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Research Article

Experimental Determination of Heat Transfer Coefficient in Stirred Vessel for Coal-Water Slurry Based on the Taguchi Method

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Heat transfer in stirred vessels is important because process fluid temperature in the vessel is one of the most significant factors for controlling the outcome of process. In this study, the effects of some important design parameters for coal-water slurry in agitated vessel used in coal gasification such as stirrer speed, location of stirrer, D/d ratio, and coal-water ratio were investigated and optimized using the Taguchi method. The experiments were planned based on Taguchi's L_9 orthogonal array with each trial performed under different levels of design parameter. Signal-to-noise (S/N) analysis and analysis of variance (ANOVA) were carried out in order to determine the effects of process parameter and optimal factor's level settings. Finally, confirmation tests verified that the Taguchi method achieved optimization of heat transfer coefficient in agitated vessel.

1. Introduction

Research on heat transfer coefficient in agitated vessel is still critical and ongoing. Heat transfer in stirred vessel is important because process fluid temperature in the vessel is one of the most significant factors for controlling the outcome of process. Mechanically agitated vessels are widely used in mining, food, petroleum, chemical, pharmaceutical, pulp, and paper industries and are also used in coal gasification power plant [1]. The intensity of heat transfer during mixing of fluids like coal slurry depends on the type of the stirrer, the design of the vessel, and condition of the processes [2]. In this study the effects of some important parameters such as stirrer speed, location of stirrer, D/d ratio, and coal-water ratio were investigated and optimized.

Performing an experiment is more suitable for determination of the real performance characteristics of a system. However to prepare an experimental setup is very expensive and some systems cannot be constructed and tested in a laboratory. Also, preparing an experimental setup is a very time-consuming procedure because of the high trial numbers. Because of these difficulties, the modeling and then testing the system using numerical analysis, ANN (artificial neural network), or optimizing the trial numbers according to the Taguchi method is more appropriate and very popular nowadays [3].

Heat transfer rates in agitated vessel have been investigated for coal-water slurry in a flat bottom vessel equipped with flat-blade impeller making an angle of 45 degree to the axis of the shaft. Also the heat transfer coefficients of the flat-blade impeller parallel to the axis of the shaft results [4] were compared.

2. Experimental Detail

2.1. Experimental Setup. The schematic diagram of the experimental setup is shown in Figure 1. An agitator is driven by a vertically mounted motor which is used for stirring. The entire vessel is completely insulated. The inlet of the jacket is connected to an electrically operated boiler, which produces steam continuously at constant pressure. A pressure gauge is connected to the jacket for monitoring the jacket steam

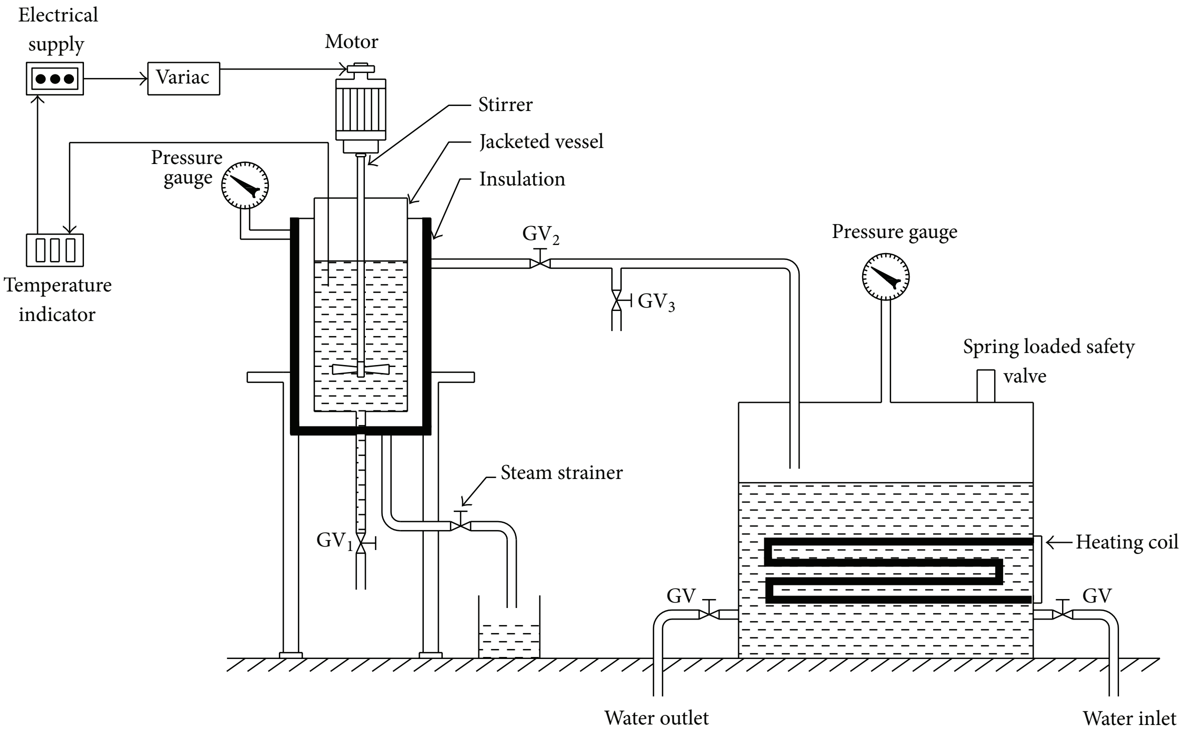

Figure 1: Experimental setup.

pressure. A vent is provided for releasing noncondensable gas and to maintain the pressure in jacket. A steam strainer is placed at the bottom of the vessel to collect the condensed steam.

A jacketed mild steel cylindrical vessel of 210 mm diameter, 6 mm thick, and 160 mm height with a flat bottom was used. Similarly the cylindrical inner vessel of 110 mm diameter, 6 mm thick and 110 mm height with similar flat bottom was used. This assures that the height of vessel is always equal to diameter of the vessel ($H = D$) [4]. The impeller used in the jacketed vessel is having four flat blades (Figure 2) and is driven by a variac controlled motor. The impeller makes an angle of 45° to the axis of the shaft. The thickness of each blade is 1.6 mm and having a width of 17.5 mm. Outlets are given at the bottom side of the agitated vessel for collection of samples.

The cylindrical vessel of 210 mm diameter, 6 mm thick, and 160 mm height with a flat bottom was used which is named as jacketed vessel. Similarly the cylindrical inside vessel of 110 mm diameter, 6 mm thick and 110 mm height with same flat bottom was used. So the height of vessel is equal to diameter of the vessel ($H = D$) [4]. The impeller used is four flat blade whose details as given in Figures 2(a)–2(c).

2.2. Experimental Procedure. Initially the drain valve provided at the bottom of the jacketed vessel and gate valve 1 was closed. The vessel was first filled with a known volume of water and mix with coal particle (size: BSS 36). The initial temperature of the slurry (t_1 °C) can be noted through the digital temperature indicator (Micro sensor Make, T-type), which was connected to a thermocouple (T-type, copper constant). The boiler was filled with required amount of water. Now the gate valve 2 was closed and the boiler was switched on. After steam was produced gate valve 3 was closed. The variac (Continuously variable auto transformer, Automatic Electric Ltd, Range 0 to 270 V) was used to vary the stirrer speed. When the boiler steam pressure reaches 2.5 kg/cm^2 (gauge)-(Bourdon type, Gurn Make) open the gate valve 2 and allow the steam into the jacketed vessel. Now keep the pressure gauge at 2.0 kg/cm^2 (gauge) by adjusting the gate valve 2 and start the stopwatch. When the temperature reaches the saturation temperature of the water (100°C) the time period (τ sec) was noted and this period is called heating period (unsteady state). The above procedure was repeated for other sets of readings.

3. Preparation of Coal-Water Slurry

Coal gasification is a key process in integrated and coal gasification combined cycle (IGCC) power plant. Being one of the most competitive and promising coal gasification technologies, the slurry feed-type entrained-flow coal gasification process is shown in Figure 3, which has been extensively used in the foreign countries. Coal-water slurry (CWS) is a mixture of water and coal. First pulverize coal mix with water according to proper proportion. (coal : water = (40 to 70) : (60 to 30) and then add a little additive (about 1% of the total soiled weight; the coal-water two-phase flow is formed after strong agitation [6]. In an entrained-flow gasifier using coal-water slurry, it should be necessary to uniformly mix the coal-water

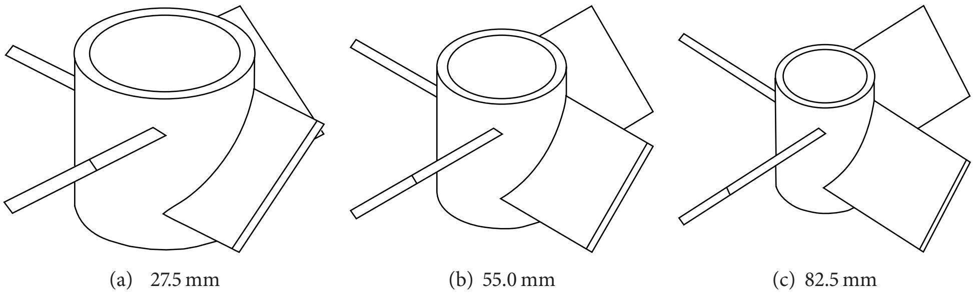
(a) 27.5 mm (b) 55.0 mm (c) 82.5 mm

Figure 2: Details of Flat-blade impeller. All dimensions are in “mm.”

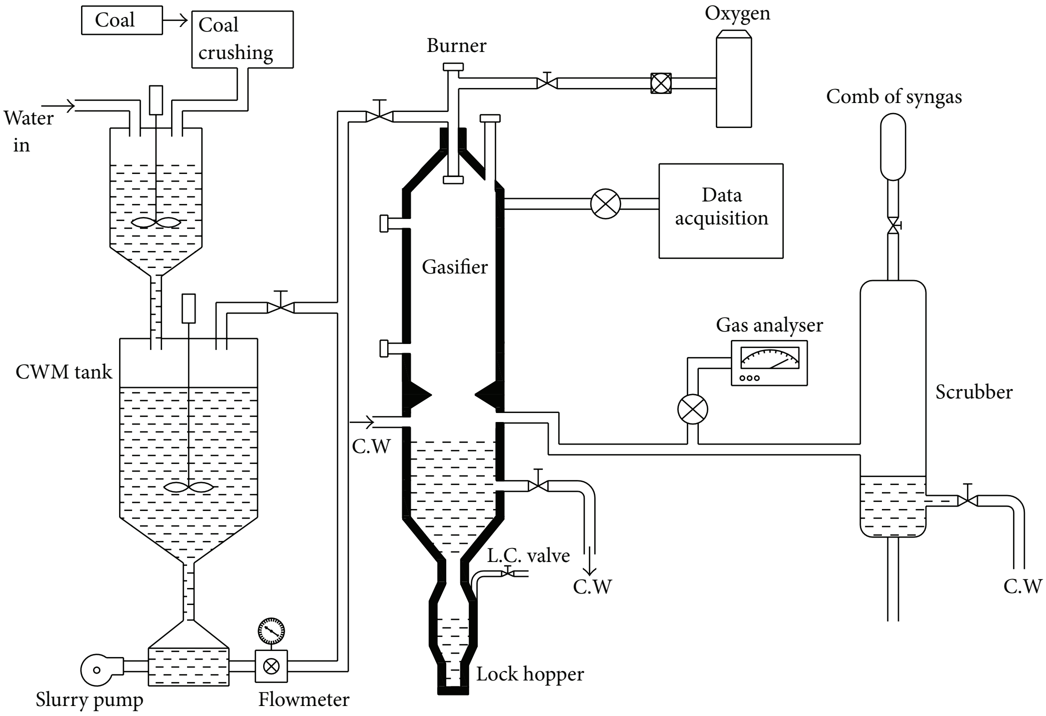

Figure 3: Entrained-flow coal gasification process—slurry feed type [5].

slurry with oxygen to obtain the higher carbon conversion in short residence time (0.4–5 s).

The proximate and ultimate analysis of the Indian coal used in the preparation of the slurries is given in Table 1.

Additive is one of the key factors affecting CWS quality. Usually additive dosage accounts for about 1% of the total weight. Based on function, additives can be used like dispersant and stabilizing agents which are used in this project, that is, sodium carbonate and sodium salt of carboxyl methyl cellulose (Na-CMC), respectively. The best dosages of dispersant and stabilizers are 0.75% by wt. of solids and 0.1% by wt. of total solids [7].

The concentration of coal slurry could be maintained from 40% to 70% which is able to feed into the gasification without any feeding problem [8], so that the concentrations chosen are 40%, 50%, and 60%. The coal particle size used for coal-water slurry preparation is BSS 36 (0.422 mm).

Table 1: Coal analysis details.

Proximate analysis	Weight basis in %
Moisture	6.64%
Ash	48.71%
Volatile matter	19.12%
Fixed carbon	25.53%
Gross calorific value in Kcal/Kg.	3491
Ultimate analysis	Weight basis in %
Carbon as C	34.53%
Hydrogen as H	1.81%
Nitrogen as N	1.05%
Sulphur as S	0.47%
Oxygen by difference	1.92%

4. Uncertainty Analysis

The objective of a measurement is to determine the value of the measurand, that is, the value of the particular quantity to be measured. A measurement therefore begins with an appropriate specification of the measurand, the method of measurement, and the measurement procedure. In general, the result of a measurement is only an approximation or estimate of the value of the measurand and thus is complete only when accompanied by a statement of the uncertainty of that estimate [9]. Through there are many factors in the measurement uncertainty, in this study, it is assumed that the major factors of resolution or detection of sensors and the variation of the measured data during repeated tests at the test condition. It defined the measurand, the output quantity as a function $Y = f(X)$ of the input quantities X.

The uncertainties of the measured data were calculated by combining the type A and B [10]. The type A uncertainty was evaluated by statistical analysis of series of observation of the 50 times sampled data and the type B uncertainty was calculated by previous measurements, specifications from the manufacturer, hand-books, calibration certificates, and so forth [11]. The standard uncertainty was computed as root mean square error (RSM) of the type A and B uncertainties. Table 2 Shows the uncertainty estimation of each measured parameter and 50 samples were collected in each test [11].

Table 2: Uncertainty estimation of variables.

Measurements	Unit	A-type	B-type	$u(y)$
Temperature (T)	°C	$1.51e-2$	$1.00e-2$	$1.01e-2$
Pressure	Kg/cm^2	$2.522e-2$	$1.50e-2$	$2.25e-2$
Speed	rpm	$1.05e-2$	$1.12e-2$	$1.02e-2$

Table 3: Factors and their specified levels.

Sl. no.	Variables	Levels		
		I	II	III
1	Stirrer speed in rpm	100	200	300
2	Stirrer location from free surface in cm	27.5	55	82.5
3	D/d ratio	4.0	2.0	1.3
4	Coal-water ratio	40 : 60	50 : 50	60 : 40

Table 4: L_9 (3^4) standard orthogonal array.

Experiment no.	Stirrer speed	Stirrer location	D/d ratio	C-w ratio
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

5. Application of Taguchi Method

The quality engineering methods of Taguchi, employing design of experiments (DOE), is one of the most important statistical tools for designing high quality system at reduced cost. Taguchi methods provide an efficient and systematic way to optimize designs for performance, quality and cost. Optimization of process parameter is the key step in the Taguchi method to achieve high quality without increasing cost [12]. Taguchi's parameter design method is a powerful tool for optimizing the performance characteristics of a process [13, 14]. The experiments were designed based on the orthogonal array technique. Using the Taguchi experimental design, an orthogonal array was selected for four factors and three levels for each factor. The orthogonal array selected for this study is the L_9 orthogonal array which is shown in Table 2.

Based on orthogonal arrays, the number of experiments that may cause an increase in time and cost can be reduced by means of the Taguchi technique. It uses a special design of orthogonal arrays to learn the whole parameter space with a small number of experiments [15, 16].

The selection of control factors and their levels is made on the basis of some preliminary trial experiments conducted in the laboratory and also from the literature review on the subject. The choice of three levels has been made because the effect of these factors on the performance characteristics can be estimated simultaneously while minimizing the number of test runs. An L_9 (3^4) standard orthogonal array [14] as shown in Table 3 was employed for the present investigation. This array is most suitable to provide the minimum degrees of freedom as 9 required for the experimental exploration.

The experimental layout for the process parameter using the L_9 (3^4) orthogonal array is shown in Table 4. The application steps in the Taguchi method are given in Figure 4.

6. Results and Discussion

The heat transfer coefficient was determined as per experiment runs. Three readings (corresponding to the three replications) are recorded for each experimental condition as shown in Table 5.

6.1. Statistical Analysis. Statistical analyses (over all loss function, S/N ratio, ANOVA) are carried out for a significance level of 0.05, that is, for a confidence level of 95%. The statistical errors in the experiment are normally distributed in normal probability plot as shown in Figure 5.

6.2. Overall Loss Function. A loss function is then defined to calculate the deviation between the experiment value and the desired value. The control factors that may contribute to reduce variation (improved quality) can be quickly identified

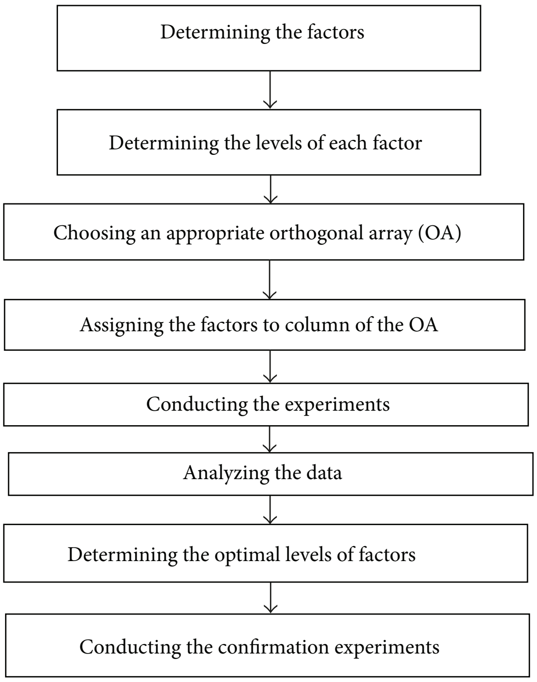

Figure 4: Application steps in the Taguchi method.

Table 5: Experimental layout using an L_9 (3^4) orthogonal array.

Sl. no.	Stirrer speed in rpm	Stirrer location from free surface in mm	D/d ratio	C-w ratio
1	100	27.5	4.0	40
2	100	55	2.0	50
3	100	82.5	1.3	60
4	200	27.5	2.0	60
5	200	55	1.3	40
6	200	82.5	4.0	50
7	300	27.5	1.3	50
8	300	55	4.0	60
9	300	82.5	2.0	40

by looking at the amount of variation present as a response. Taguchi recommends the use of the loss function to measure the deviation of the quality characteristics from the desired value. The four control variables belong to the higher-the-better quality characteristic. The loss function of the-higher-the-better quality characteristic can be expressed as follows.

The higher is better

$$L_{ij} = \left[\frac{1}{r}\sum\frac{1}{y_{ijk}^2}\right], \tag{1}$$

where L_{ij} is the loss function of the ith quality characteristic in the j^{ij} experiment, r is the number of tests, and y_{ijk} is the experimental value of the ith quality characteristic in the jth experiment at the kth test [9]. As a result, four quality characteristics corresponding to the four control variables and heat transfer coefficient are obtained using (1).

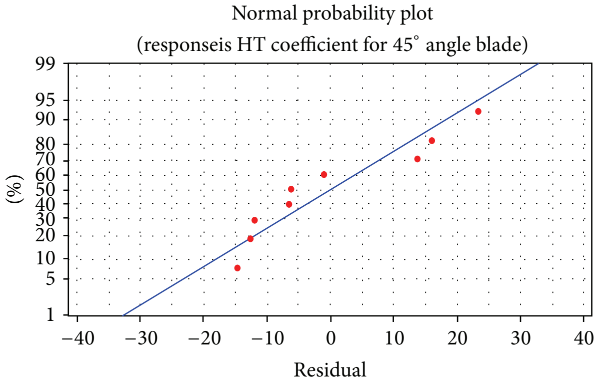

Figure 5: Normal probability plot (response is HT coefficient).

6.3. Signal-to-Noise Ratio. In Taguchi technique, the variation of the response is also examined using an appropriately chosen S/N ratio. Broadly speaking, the S/N ratio is the ratio of the mean (signal) to the standard deviation (noise). These S/N ratios, derived from the quadratic loss function, are expressed on a decibel (dB) scale. The formula used to compute the S/N ratio depends on the objective function. The overall loss function is further transformed into the signal-to-noise (S/N) ratio [9]. In the present study, heat transfer coefficient is a "the higher the better" type of quality characteristic since the goal is to maximize the heat transfer coefficient. The S/N ratio η_j in jth experiment can be expressed as follows:

$$\eta_j = -10\log\left(L_{ij}\right). \tag{2}$$

The signal-to-noise ratios corresponding to overall loss function are computed using (2) for each of the nine experimental conditions and are reported in Table 5. Since the experimental design is orthogonal, the factor effects can be separated out in terms of the S/N ratio and in terms of the mean response. The average values of S/N ratios of the four control factors at each of the four levels are shown in Figure 6, and from which the levels corresponding to the highest S/N ratio values are chosen for each parameter representing the optimum condition. Here, the optimum condition corresponds to the maximization of the heat transfer coefficient. It is clear from Figure 6 that the optimum levels are stirrer speed (300 rpm), stirrer location (55.0 mm), D/d ratio (2), and C-w ratio (60 : 40), respectively.

In addition to S/N analysis, main effects of the process parameters on the mean response are also analyzed. The mean response refers to the average value of the quality characteristic for each factor at different levels. Thus, the average values of the heat transfer coefficient for each factor at the three levels have been calculated and also indicated the same optimum level of the parameters as obtained in S/N ratio analysis.

Table 6: Results for quality characteristics and signal-to-noise ratio.

Experiment no.	Heat transfer coefficient W/m^2 K. Reading 1	Reading 2	Reading 3	Mean	S/N ratio (dB)
1	521.86	525.47	540.09	529.14	54.47
2	615.36	626.27	625.60	622.41	55.88
3	608.48	612.96	624.49	615.31	55.78
4	652.78	654.89	675.12	660.93	56.40
5	624.12	629.38	640.25	631.25	56.00
6	576.41	583.94	584.57	581.64	55.29
7	679.83	676.14	679.80	678.59	56.63
8	630.82	634.15	640.51	635.16	56.06
9	678.83	684.33	680.23	681.13	56.66

6.4. Analysis of Variance (ANOVA). ANOVA is a method most widely used for determining significant parameters on response and measuring their effects. Table 6 shows the computed results of the ANOVA with 95% confidence. In ANOVA, the ratio between the variance of the process parameter and the error variance called as F-ratio determined whether the parameter has significant effect on the quality characteristic. This process is carried out by comparing the F-ratio value of the parameter with the standard F table value ($F_{0.05}$) at the 5% significance level. If the F-ratio value is greater than $F_{0.05}$, the process parameter is considered significant. Depending on it, it can be seen that the effects of all the factors on heat transfer coefficient are significant. The last column of Table 6 indicates the percentage contribution (significance rate) of each process parameter of the total variation, indicating their degree of influence on the results. According to Table 6 D/d ratio ($P = 47.60\%$) has the most dominant effect on total variation and it is followed by stirrer speed ($P = 45.65\%$), C-w ratio ($P = 4.16\%$), and stirrer location ($P = 0.17\%$). However, C-w ratio yields the most significant effect on the measured response as shown by the much higher F-ratio (256.51) and also percent contribution (47.60). The percentages of contribution of each variable are shown in Figure 7.

6.5. Prediction of Optimum Heat Transfer Coefficient. From the analysis of S/N ratio and the mean response characteristic, the optimum levels of the control factors are determined as stirrer speed$_3$, stirrer location$_2$, D/d ratio$_2$, and C-w ratio$_3$. Hence, the predicted mean of the quality characteristic (heat transfer coefficient) has been computed as shown by [17] as per (3):

$$\begin{aligned}\eta_{\text{opt}} = \eta_m &+ \left(\text{Speed}_{\text{opt}} - \eta_m\right) + \left(\text{Location}_{\text{opt}} - \eta_m\right) \\ &+ \left(\text{D/d ratio}_{\text{opt}} - \eta_m\right) + \left(\text{C-w ratio}_{\text{pot}} - \eta_m\right),\end{aligned} \tag{3}$$

where η_{opt} = predicted optimum heat transfer coefficient and η_m is the overall average of all the experimental data for heat transfer coefficient.

The calculated values of various response averages are η_m = 626.17 W/m^2 K, speed$_{\text{opt}}$ = 665.0 W/m^2 K, location$_{\text{opt}}$ = 629.6 W/m^2 K, D/d ratio$_{\text{opt}}$ = 654.8 W/m^2 K, and C-w ratio$_{\text{pot}}$ = 637.1 W/m^2 K. So substituting these values in (3), the mean optimum value of the heat transfer has been predicted as η_{opt} = 707.99 W/m^2 K.

6.6. Confidence Interval (CI) for Predicting a Confirmation Experiment. A confirmation experiment is used to verify that the factors and levels chosen from an experiment cause a product or process to behave in a certain fashion. A selected number of tests are run under constant, specified conditions to observe results that, the experimenter hopes, are close to the predicted value. Thus a 95% confidence interval (CI) for the predicted mean of optimum heat transfer on a confirmation test is estimated using (4) [18]:

$$\text{CI} = \sqrt{F}\left(\alpha \cdot 1 \cdot f_e\right)\ V_e\left[\frac{1}{n_{\text{eff}}} + \frac{1}{r}\right], \tag{4}$$

$$N_{\text{eff}} = \frac{N}{1 + T_{\text{DOF}}}, \tag{5}$$

where $F(\alpha\cdot 1\cdot f_e)$ is the F-ratio required 100 $(1-\alpha)$ percent confidence interval, f_e is DOF for error, V_e is the error variance, r is number of replications for confirmation experiment (=3), and n_{eff} is effective number of replication. N is total number of experiments (=27 (9 × 3)) and T_{DOF} is the total degrees of freedom (=8 (2 × 4)) associated with the estimate of mean optimum. From Table 6, the values are $V_e = 15.101$, $f_e = 18$, and from standard statistical table in (15), the required F-ratio for $\alpha = 0.05 : F\ (0.05, 1, 18) = 4.41$. Substituting these values in (4) and (5), the calculated confidence interval is CI = ±12.47. Thus the 95% confidence interval of the predicted optimal heat transfer coefficient is obtained as 707.99 $Wm^{-2}\,K^{-1}$; that is, 695.52 W/m^2 K < 707.99 W/m^2 K < 720.46 W/m^2 K.

6.7. Confirmation Experiment. In order to test the predicted result, confirmation experiment has been conducted by running other three replications at the optimal settings of the process parameters determining the analysis.

The results are shown in Table 7 and it is observed that the mean heat transfer coefficient obtained from the confirmation experiments is 712.87 W/m^2K, which falls within the predicted 95% confidence interval.

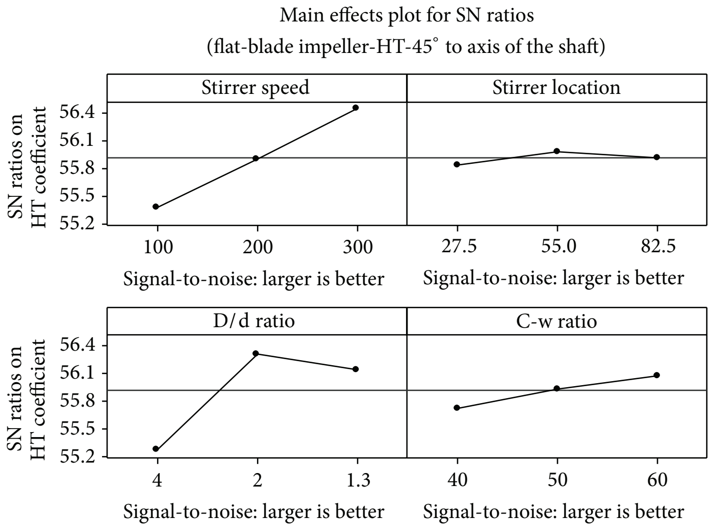

Figure 6: Main effects plots for S/N ratios of coal-water slurry.

Table 7: Analysis of variance (ANOVA) for heat transfer coefficient.

Factor	Sum of squares (SS)	Degrees of freedom	Variance (V)	F-ratio	$F_{0.05}$	Pure sum of squares (SS′)	Percent contribution in % (p)
Stirrer speed	26029.70	2	13014.85	246.02*	3.55	25923.89	45.65
Stirrer location	203.50	2	101.75	1.92	3.55	97.70	0.17
D/d ratio	27139.22	2	13569.61	256.51*	3.55	27033.42	47.60
C-w ratio	2467.07	2	1233.54	23.32*	3.55	2361.26	4.16
Errors	952.23	18	52.90	—	—	1375.45	2.42
Total	56791.72	26	—	—	—	56791.72	100

Tabulated F-ratio at 95% confidence level: F (0.05, 2, 18) = 3.55.
*Significant at 95% confidence level.

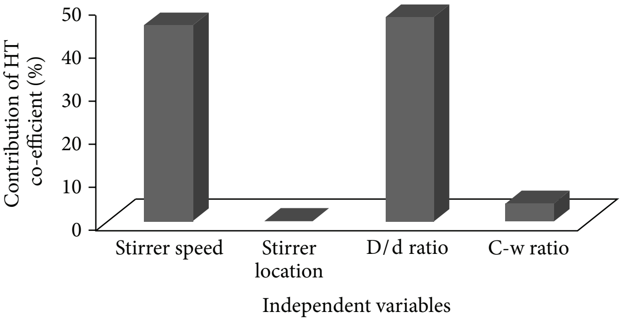

Figure 7: % of contribution of each design variables.

Table 8: Results of confirmation experiments.

Heat transfer coefficient $Wm^{-2}\,K^{-1}$	Replications			Mean
	Reading 1	Reading 2	Reading 3	
	713.78	715.21	709.62	712.87

7. Comparison between Blade Geometry of Stirrer

The optimal parameter of heat transfer coefficient from the previous literature study in agitated vessel with flat blade impeller parallel to the axis of the shaft was determined and optimized as 258.23 $W/m^2\,K$ based on the Taguchi method [4]. But in this study, the blade angle is changed making 45° angle to the axis of the shaft. As per comparison between these two types of blades, the flat-blade impeller making 45° angle to the axis of the shaft is performed as the best for getting higher heat transfer coefficient (712.87 $W/m^2\,K$) during the agitation using coal slurry.

8. Conclusions

The purpose of the investigation is to determine the heat transfer coefficient for stream augmented flows in agitated vessels with flat blade impeller making 45° angle to the axis of the shaft. The rate of heat transfer is influenced by a number of physical and geometrical factors such as vessel configuration, impeller type, and process fluid like coal slurry. This study has shown the application of the Taguchi method on the performance evaluation of heat transfer coefficient for agitated vessel using coal slurry in coal gasification power plant. The following conclusions may be drawn form the present investigation work.

(i) Based on the ANOVA results, all control factors have significant effect on the quality characteristics statistically except stirrer location.

(ii) D/d ratio ($P = 47.60\%$) has the most dominant effect on total variation and it is followed by stirrer speed ($P = 45.65\%$), C-w ratio ($P = 4.16\%$), and stirrer location ($P = 0.17\%$).

(iii) The optimal levels of the process parameters were found to be stirrer speed of 300 rpm, stirrer location of 55.0 mm, D/d ratio of 2, and C-w ratio of 60%.

(iv) The optimized value of the heat transfer coefficient for a 95% interval has been predicated as $707.99\ \mathrm{W/m^2\,K}$; that is, $695.52\ \mathrm{W/m^2\,K} < 707.99\ \mathrm{W/m^2\,K} < 720.46\ \mathrm{W/m^2\,K}$.

(v) From confirmation experiments, the mean value of the heat transfer corresponding to the optimum conditions was obtained as $712.87\ \mathrm{W/m^2\,K}$ (Table 8), which fell within the predicated value.

(vi) The jacketed vessel was heated by waste steam which is exhaust from the steam turbine in the coal gasification power plant.

(vii) The Taguchi method can successfully be applied to heat transfer investigation in agitated vessel using coal gasification plant to save energy, time, and material in experimentation.

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