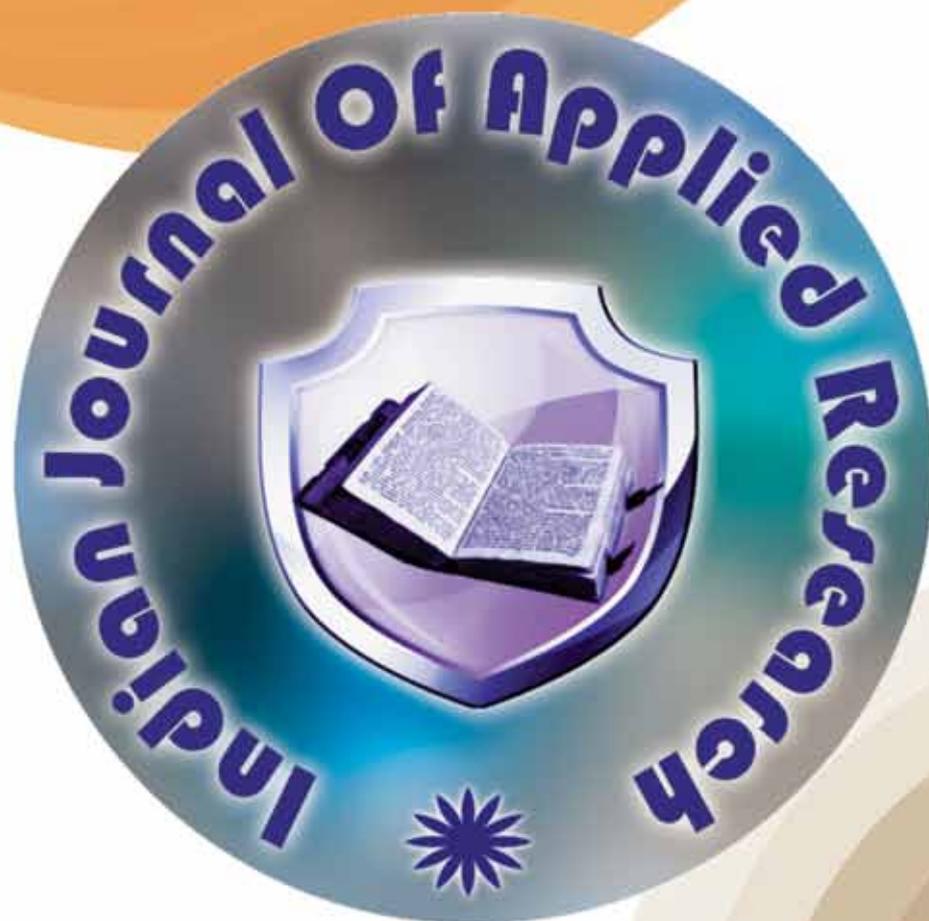


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Prediction of Heat transfer rate for Indian coal slurry based on regression analysis

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ABSTRACT

A pre-heating vaporization technology of coal water slurry was developed to increase the efficiency of coal gasification with reduction of oxygen consumption. The heat transfer rate of coal slurry in agitated vessel will depend on the operational parameters of the experiment such as stirrer speed, stirrer location, D/d ratio and coal-water ratio. The planned experiments are conducted in the agitated vessel and the signal-to-noise ratios are computed to determine the optimum parameters. The percentage contribution of each factor is validated by analysis of variance (ANOVA) technique. Multiple regression analysis (MRA) is conducted using statistical package for Minitab-15 software and the mathematical model is build to predict the heat transfer rate of coal water slurry for any given conditions.

Keywords : Agitation vessel, flat blade impeller with 30 degree angle, Heat transfer rate, coal slurry, Taguchi method, Regression analysis

1. Introduction:

Coal is the largest indigenous fossil fuel resource which currently meets about 60% commercial energy requirements of India. Power generation from coal is based on pulverized coal – fired technology. Environmental problems associated with the increased use of energy are going to attract great importance in the coming years. Advanced coal utilization technologies are being developed to respond to the energy and environmental demand of 21st century and also a utilize the coal resources efficiently, economically and cleanly. One of such approaches is coal – water slurry (CWS) which holds promise as an attractive alternative fuel for power generation industry in India [1]. CWS preparation process have been developed and commercialized with large scale production plant in foreign country. Research and development activities are in progress on various aspects of the CWS technology. CWS prepared from low-rank coals have shown excellent combustion characteristics in the gas turbine [2].

Research on heat transfer co-efficient 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 factor for controlling the outcome of process. Mechanically agitated vessels are widely used in mining, food, petroleum, chemical, pharmaceutical, pulp, paper industries and also using in coal gasification power plant [3]. 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 [4]. In this study the effect of some important parameter 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 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 [5].

2. Experimental Details

The schematic diagram of the experimental setup is shown in fig. 1 [6]. An agitator is driven by a vertically mounted motor which is used for stirring. The jacketed vessel is properly insulated with glass wool. The inlet to this vessel is connected to an electrically operated boiler that generates steam continuously at constant pressure which is monitored by a pressure gauge connected to the jacket. A vent is provided for releasing non-condensable gas and to maintain the pressure in jacket. A steam strainer is placed at the bottom of the vessel to collect the condensate. Outlets are also given at the bottom side of the agitated vessel for collection of samples.

The cylindrical jacketed vessel is of mild steel, 210mm diameter, 6mm thick, and 160 mm height with a flat bottom. Another cylindrical inner vessel of 110 mm diameter, 6 mm thick and 110 mm height with similar flat bottom was used for coal slurry mixing. This assures that the height of vessel is always equal to diameter of the vessel (H=D) [6]. The impeller used in the mixing vessel is having flat blade with four wings which is indicated in fig. 2 and is driven by a variac controlled motor. The impeller is fitted perpendicular to the axis of shaft that makes an angle of 30°. The thickness of each wing of the blade is 1.6mm thick and width of 17.5mm. When the temperature reaches the saturation temperature of the slurry (100° C), the time period (sec) was noted and this period is called heating period (Unsteady state).

The proximate and ultimate analysis of Indian coal used in the preparation of the slurries is given in table1.

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%

Additive is the main ingredient in the making of CWS, which is also one of the key factors affecting CWS quality. Usually additive dosage accounts for about 1% of the total. Based on function, additives can be used like dispersant and stabilizing agent. In this project sodium carbonate and sodium salt of carboxymethyl cellulose (Na-CMC) were used as dispersant and stabilizing agent respectively. The best dosage of dispersant and stabilizers is 0.75% by wt. of solids and 0.1% by wt. from total solids [7].

The preferred concentration of coal slurry which enables problem free feeding into the gasification plant is 40-70% [8]. The coal particle size is BSS 36(0.422mm).

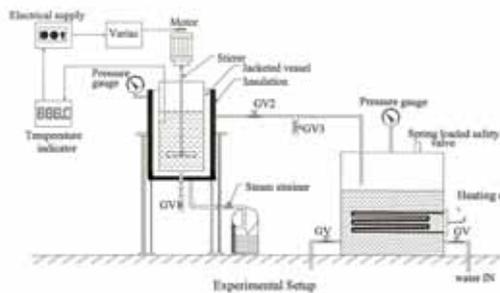


Fig. 1 Experimental Setup [6]

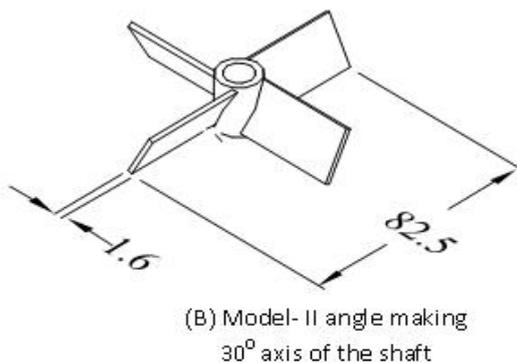


Fig. 2 Impeller detail(Maximum width)

3. Statistical Approach for finding out Heat transfer rate

3.1 Design of Experiments:

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 achieving high quality without increasing cost [9]. Taguchi's parameter design method is a powerful tool for optimizing the performance characteristics of a process [10-11]. 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. In the experimental plan, the most dominant operational parameters such as stirrer speed (x1), stirrer location(x2), D/d ratio(x3) and C-W ratio(x4) were varied at three levels. Normally, when four factors, each varied at three levels considered, 34(81) experiments are to be conducted using full factorial experimental design. In order to save on experimental cost and time, Taguchi's orthogonal array was applied to obtain the heat transfer co-efficient of the coal slurry. A L9 orthogonal array was found to be appropriate and it was chosen. The experimental array of the L9 orthogonal array and the measured Heat transfer co-efficient are shown in Table 2.

Table 2. Experimental array based on L9 orthogonal array and experimental results

Experiments No.	X1	X2	X3	X4	Heat transfer co-efficient W/m ² k
1	100	27.5	4.0	40:60	347.16
2	100	55	2.0	50:50	410.82
3	100	82.5	1.3	60:40	566.77
4	200	27.5	2.0	60:40	495.43
5	200	55	1.3	40:60	412.45
6	200	82.5	4.0	50:50	536.29
7	300	27.5	1.3	50:50	462.06
8	300	55	4.0	60:40	574.52
9	300	82.5	2.0	40:60	415.33

3.2 Regression analysis model:

Multiple regressions technique is used to ascertain the relationships among variables. The most frequently used method among social scientists is that of linear equations. Regression analysis method includes the experimental investigation, mathematical methods and statistical analysis. In the present investigation, a whole analysis was done using the experimental data in Table 2. The multiple linear regressions take the following form.

$$Y = a + b_1X_1 + b_2X_2 + b_3X_3 + \dots + b_kX_k \dots \dots \dots (1)$$

Where Y is the dependent variable, which is to be predicted: X₁, X₂, X₃,..... X_k are known variables on which the predictions are to be made and a, b₁, b₂, b₃,..... b_k are the coefficients, the values of which are determined by the method of least squares. Multiple regression analysis is used to determine the relationship between the dependent variables of heat transfer co-efficient of coal slurry with stirrer speed, stirrer location, D/d ratio and C-W ratio. The regression analysis was done by Minitab-15, a commercial statistical program. The regression analysis of the input parameters is expressed in linear equations as follows:

$$HT = - 45.6 + 0.212 \times \text{Stirrer speed} + 1.30 \times \text{stirrer location} + 6.62 \times \text{D/d ratio} + 7.70 \times \text{C-W ratio} \dots (2)$$

Heat transfer rate is dependent variable and stirrer speed, stirrer location, D/d ratio and C-W ratio are independent variables. Corresponding coded levels given table 1 are used in Eq.(2). From the above equations, values of Heat transfer rate can be predicted for any given values of operational parameters. It is clear that statistical model can predict the heat transfer co-efficient of coal slurry with sufficient accuracy depending on the obtained correlation coefficient (R²=92.2%). The mathematical model is built by MINI TAB software package for heat transfer rate of coal slurry. The output results from the predicted model are calculated for the corresponding input data. Measured values from the experiment and the predicted values from the multiple regression technique are shown in Table 3. The comparison of heat transfer rate between the experimental values and the predicted multiple regression analysis model are given in fig.3.

Table 3. Experimental/Predicted results

Experiments Number	Experimental Heat transfer co-efficient W/m ² k	Predicted Heat transfer co-efficient W/m ² k	Error %
1	347.16	345.83	0.383
2	410.82	445.34	7.751
3	566.77	553.46	2.348
4	495.43	507.79	2.434
5	412.45	384.91	6.677
6	536.29	515.53	3.871
7	462.06	447.36	3.181
8	574.52	577.98	0.599
9	415.33	446.49	6.986

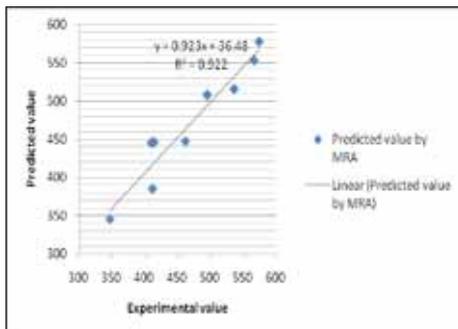


Fig. 3 Comparison of Heat transfer rate of coal slurry

3.3 Confirmation experiment

In order to test the predicted result, confirmation experiment has been conducted by running another three replications at the optimal settings of the process parameters determined the analysis.

Table 4 - Results of confirmation experiments using optimal factors

Heat transfer co-efficient Wm ⁻² K ⁻¹	Replications			Mean
	Reading 1	Reading 2	Reading 3	
	615.35	616.72	616.07	616.07

The results are shown in tab.4 and it is observed that the mean heat transfer co-efficient obtained from the confirmation experiments is 616.07 Wm⁻²K⁻¹, which falls within the predicted 95% confidence interval.

The final step in verifying the results based on Taguchi experimental design is the experimental confirmation test. Table 5 shows the experimental conditions at optimal factor settings. This table indicates the comparative test results for heat transfer rate of coal slurry in agitated vessel. From the confirmation test results, average 3.33% error was obtained between predicted values by the regression model and confirmation test results. It can be concluded that Taguchi method achieves the statistical assessment of maximum heat transfer rate of coal slurry in the agitated vessel with sufficient accuracy.

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Table 5. Comparison of confirmation experimental results with regression equation

Test	Experimental results	Results as per developed model Eq.(2)	Error in %
01.	615.35	595.56	3.22
02.	616.72	595.56	3.43
03.	616.07	595.56	3.33

4. Result and discussion

The heat transfer co-efficient was determined as per experiment runs. The optimal level of the process parameters were found to be stirrer speed of 300rpm, stirrer location of 82.5mm, D/d ratio of 1.3 and C-W ratio of 60%.

The optimized value of the heat transfer co-efficient for a 95% interval has predicated as 614.76 W/m² K. i.e., 608.10 W/m² K < 614.76 W/m² K < 621.42 W/m² K).

From confirmation experiments, the mean value of the heat transfer corresponding to the optimum conditions was obtained as 616.07 W/m² K, which fell within the predicated value. Ten confirmation experiments including optimum experiment condition were conducted and as a result of the comparisons between predicted values by the regression model and confirmation test results, the average error of 3.80% was obtained. This result indicates that Taguchi method can be used in the optimization of heat transfer rate of coal slurry in agitated vessel performance.

Multiple regression analysis(MRA) is conducted using Minitab-15 software package and the mathematical model is build to predict the heat transfer rate of coal water slurry for any given operational parameter conditions. Three confirmation experiments including at optimum experimental condition were conducted and as a result of the comparisons between predicted values by the regression model and confirmation test results, the average error of 3.33% was obtained.

The Taguchi method can successfully be applied to heat transfer rate investigation in coal water slurry used in coal gasification plant to save energy, time, and material in experimentation.

5. Conclusions

In the current study, empirical models were developed with multiple nonlinear regression method using results predicted with Taguchi experimental design in order to optimize heat transfer rate of coal slurry. The methodology of model development is described and validated. In Taguchi method, an orthogonal array (L₉) was selected for four factors and three levels for each factor. In the experimental plan, the most dominant operational parameters such as stirrer speed, stirrer location, D/d ratio and C-W ratio were varied at three levels. The nonlinear regression model with four independent variables is developed as the best-fit model (R² is 0.92) to optimize the heat transfer rate. The newly developed approach gives a new scope of calculation to predict the heat transfer rate for coal slurry.

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