 \end{aligned} \tag{8}$$

Table 2. Statistical values of data generated using T1.

Std. Deviation	28.05114
Mean	488.1444
R-Squared	0.984486
Adj R-Squared	0.979695
Pred R-Squared	N/A
Adeq Precision	56.48944
C.V. %	5.746484
PRESS	N/A

The effects of air velocity and operating time on a specific feedstock are shown in Figure 1 - Figure 3, with Figure 3 showing a more pronounced effect. This waved shaped plot of the temperature could be attributed to the density and moisture content of the agricultural waste samples. The low temperature at the left hand side of the graph is as a result of the start-up conditions within the incinerator. The progressive drops at the centre result from the moisture content of agricultural waste samples. These drops deepen from Rice husk, Bagasse and lastly groundnut shell. This shows that most of the energy released is used to drive away the moisture, before the graph rises sharply to the right showing that the moisture has been overcome and all the remaining energy can be used to release more heat for the purpose intended. Another reason could be the frequent opening and closing of the incinerator door to assess the burning of the agricultural waste samples.

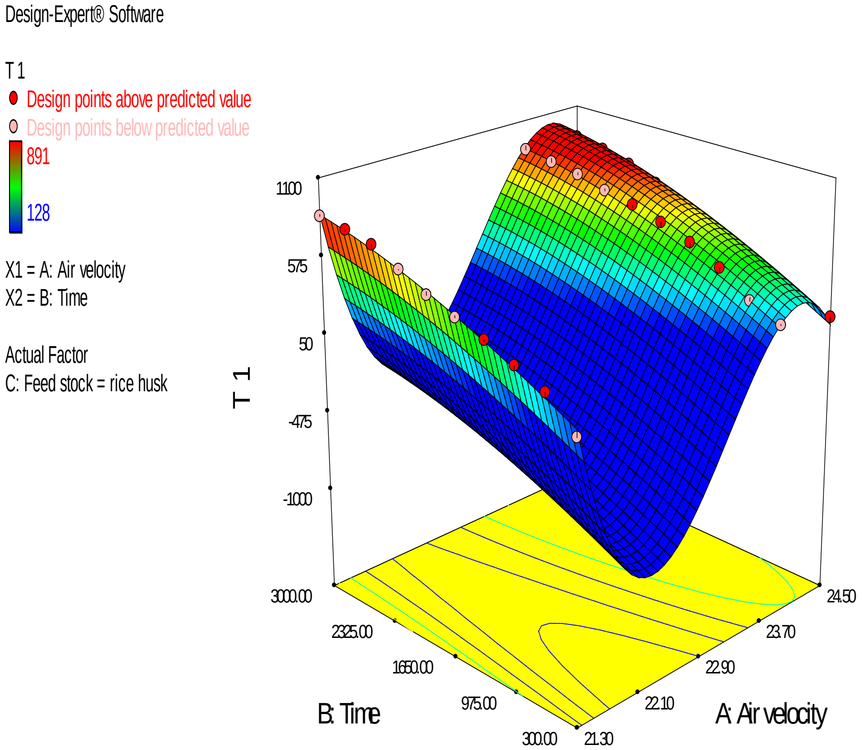

Figure 1. Relationship of Air velocity, Time for Rice husk using Thermocouple 1

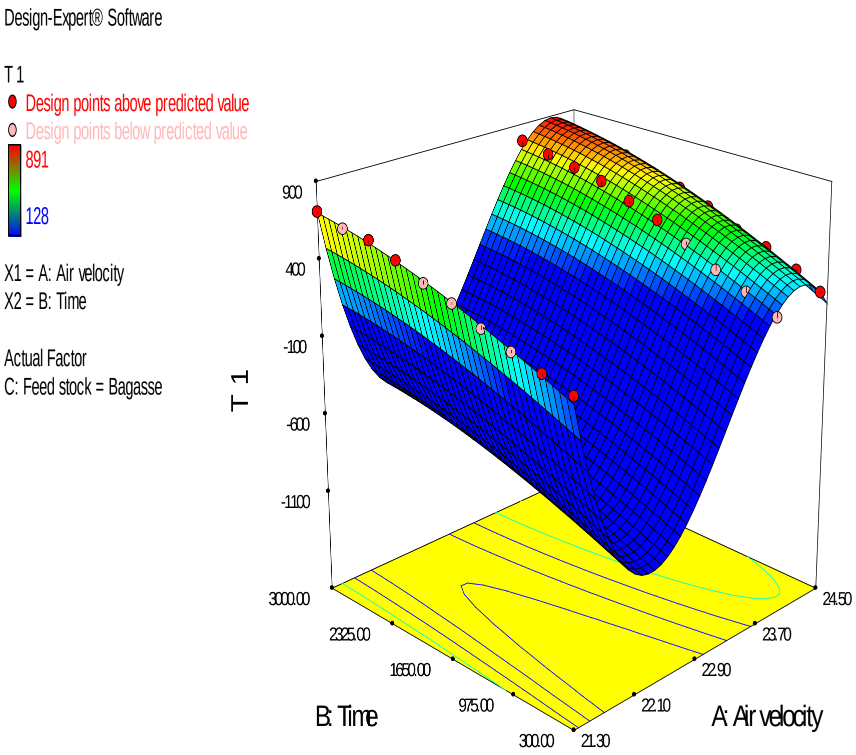

Figure 2. Relationship of Air velocity, Time for Bagasse husk using Thermocouple 1

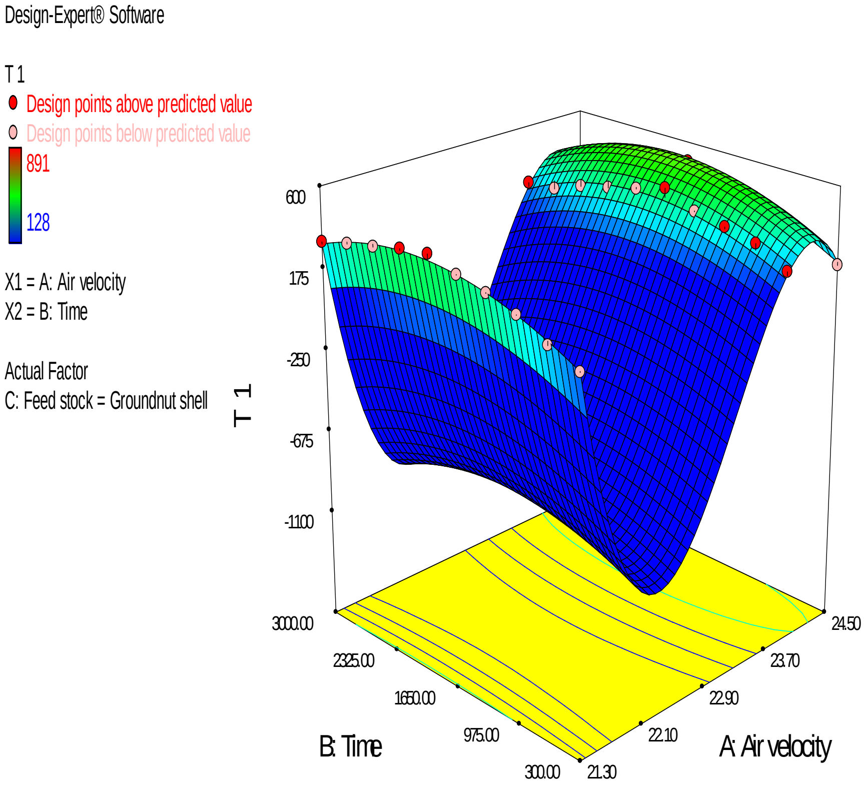

Figure 3. Relationship of Air velocity, Time for Groundnut shell using Thermocouple 1

3.2. Effect of Time on the Various Agricultural Waste Samples Using Thermocouple T1

Figure 4- Figure 6 show a comparison of the effect of air velocity on the feedstocks under consideration. These graphs show clearly the interactions of the various agricultural waste samples in one graph at the level of thermocouple T1, at different time intervals, namely 300 seconds, 1650 seconds and 3000 seconds respectively. The graphs tend to detach themselves from each other, but preserving the same shapes as shown by the R-square value of 0.9844 in Table 2. As the time increases, the temperature falls then rises again. This pattern is due to

the experimental set up in which the air being blown by the blower burns; first, the agricultural waste sample in the direction of flow of its duct. The agricultural waste sample in that zone is completely burned. Thus the temperature will rise sharply when the process starts and declines as the waste is being consumed. Secondly, as the temperature declines from the first stage, the air being blown starts burning the remaining agricultural waste sample at the surroundings of the blower ducts. That waste could also be pushed back into the direction of flow of the blower duct.

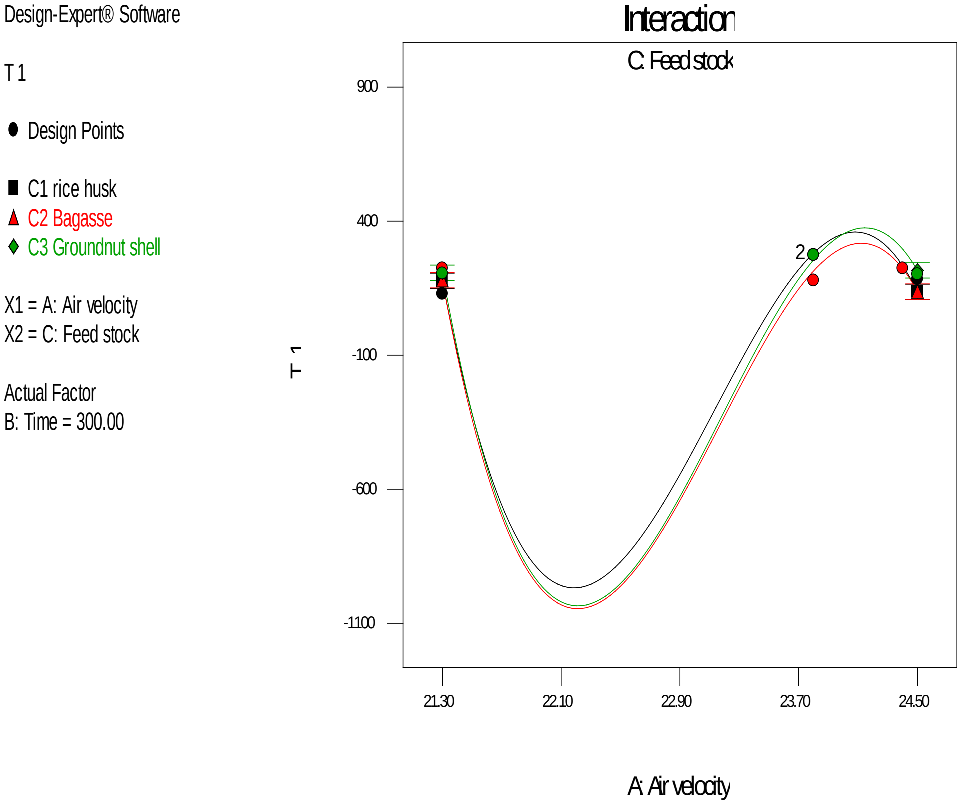

Figure 4. D comparative graph of agricultural waste samples at t= 300 sec, using Thermocouple T1

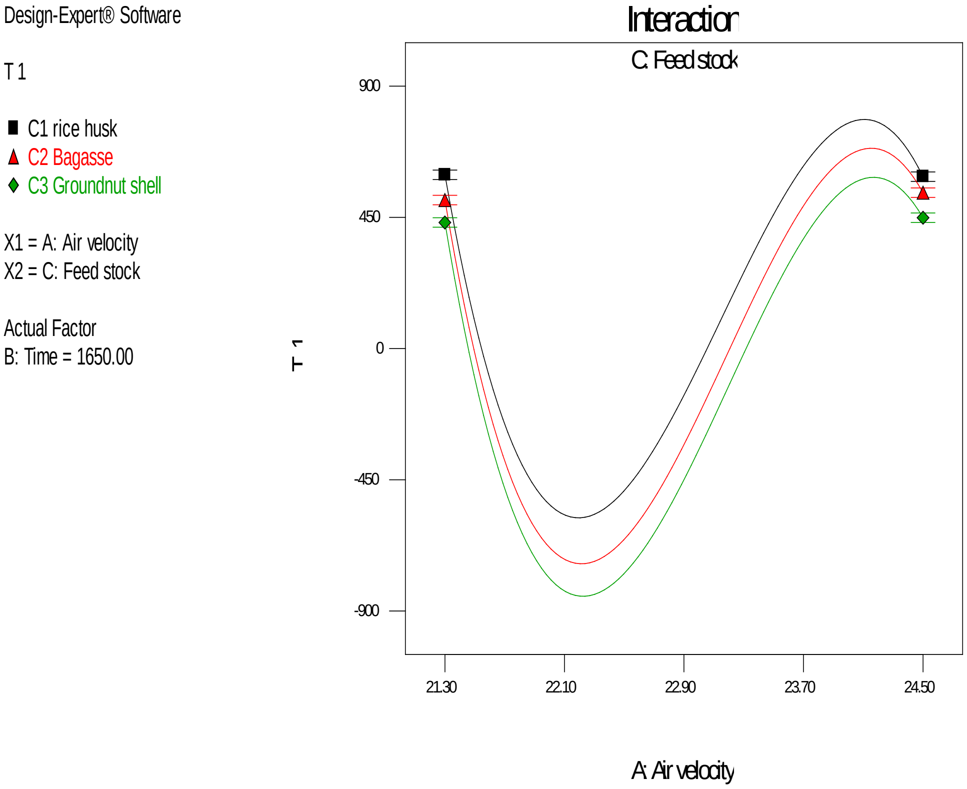

Figure 5. 2D comparative graph of agricultural waste samples at t= 1650 sec, using Thermocouple T1

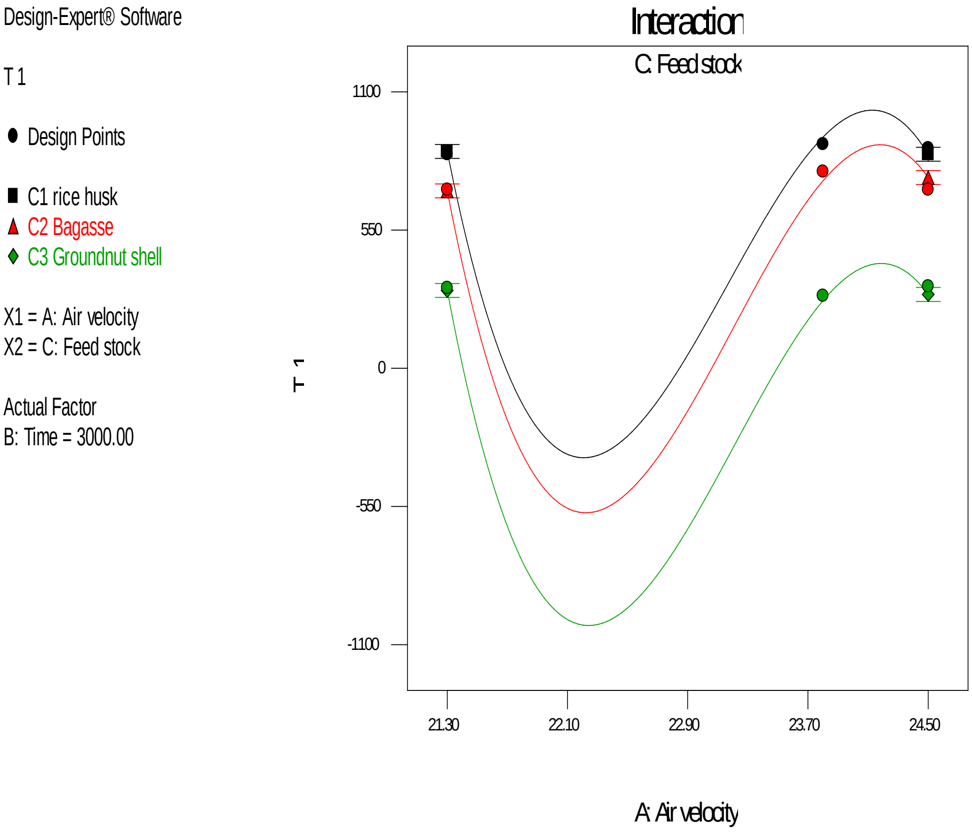

Figure 6. 2D comparative graph of agricultural waste samples at t= 3000 sec, using Thermocouple T1

3.3. Comparative Effect of Time on Air Velocities Using Thermocouple T1.

Figures (7 - 9) show the interaction between feedstock and operating times at different air velocities. It is observed that rice husk gave the highest temperature followed by bagasse and the least being groundnut shell. It was also observed that for rice husk and bagasse, the temperature increases continuously while for groundnut shell the temperature increases to a maximum value of 494°C at operation time of 1650 seconds thereafter decreases, while using Thermocouple T1.

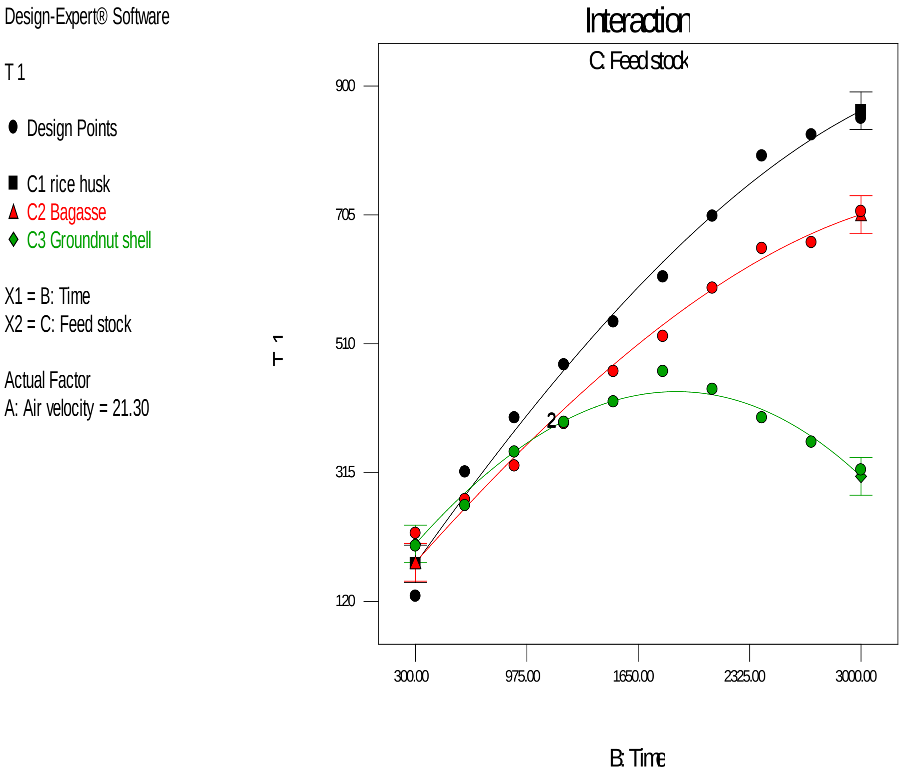

Figure 7. Line graph showing interaction between feedstocks and operating time at 21.3 m/s using Thermocouple T1

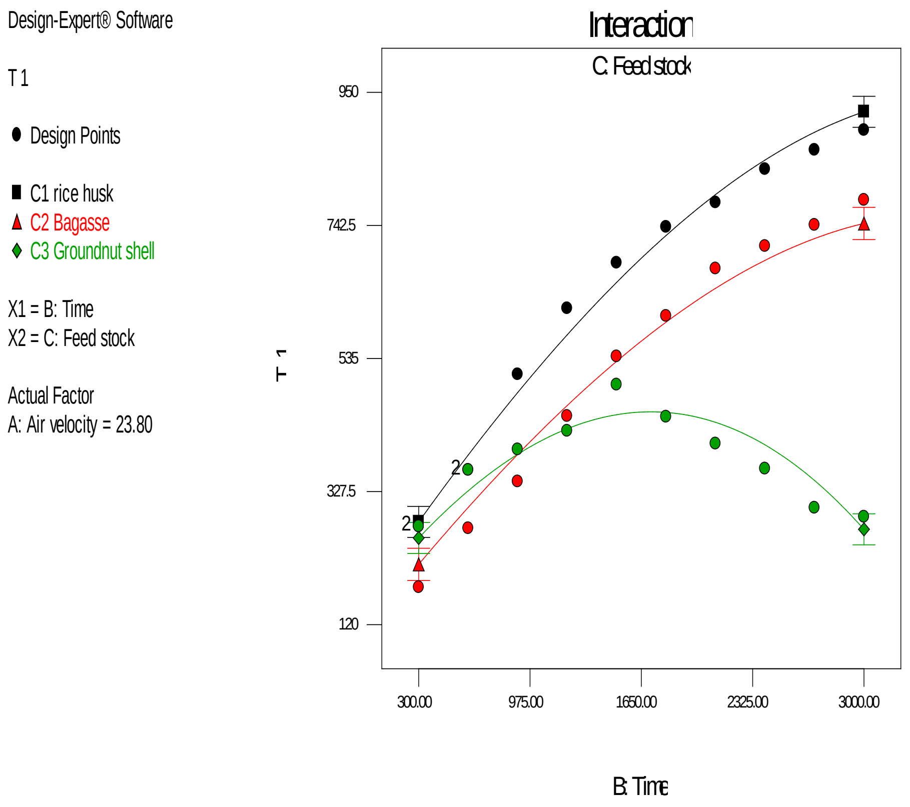

Figure 8. Line graph showing interaction between feedstocks and operating time at 23.8 m/s using Thermocouple T1

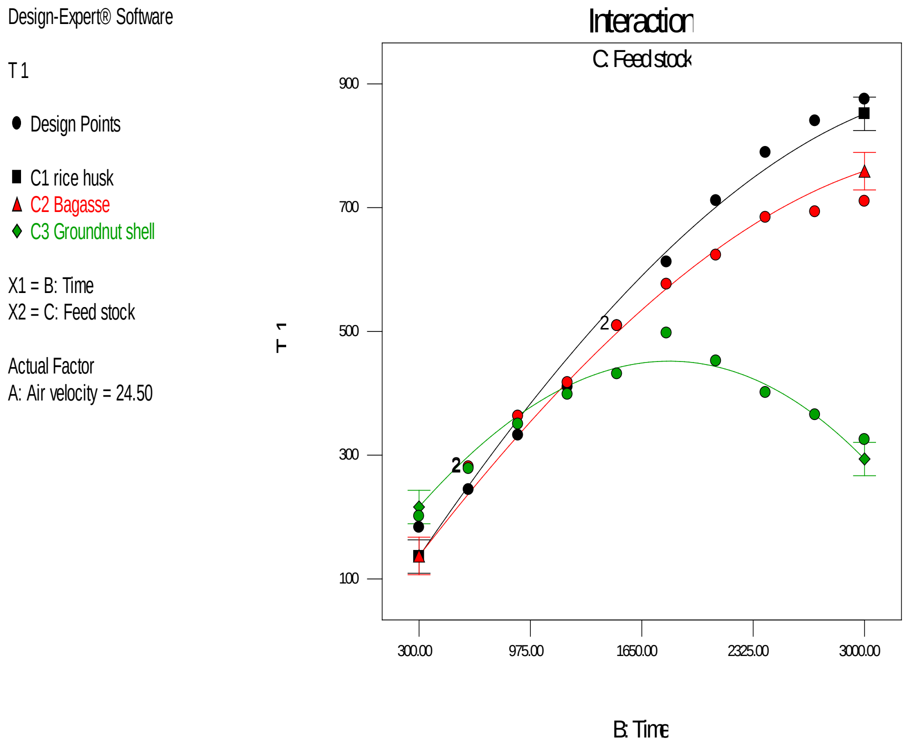

Figure 9. Line graph showing interaction between feedstocks and operating time at 24.5 m/s using Thermocouple T1

3.4. Effects of Air Velocity and Operating Time on Specific Feed Stock Using Thermocouple T2

The Model F-value of 26.67(Table 3) implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise.Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case C, B^2, A^2C, B^2C, B^3 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant.

"Adeq Precision" (Table 4) measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 20.530 indicates an adequate signal. This model can be used to navigate the design space.

Table 3. ANOVA for Response Surface Cubic Model for T2

Analysis of variance table [Classical sum of squares - Type II]						
Source	Sum of Squares	Degree of freedom	Mean Square	F Value	p-value Prob> F	
Model	550258	21	26202.76	26.67242	< 0.0001	significant
A-Air velocity	1669.211	1	1669.211	1.699131	0.1968	
B-Time	781.25	1	781.25	0.795253	0.3757	
C-Feedstock	164050.2	2	82025.11	83.49534	< 0.0001	
AB	965.3079	1	965.3079	0.98261	0.3251	
AC	135.5416	2	67.77082	0.068986	0.9334	
BC	3317.521	2	1658.76	1.688492	0.1925	
A^2	331.4497	1	331.4497	0.337391	0.5633	
B^2	322081.5	1	322081.5	327.8545	< 0.0001	
ABC	673.0104	2	336.5052	0.342537	0.7112	
A^2B	75.72165	1	75.72165	0.077079	0.7821	
A^2C	10031.99	2	5015.993	5.1059	0.0086	
B^2C	8752.998	2	4376.499	4.454944	0.0152	
B^3	12752.4	1	12752.4	12.98097	0.0006	
Residual	66802.62	68	982.3915			
Cor Total	617060.6	89				

Table 4. Statistical values of data generated using T2

Std. Deviation	31.34312
Mean	208.3556
R-Squared	0.891741
Adj R-Squared	0.858308
Pred R-Squared	N/A
Adeq Precision	20.53015
C.V. %	15.0431
PRESS	N/A

The fiinal Equation in Terms of Coded Factors for Thermocouple 2 could be written as :

$$T2 = -209.69 + 32.09C_1 + 38.17C_2 - 172.91B^2 - 46.43A^2C_1 + 37.58A^2C_2 - 9.38B^2C_1 - 28.88B^2C_2 + 62.94B^3 \qquad (9)$$

Figure 10, Figure 11 and Figure 12 show a significant effect of air velocity of temperatures, with Figure 12 showing a more pronounced effect just as in the case of Figure 3 whose temperature is measured with thermocouple T2. This waved shaped plot of the temperature could be attributed to the density and moisture content of the agricultural waste samples, irrespective of the position. The low temperature at the left hand side of the graph is as a result of the start-up conditions within the incinerator. The progressive drops at the centre result from the moisture content of agricultural waste samples. These drops deepen from Rice husk, Bagasse and lastly groundnut shell with the deepest. This shows that most of the energy released is used to drive away the moisture, before the graph rises sharply to the right showing that the moisture has been overcome and all the remaining energy can be used to release more heat for the purpose intended. Another reason could be the frequent opening and closing of the incinerator door to assess the burning of the agricultural waste samples.

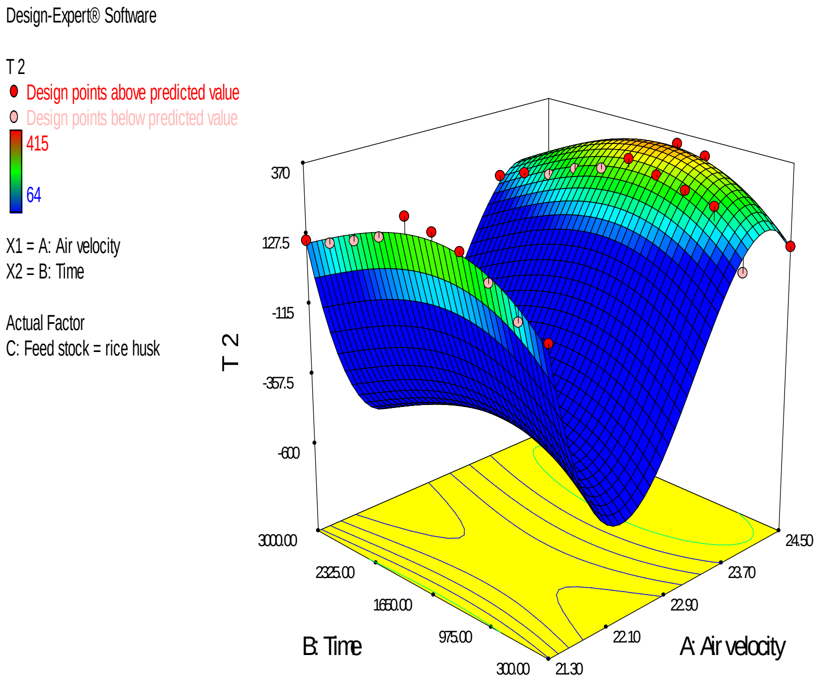

Figure 10. Relationship of Air velocity, Time for Rice husk using Thermocouple 2

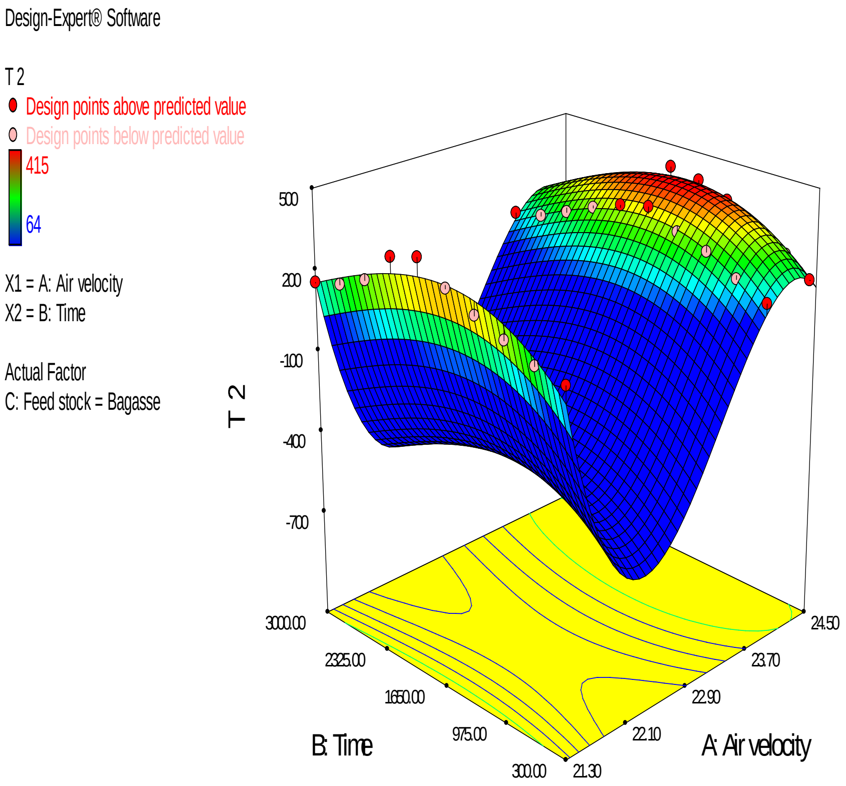

Figure 11. Relationship of Air velocity, Time for Bagasse using Thermocouple 2

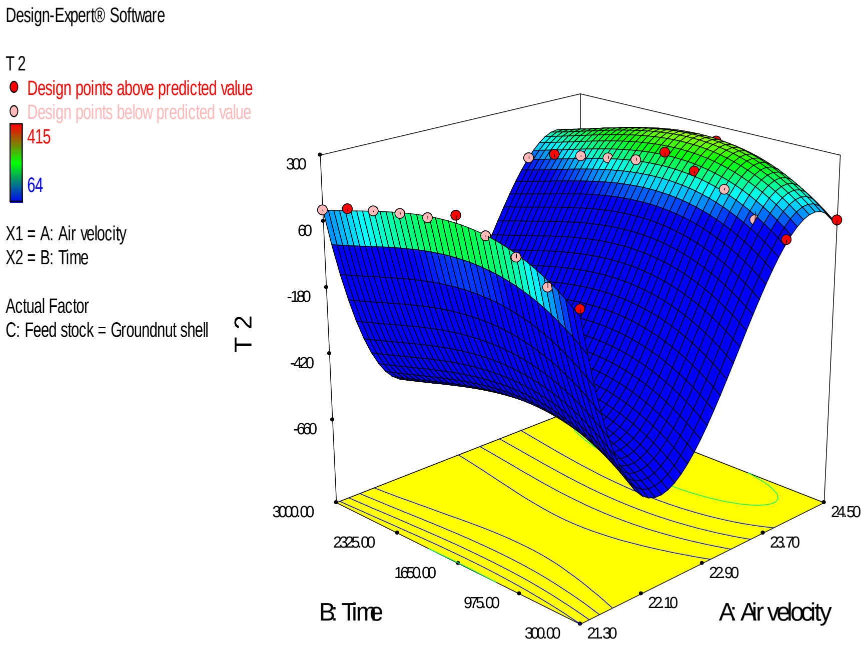

Figure 12. Relationship of Air velocity, Time for Groundnut shell using Thermocouple 2

3.5. Effect of Time on the Various Agricultural Waste Samples Using Thermocouple T2.

Figure 13, Figure 14 and Figure15 show the 2D interactions of the various agricultural waste samples in a one graph in order to clearly show the effect of air velocity on the temperature at the level of thermocouple T2, a different time intervals, namely 300 seconds, 1650 seconds and 3000 seconds respectively. The graphs tend to tangle into each other particularly Figure 13 and 15, while Figure 14 shows a clearly detached pattern of the curves from each other, but preserving the same shapes as shown by the R-square value of 0.8917 in Table 4. As the time increases, the temperature falls then rises again. This pattern is due to the experimental set up in which the air being blown by the blower beneath the grate. The agricultural waste sample above the grate is completely burned. Thus the temperature will rise sharply when the process starts and declines as the waste is being consumed.

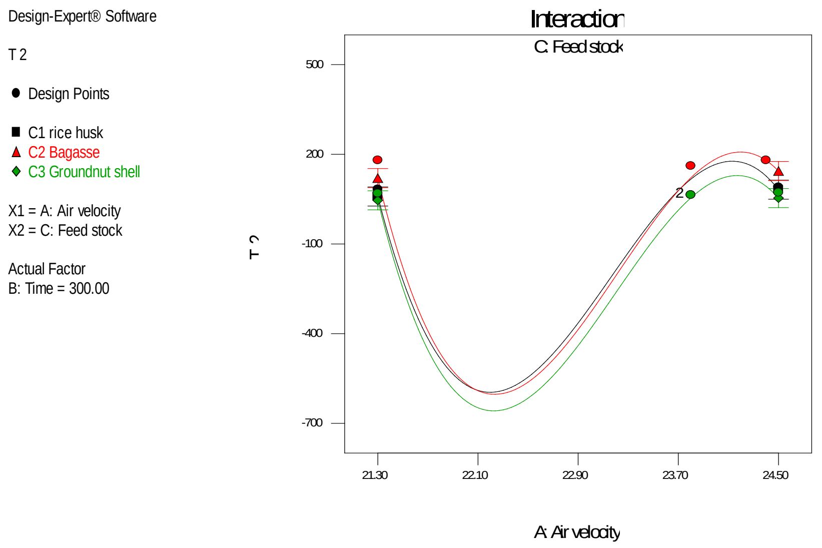

Figure 13. 2D comparative graph of agricultural waste samples at t= 300 sec, using Thermocouple T2

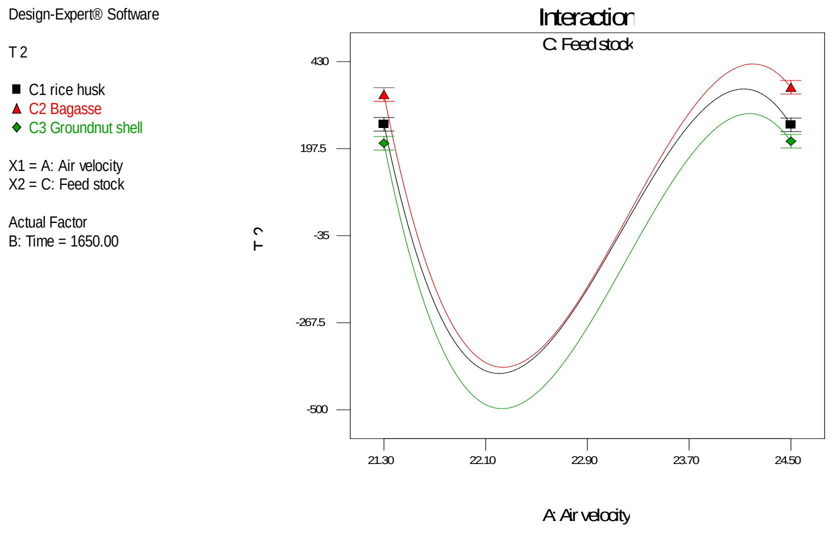

Figure 14. 2D comparative graph of agricultural waste samples at t= 1650 sec, using Thermocouple T2

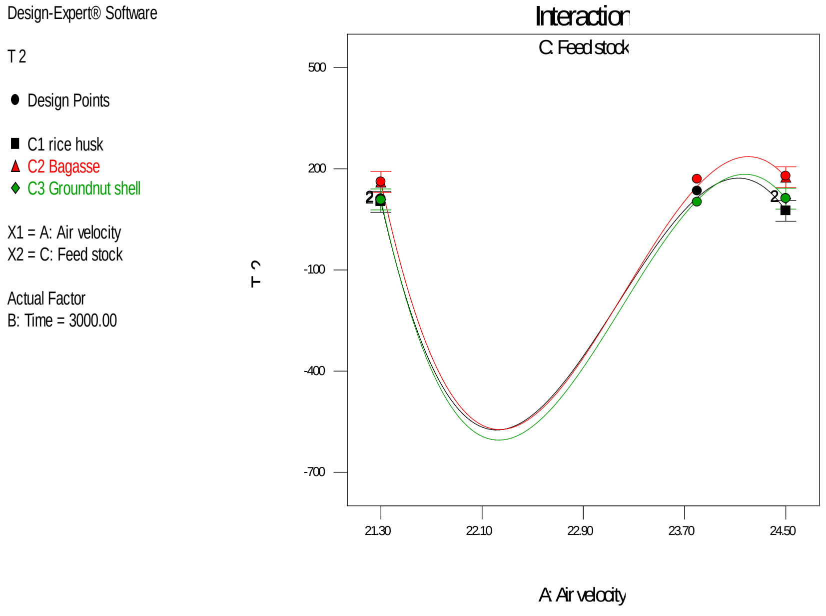

Figure 15. 2D comparative graph of agricultural waste samples at t= 3000 sec, using Thermocouple T2

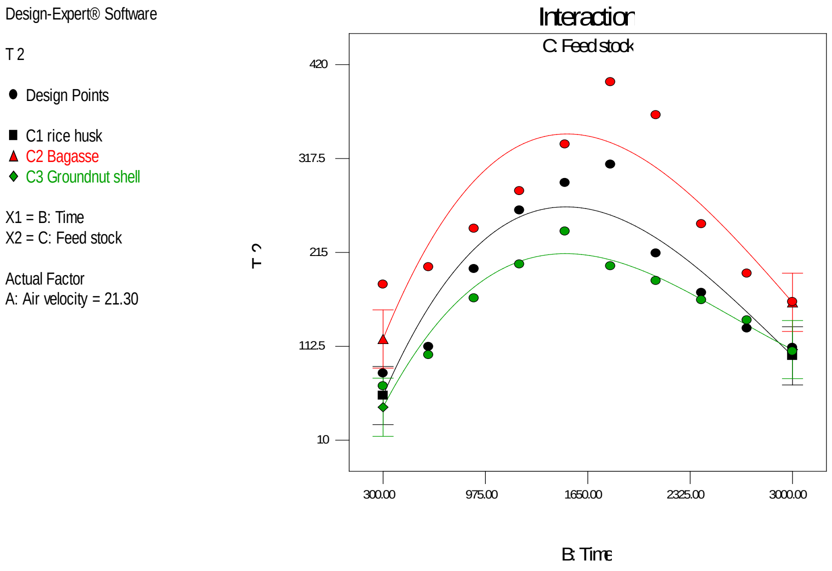

Figure 16. Line graph showing interaction between feedstocks and operating time at 21.3 m/s using Thermocouple T2

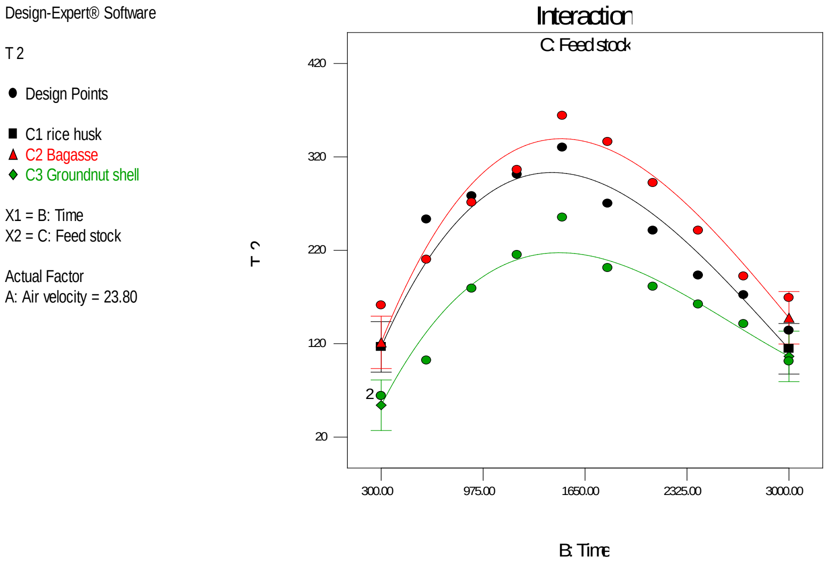

Figure 17. Line graph showing interaction between feedstocks and operating time at 23.8 m/s using Thermocouple T2

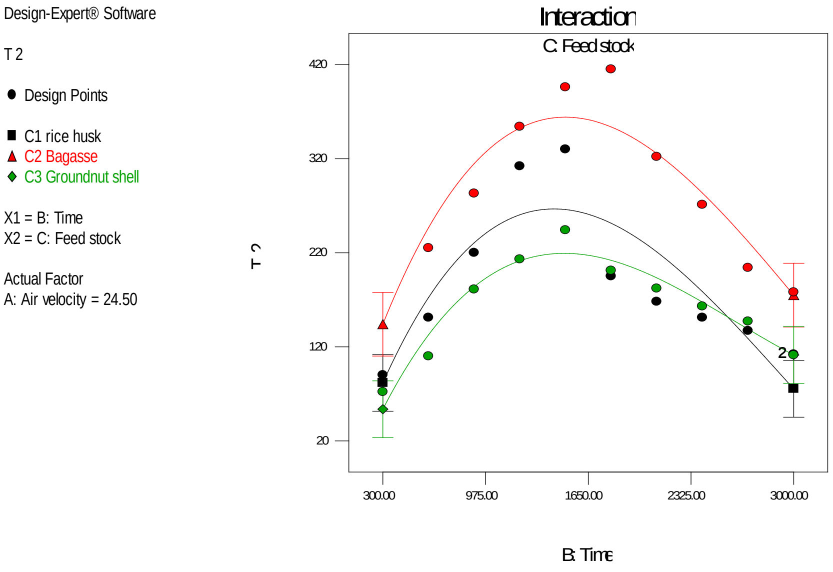

Figure 18. Line graph showing interaction between feedstocks and operating time at 24.5 m/s using Thermocouple T2

3.6. Comparative Effect of Time on Air Velocities Using Thermocouple T2.

Figure 16 – Figure 18 show the interaction between feedstock and operating times at different air velocities. It is observed that bagasse gave the highest temperature followed by rice husk and the least being groundnut shell. It was also observed that for rice husk and bagasse, the temperature increases continuously while for groundnut shell the temperature increases to a maximum value of 255°C at operation time of 1650 seconds thereafter decreases, using thermocouple 2. This behavior could be attributed to the positioning of the thermocouple as well as the variations caused by the opening and closing of the incinerator door.

Upon testing and analyses of the results, the working characteristics of the blower were determined (Table 5) using BS 848 methods of testing performance [25].

Table 5. Basic technical characteristics of the designed blower

Basic Characteristics	Tests Run		
	Test 1	Test 2	Test 3
Air density (kg/m^3) [2]	1.225	1.225	1.225
Air velocity (m/s)	24.5	23.8	21.3
Duct cross sectional area (m^2)	0.00385		
Volumetric flow rate (m^3/s)	0.0943	0.0916	0.0820
Avg. volumetric flow rate (m^3/s)	0.0943	0.0916	0.0820
Power output of the blower (kW)	0.56		
Mechanical Efficiency of blower (%)	62	60	55

The characteristics obtained are ±5% accurate as the pressures were calculated and not measured using a manometer as prescribed by the BS 848. The fluctuations can be attributed to the velocity drop in the blower from 24.5 m/s to 21.3 m/s. these results fall within the range of 40% to 665 as found by Seong [26].

4. Conclusion

1. A peak temperature of 891°C was recorded at 3111 rpm and an air velocity of 23.8 m/s.
2. The two digital thermocouples were able to record temperatures whose R- square values were found to be: 0.984 and 0.891 for Thermocouple 1 and 2 respectively, on all the agricultural waste samples used.
3. Major characteristics of the blower such as the power output were found to be 0.56 kW while the mechanical efficiency was varying between 55% and 62%.
4. The designed blower is suitable for gasification operations which require a temperature of about 750°C.

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