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Research paper

Optimization of Temperature of Circulating Fluidised Bed Combustion Boiler Using Conventional Techniques Anova and Rsm

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Abstract

In recent years, significant advances have been made in understanding and predicting the behavior of ash in combustion and gasification systems. In CFBC boilers ash sintering may contribute to deposit formation in the cyclone, return leg and post cyclone flue gas channel. Rapid sintering can lead to heavy agglomerate formation, which may finally inhibit circulation in dense phase areas (such as seal pot and return leg). Hence understanding the sintering behavior before the coal is used, would be desirable for avoiding problems. The present work is aimed at determining the influence of operating parameters on the temperature of circulating fluidized bed boiler. Ranking given to operating parameters by observing their contribution in the temperature of boiler by combustion of coal. A design of experiments technique was adopted in the form of Taguchi's L9 orthogonal array. The selected parameters were coal mass flow rate, coal particle size, primary air velocity and secondary air velocity. The combustion has done in modelled CFBC boiler using three quality lignite coal to analyze the temperature. The results were then analyzed and the major contributing factor towards temperature of boiler was found out based on the Analysis of Variance (ANOVA) and Response Surface Methodology (RSM) calculations. Boiler combustor temperature value optimized at targeted temperature value (1220 K) by using above method. The general trend indicates that as the temperature increases the possible of ash agglomeration in those area increases. Ash shows their sticky behavior if combustor temperature increase beyond the Ash fusion temperature (> 1400 K). Agglomeration of the bed material manifests itself in various forms within the combustor and associated system components. Ash deposition in the utility boilers is a major problem that may result in decreased efficiency, unscheduled outages, equipment failures, increased cleaning, and high maintenance costs. So this study helped to find out optimum condition for process parameter and to control boiler temperature.

Keywords: *CFBC; Ash agglomeration; ash deposit; ANOVA; TAGUCHI; RSM*

1. Introduction

This document can be used as a template for Microsoft Word versions 6.0 or later. In CFBC boiler coal combustion is main process function. The boiler temperature from bed to top is important output parameter to analyze the ash agglomeration propensity [1]. Location of the higher temperature shows the ash agglomeration possible region [2], [3]. There are four input parameter for the bed temperature output coal mass flow rate, coal particle size, Primary air Velocity and Secondary Air Velocity and each input parameter have three values. As per input parameter there are 81 experiments by applying TAGUCHI method we have reduced 81 experiments in 9 experiments. The analysis of variance (ANOVA) and Response Surface Methodologies (RSM) are employed to identify the optimal combination of process parameter to maintain boiler combustor temperature at 1220 Kalvin and to find the percentage of contribution of each process parameters on the boiler combustor temperature.

2. Selection of Process & Performance Parameters

Here input parameters decided and output parameter selected for optimization.

2.1 Process Parameters:

In this research attempt following four input parameters with three levels as depicted in table 1 are selected.

Table 1 : Selected input parameters with three levels

Factor	**Levels**		
	1	**2**	**3**
A. Coal mass flow rate (kg/s)	10	14	18
B. Coal particle size (m)	0.004	0.006	0.008
C. Primary Air Velocity (m/s)	3	4.5	6
D. Secondary Air Velocity (m/s)	10	15	20

2.2 Performance Parameters:

Based on the analysis parameters and discussion with practicing engineers as following performance parameters are selected.

Bed average temperature,

Bed average pressure

Coal-volatile-air & ash volume fraction

Mass imbalance

These are one of the most important quality characteristics in the Circulating Fluidized Bed Boiler which influence the performance of boiler and also influence ash deposition and agglomeration phenomenon. The analysis process based on Bed Average Temperature so optimization technique follows this method.

3. Design of Experiment (Optimization Technique Applying on Analysis Results)

A fractional factorial design implementing an L9 Taguchi orthogonal array (OA) was established to conduct coal combustion experiment in modeled CFBC boiler [4]. Fractional factorial design specifics involve the statistical elimination of insignificant parameters, thus reducing experimental runs without the loss of useful information. Following table shows the L9 Taguchi orthogonal array (OA) for four factorial and there three levels.

Table 2: L9 Orthogonal Array of input process variables (source: Quality Engineering Using Robust Design [4])

	Factors				
		A	B	C	D
	1	1	1	1	1
	2	1	2	2	2
	3	1	3	3	3
	4	2	1	2	3
	5	2	2	3	1
	6	2	3	1	2
	7	3	1	3	2
	8	3	2	1	3
	9	3	3	2	1
Experiments	$L_9 (3^4)$				

Here,

A- Coal mass flow rate (kg/s)

B- Coal particle size (m)

C- Primary Air velocity (m/s)

D- Secondary Air velocity (m/s)

In this array, the columns are mutually orthogonal. That is, for any pair of columns, all combinations of factor levels occur, doing so an equal number of times. Here, there are four parameters: A, B, C, and D, each rgpvat three levels. This is called an “L9” design, the 9 representing the nine rows, configurations or prototypes to be tested. Specific test characteristics for each experimental evaluation are identified in the associated row of the table. Thus, L9(34) means that nine experiments are to be carried out to study four variables at three levels [5]. The number of columns of an array represents the maximum number of parameters that can be studied using that array.

Table 3 : Process versus Performance parameter for lignite volatile.

Exp. No.	Input Variable Parameters				Output
	Factor A	Factor B	Factor C	Factor D	BAT
1	10	0.004	3	10	1184.46
2	10	0.006	4.5	15	1294.66
3	10	0.008	6	20	1378.65
4	14	0.004	4.5	20	1369.87
5	14	0.006	6	10	1172.44
6	14	0.008	3	15	1316.13
7	18	0.004	6	15	1237.42
8	18	0.006	3	20	1354.92
9	18	0.008	4.5	10	1139.15

Bed Average Temperature (BAT) in Kalvin

Applied conventional optimization technique ANOVA and RSM (Using the Minitab tools) to find out the results for three types of coal such as Lignite Volatile, Barsingsar India61 Lignite (BIL) and Suruka India Lignite (SIL). Moreover, the most influenced parameters on the outputs are identified by the ANOVA & RSM. It can be done by determining the percentage of contribution of each parameter. After the finding of optimal combination of the parameters with the best outputs, a confirmation test is performed to examine the selected combination of parameters.

3.1 Analysis of Variance (ANOVA) for Lignite Coal

Table 4: ANOVA results for Lignite Coal

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Coal Mass flow (kg/s)	2	3562.6	1781.3	-	-
Coal particle size(m)	2	315.3	157.6	-	-
PA velocity (m/s)	2	822.8	411.4	-	-
SA velocity (m/s)	2	62009.1	31004.5	-	-
Error	0	-	-		
Total	8	66709.8			

Thus, Secondary Air velocity explains a major portion of the total variation of Average Temperature|. In fact, it is responsible for (62009.1/66709.8) x 100 = 92.95 percent of the variation of Average Temperature. Coal Mass flow Rate is responsible for the next largest portion, namely 5.34 percent; and Coal Particle Size and Primary Air velocity together are responsible for only a small portion, a total of 1.8 percent, of the variation in Average Temperature.

So the Factor D is First rank Factor A rate is Second rank Factor C is Third rank and Factor B is in Fourth rank.

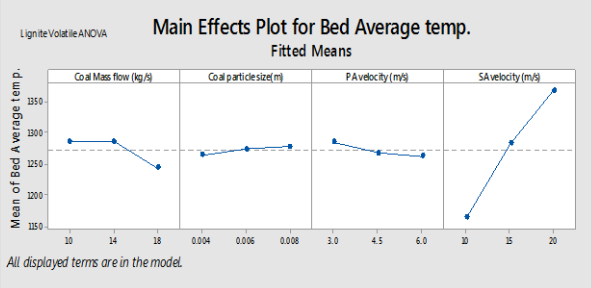

Figure 1 Main Effects Plot for Bed Average Temperature (ANOVA) for Lignite Coal

From figure it is clear that SA velocity and Coal mass flow rate are main parameter effecting the Bed average temperature.

3.2 Response Optimization:Bed Average Temperature (K)

Optimization done for targeted value 1220 Kalvin

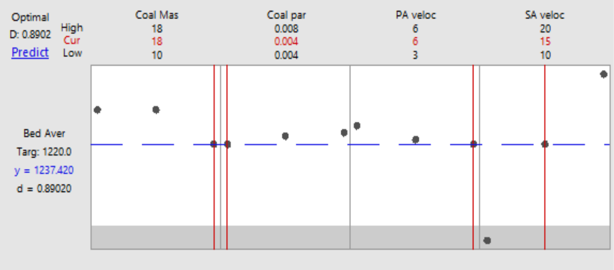

Figure 2 Optimization Plot (ANOVA) for Lignite Coal

Optimum value for targeted Bed Average Temperature (1220 K) the Coal Mass flow rate should be 18 kg/s, Coal Particle size should be 0.004 m, Primary Air Velocity should be 6 m/s and Secondary Air Velocity should be 15 m/s with composite desirability 0.89.

3.3 Response Surface Methodologies (RSM) forVolatile

Table 5 : Shows results of RSM for lignite volatile

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	65189.6	16297.4	42.88	0.002
Coal Mass flow (kg/s)	1	2657.8	2657.8	6.99	0.057
Coal particle size(m)	1	296.5	296.5	0.78	0.427
PA velocity (m/s)	1	748.2	748.2	1.97	0.233
SA velocity (m/s)	1	61487.1	61487.1	161.79	0.000
Error	4	1520.2	380.0		
Total	8	66709.8			

Thus, Secondary Air velocity explains a major portion of the total variation of Bed Average Temperature|. In fact, it is responsible for (61487.1/66709.8) x 100 = 92.17 percent of the variation of Average Temperature. Coal Mass flow Rate is responsible for the next largest portion, namely 3.98 percent; and Coal Particle Size and Primary Air velocity together are responsible for only a small portion, a total of 1.56 percent, of the variation in Average Temperature.

So the Factor D is First rank Factor A rate is Second rank Factor C is Third rank and Factor B is in Fourth rank.

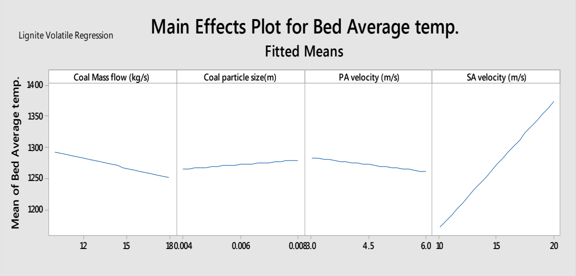

Figure 3 Main effects plot for bed average temperature.(RSM)

From figure it is clear that SA velocity and Coal mass flow rate are main parameter effecting the Bed average

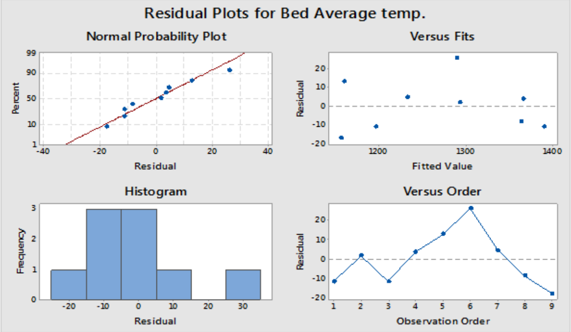

Figure 4 Residual Plots (Four in one) for Bed Average Temperature (Lignite volatile)

3.4 Response Optimization: Bed Average Temperature

Optimization done for targeted value 1220 Kalvin

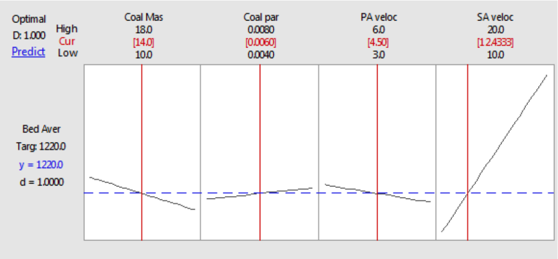

Figure 5 Optimization Plot.(RSM)

Optimum value for targeted Bed Average Temperature (1220 K) the Coal Mass flow rate should be 14 kg/s, Coal Particle size should be 0.006 m, Primary Air Velocity should be 4.5 m/s and Secondary Air Velocity should be 12.433 m/s with composite desirability 1.00.

3.5 Optimization Technique Used For BIL Coal

Using Minitab 18 applied conventional optimization technique ANOVA and RSM and find out the results.

Table 6: Design of experiments for BIL Coal

Exp.	Input Variable Parameters				Output
	Factor A	Factor B	Factor C	Factor D	BAT
1	10	0.004	3	20	1120.42
2	10	0.006	4.5	25	1168.39
3	10	0.008	6	30	1215.62
4	14	0.004	4.5	30	1138.31
5	14	0.006	6	20	1022.41
6	14	0.008	3	25	1105.54
7	18	0.004	6	25	1008.59
8	18	0.006	3	30	1108.71
9	18	0.008	4.5	20	973.77

3.6 Analysis of Variance (ANOVA) for BIL Coal

Table 7 : Shows ANOVA results for BIL Coal

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	49854.2	12463.6	151.22	0.000
Coal Mass flow Kg/s	1	28477.7	28477.7	345.52	0.000
coal particle size	1	127.1	127.1	1.54	0.282
PA Velocity m/s	1	1292.1	1292.1	15.68	0.017
SA velocity m/s	1	19957.3	19957.3	242.14	0.000
Error	4	329.7	82.4		
Total	8	50183.9			

Thus, Coal Mass Flow Rate explains a major portion of the total variation of Average Temperature. In fact, it is responsible for (28698.1/50183.9) x 100 = 57.18 percent of the variation of Average Temperature. Secondary Air Velocity is responsible for the next largest portion, namely 39.8 percent; and Coal Particle Size and Primary Air velocity together are responsible for only a small portion, a total of 3.023 percent, of the variation in Average Temperature.

So the Factor A is First rank Factor D rate is Second rank Factor C is Third rank and Factor B is in Fourth rank.

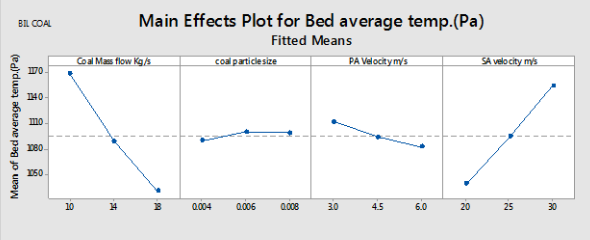

Figure 6 Main effects plot for bed average temperature.(ANOVA)

From figure it is clear that SA velocity and Coal mass flow rate are main parameter effecting the Bed average temperature.

3.7 Response Optimization: Bed Average Temp.(K)

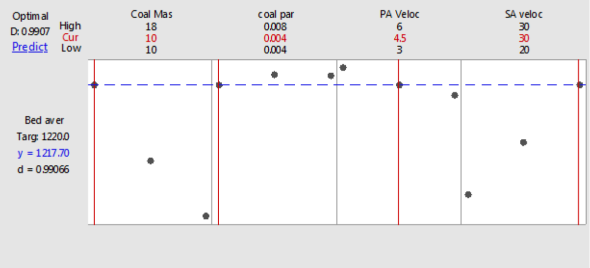

Figure 7 Optimization Plot (ANOVA) for BIL Coal

Optimum value for targeted Bed Average Temperature (1220 K) the Coal Mass flow rate should be 10 kg/s, Coal Particle size should be 0.004 m, Primary Air Velocity should be 4.5 m/s and Secondary Air Velocity should be 30 m/s with composite desirability 0.99.

3.8 Regression Analysis (RSM) For Lignite Coal

Table 8 : Shows results of RSM

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Regression	4	49854.2	12463.6	151.22	0.000
Coal Mass flow Kg/s	1	28477.7	28477.7	345.52	0.000
Coal particle size	1	127.1	127.1	1.54	0.282
PA Velocity m/s	1	1292.1	1292.1	15.68	0.017
SA velocity m/s	1	19957.3	19957.3	242.14	0.000
Error	4	329.7	82.4		
Total	8	50183.9			

Thus, Coal Mass flow Rate explains a major portion of the total variation of Average Temperature|. In fact, it is responsible for (28477.7/50183.9) x 100 = 56.74 percent of the variation of Average Temperature. Secondary Air velocity is responsible for the next largest portion, namely 39.46 percent; and Coal Particle Size and Primary Air velocity together are responsible for only a small portion, a total of 2.82 percent, of the variation in Average Temperature.

So the Factor A is First rank Factor D rate is Second rank Factor C is Third rank and Factor B is in Fourth rank.

0 or Minimum P value and Negative values of T-value shows these are main factor effected the Bed Average Temperature.

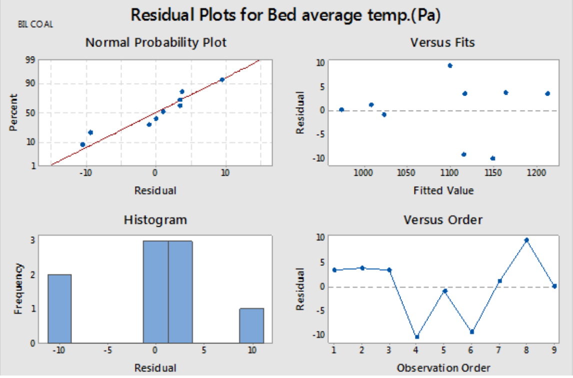

Figure 8 Residual Plots (Four in one) for Bed Average Temperature (BIL Coal)

3.9 Response Optimization: Bed Average Temp.(K)

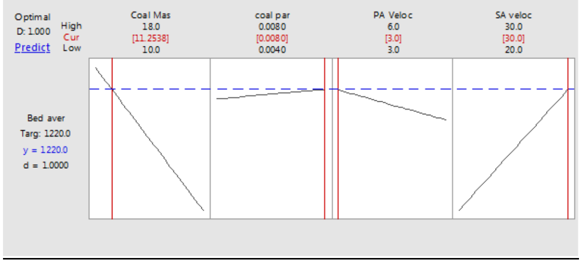

Figure 9 Optimization Plot.(RSM)

Optimum value for targeted Bed Average Temperature (1220 K) the Coal Mass flow rate should be 11.25 kg/s, Coal Particle size should be 0.008 m, Primary Air Velocity should be 3 m/s and Secondary Air Velocity should be 30 m/s with composite desirability 1.00.

3.10 Optimization Technique Used For SIL Coal

Using Minitab 18 applied conventional optimization technique ANOVA and RSM and find out the results.

Table 9 : Design of experiments for SIL Coal

	Input Variable Parameters (Factors)				Output
	A	B	C	D	BAT (K)
1	10	0.004	3	10	1128.67
2	10	0.006	4.5	15	1270.97
3	10	0.008	6	20	1387.21
4	14	0.004	4.5	20	1297.02
5	14	0.006	6	10	1058.73
6	14	0.008	3	15	1217.02
7	18	0.004	6	15	1103.08
8	18	0.006	3	20	1278.26
9	18	0.008	4.5	10	1049.05

3.11 Analysis of Variance (ANOVA)

Table 10 : Shows ANOVA results for SIL Coal

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Coal Mass flow (kg/s)	2	21463	10731.4	*	*
Coal particle size(m)	2	2648	1323.8	*	*
PA velocity (m/s)	2	1143	571.6	*	*
SA velocity (m/s)	2	87871	43935.7	*	*
Error	0	*	*		
Total	8	113125			

Thus, Secondary Air Velocity explains a major portion of the total variation of Average Temperature. In fact, it is responsible for (87871/113125) x 100 = 77.67 percent of the variation of Average Temperature. Coal Mass Flow Rate is responsible for the next largest portion, namely 18.97 percent; and Coal Particle Size and Primary Air velocity together are responsible for only a small portion, a total of 3.35 percent, of the variation in Average Temperature.

So the Factor D is First rank Factor A rate is Second rank Factor B is Third rank and Factor C is in Fourth rank.

3.11 Response Optimization: Bed average temp.(K)

Optimization Plot for SIL Coal

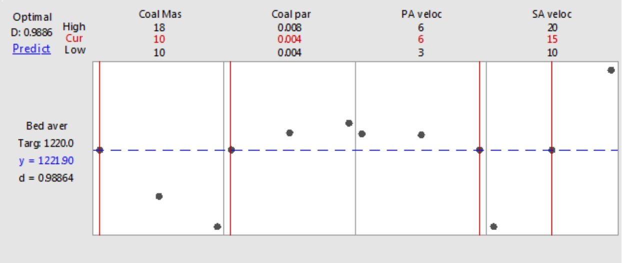

Figure 10 Optimization Plot (ANOVA)

Optimum value for targeted Bed Average Temperature (1220 K) the Coal Mass flow rate should be 10 kg/s, Coal Particle size should be 0.004 m, Primary Air Velocity should be 6 m/s and Secondary Air Velocity should be 15 m/s with composite desirability 0.98.

3.12 Regression Analysis (RSM) for SIL Coal

Table 11 : shows results of RSM for SIL Coal

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	112553	28138.1	196.60	0.000
Coal Mass flow (kg/s)	1	21177	21177.3	147.97	0.000
Coal particle size(m)	1	2584	2583.8	18.05	0.013
PA velocity (m/s)	1	936	935.8	6.54	0.063
SA velocity (m/s)	1	87856	87855.7	613.85	0.000
Error	4	572	143.1		
Total	8	113125			

Thus, Secondary Air velocity explains a major portion of the total variation of Average Temperature|. In fact, it is responsible for (87856/113125) x 100 = 76.66 percent of the variation of Average Temperature. Coal Mass flow Rate is responsible for the next largest portion, namely 18.72 percent; and Coal Particle Size and Primary Air velocity together are responsible for only a small portion, a total of 3.11 percent, of the variation in Average Temperature.

So the Factor D is First rank Factor A rate is Second rank Factor C is Third rank and Factor B is in Fourth rank.

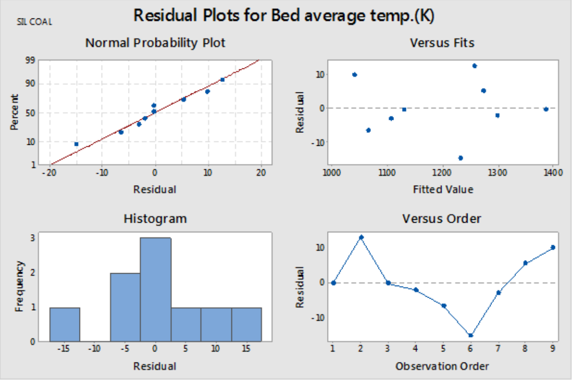

Figure 11 Residual Plots (Four in one) for Bed Average Temperature

3.13 Response Optimization: Bed average temp.(K)

Optimization Plot

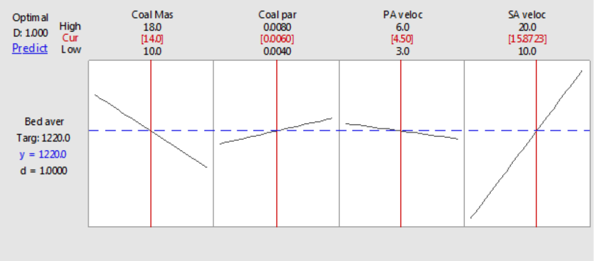

Figure 12 Optimization Plot.(RSM)

Optimum value for targeted Bed Average Temperature (1220 K) the Coal Mass flow rate should be 14 kg/s, Coal Particle size should be 0.006 m, Primary Air Velocity should be 4.5 m/s and Secondary Air Velocity should be 15.87 m/s with composite desirability 1.00.

4. Conclusion

1. Using ANOVA technique for Lignite Volatile coal to find optimum value of process parameters for targeted Bed Average Temperature at 1220 K, hence the corresponding values for process parameters as coal mass flow rate, coal particle size, primary air velocity and secondary air velocity are 18 kg/s, 0.004 m, 6 m/s and 15 m/s respectively with composite desirability 0.89.

Using RSM technique for Lignite Volatile coal to find optimum value of process parameters for targeted Bed Average Temperature at 1220 K, hence the corresponding values for process parameters as coal mass flow rate, coal particle size, primary air velocity and secondary air velocity are 14 kg/s, 0.006 m, 4.5 m/s and 12.433 m/s with composite desirability 1.00.

2. Using ANOVA technique for BIL coal to find optimum value of process parameters for targeted Bed Average Temperature at 1220 K, hence the corresponding values for process parameters as coal mass flow rate, coal particle size, primary air velocity and secondary air velocity are 10 kg/s, 0.004 m, 4.5 m/s and 30 m/s respectively with composite desirability 0.99.

Using RSM technique for BIL coal to find optimum value of process parameters for targeted Bed Average Temperature at 1220 K, hence the corresponding values for process parameters as coal mass flow rate, coal particle size, primary air velocity and secondary air velocity are 11.25 kg/s, 0.008 m, 3 m/s and 30 m/s with composite desirability 1.00.

3. Using ANOVA technique for SIL coal to find optimum value of process parameters for targeted Bed Average Temperature at 1220 K, hence the corresponding values for process parameters as coal mass flow rate, coal particle size, primary air velocity and secondary air velocity are 10 kg/s, 0.004 m, 6 m/s and 15 m/s respectively with composite desirability 0.98.

Using RSM technique for SIL coal to find optimum value of process parameters for targeted Bed Average Temperature at 1220 K, hence the corresponding values for process parameters as coal mass flow rate, coal particle size, primary air velocity and secondary air velocity are 14 kg/s, 0.006 m, 4.5 m/s and 15.87 m/s with composite desirability 1.00.

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