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MODELING OF MELTING RATE OF AN HYBRID FUEL-FIRED CUPOLA FURNACE

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Abstract

The melt ratio of a hybrid (2.5 kg of Okaba coal + 0.5 kg of *Erythrophleum Suaveolens* charcoal) fuel-fired cupola furnace used in melting scraps of cast iron was 5.6:1. This work presents formulation of multiple linear regression model for the melting rate of a hybrid fuel-fired cupola furnace as a function of air blast pressure, melting time and fuel consumed. The model validation confirmed the existence of statistical relationships between the melting rate and air blast pressure, melting time and fuel consumed. Appling the experimental data, R^2 values of 99.9% was obtained. The coefficients b_{00kc}, b_{10kc}, b_{20kc} and b_{30kc} were determined as 35.204, -35.079, 0.931 and 1.796 respectively; and the results of the t- test indicated that regression coefficients b_{10kc}, b_{20kc} and b_{30kc} were statistically significant and not equal to zero (as given by hypothesis ii) at 0.025 level of significance and 11 degrees of freedom (table t-value= $t_{0.025}$, 11 = 2.201). The variance inflation factor VIF of 1.004 indicated that multi co-linearity was not a problem in this application (i.e. VIF < 4), which clearly demonstrated that air pressure; melting time and fuel consumed were not significantly interacting factors. The developed model can be used to develop a computer software to predict the behavior of meting rate of an okaba coal and erythrophleum suaveolens charcoal blend-fired cupola furnace as a function of air blast pressure, melting time and fuel consumed for the purpose of reducing the energy consumption in iron melting.

Key words: Modeling, melting rate, hybrid fuel, cupola furnace, *Erythrophleum Suaveolens* charcoal

1.0 Introduction

Energy cost represents a significant portion of the overall production cost and thus has an impact on product pricing and marketing. Energy cost is about 2% of production cost for electronics and printing industries, 35% for iron and aluminum industries, 55% for cement industries and 65% of production cost for oil refineries and similar industries (Jacques *et al.*, 1998). Since energy represents a variable cost item, energy management has gained increased importance and therefore, energy becomes a controllable factor that has significant effect on the expenses of businesses (Olorunnishola and Egbo, 2007).

The metal casting industry is one of the most energy-intensive manufacturing sectors with the melting process accounting for over half (55%) of its energy consumption. Although its high energy expenses have been a significant concern for metal casters, the industry continues to use melting technologies with poor energy efficiency (Energetics, 2000).

The U.S. metal casting industry, primarily consisting of small businesses (80% have less than 100 employees), are averse to taking new financial risks due to the typically small profit margins of the metal casting operations; they are, therefore, hesitant to invest in long-term R and D and to implement advanced technologies that involve replacing the entire furnace, even if they offer significant energy savings. The prime criterion for the commercial acceptance of new advanced melting technologies is that they must not be capital intensive for installation (Robert *et al.*, 2005).

Emerging technologies such as solar melting, microwave melting, infrared heating, or plasma heating offer unconventional ways of providing enormous amounts of energy effectively to the metals; however, barriers like limited capital resources and melting capacities, and/or large space requirements make these innovative methods financially unviable for the metal casting industry (Schifo, 2005). The plausible advances in melting technologies that hold potential for energy reduction, therefore, center on retrofit improvements for existing furnaces; these advances include oxygen-enriched fuel combustion, preheating of charge, molten metal delivery, and heat recovery from flue gases (Ighodalo, 2011). In this work alternative source of fuel for cupola furnace was explored by experimenting the blend of okaba coal and erythrophleum suaveolens charcoal as fuel. The data obtained from the experiment was used to generate a model for a hybrid fuel-fired cupola furnace. This work will provide input data for improving energy

consumption of the furnace through identifying, validating, and controlling statistically significant control factors that can influence iron melting rate.

Captions Statistical methods such as cluster analysis, pattern recognition, design of experiments, factor analysis, and regression analysis are some of the statistical techniques which enable one to analyze the experimental data and build empirical models to obtain the most accurate representation of physical situations (Kumar and Singh, 2012). In this work, regression modeling was adopted as a modeling technique. There are a number of variables controllable to varying degrees which affect the quality and composition of the out-coming molten metal. These variables, such as flame temperature, preheat air temperature, blast air pressure, excess air percentage, melting time, fuel consumption and melting rate play significant role in determining the molten metal's properties and should be controlled throughout the melting process (Singh et al, 2006).

Numbers of heats were produced by varying some of the critical input parameters and output as melting rate was observed from the regressive experiments. According to Kumar and Singh (2012), the Critical input Parameters affecting the melting rate are: Blast air pressure (in Pa) which is the pressure of the air supplied by the blower, Melting Time (in Minutes) which is the melting time of metal and Fuel Consumed (in Kilogram) which is the fuel consumed in melting the metals.

Therefore, to keep the experiments manageable, the above mentioned critical variables with their nominal values were selected.

2.0 Experimental Procedure

Cast iron scraps were sourced from car engine blocks. In the experimentation, firstly, a predetermined quantity of metal (17 kg) was melted with the mixture of OK/ES (2.5 kg of Okaba coal + 0.5 kg of *Erythrophleum Suaveolens* charcoal) as fuel per charge. Each charge was accompanied with 1 kg of limestone in order to separate the slag from the molten iron. Also 1 kg of ferrosilicon was introduced to the charge at an interval before the iron was tapped in order to improve the machinability of the cast iron. This experiment was conducted at different values of air blast pressure of 1.03 and 1.02 bars, while using the hybrid fuel (OK/ES) to melt the charge. The temperature readings were obtained by using digital multi-meter with k type thermocouple. The values of melting and tapping temperatures for the experiment are presented as shown in Table 1.

While conducting the experiment the variations of the rate of melting, fuel consumption and melting time with air blast pressure were recorded as shown in Table 2.

Fuel type	Melting zone temperature	Tapping temperature		
	(°C)	(°C)		
Okaba coal/ES charcoal blend	1230	1200		
Results of present research				

Table 1: Melting Zone and Tapping Temperatures

Table 2: Ok/Es fuel based experiment

Air blast	Melting Time (T)	Fuel Consumed	Melting Rate (\dot{M}_{4exp}				
Pressure(P) (bar)	(min.)	(F) (Kg)	$(Kg/min.) \ge 10^1$				
1.03	10	2.49	13.44				
1.03	20	4.78	25.98				
1.03	30	6.99	39.89				
1.03	40	9.88	53.75				
1.03	50	12.39	66.95				
1.03	60	13.98	80.62				
1.02	10	10 2.46					
1.02	20	4.88	26.90				
1.02	30	30 6.99					
1.02	40	9.65	55.03				
1.02	50	12.04	67.98				
1.02	60	60 14.66					
			$\dot{\boldsymbol{M}}_{3m} = \frac{1}{n} \sum_{i=1}^{n} M_i$				
			$=\frac{1}{12}(523.67)$ $= 44.47$				
			$ imes 10^{-1} kg$				
			/min.				

2.1 OK/ES Fuel Based Experimental results discussion

Table 2 showed that with an increase in air blast pressure from 1.02 bar to 1.03 bar, fuel consumption decreases gradually and this result in more output in terms of melting rate. From Table 2 while the average fuel consumed per minute was 0.84 kg at the pressure of 1.03 bar, the average metal melted per minute was approximately 4.677 kg. Therefore, while the fuel consumed per hour was 50.51 kg, the amount of metal melted per hour was 280.63 kg. Table 2 also showed that at 1.02 bar the average fuel consumed per minute was 0.845 kg while the amount of metal melted per minute was 4.717 kg. Therefore, the amount of fuel consumed per hour was 50.68 kg while the melting rate was 283.04 kg/hr. The above statements implied that at 1.03 bar, the ratio of metal melted to fuel consumed in melting the metal was 5.56:1 while at 1.02 bar the ratio was 5.58:1 (\approx 5.6:1). The results implied that at high pressure, even though the coal burns faster but because it contains high percentage of volatile matter, its ability to retain enough heat for efficient melting of iron was reduced. Table 1 showed that the tapping and melting temperatures were 1200 °C and 1230 °C respectively. The efficiency of the cupola furnace with a mixed Okaba coal and ES charcoal burnt as fuel was calculated to be 83.2 %.

3.0 Modeling theory

Melting Rate is taken as single output Parameter. Melting Rate (M), which is a function of Blast air Pressure (P), Melting Time (T) and Fuel Consumed (F), is as follows:

$$M = C_0 \times P^{C_1} \times T^{C_2} \times F^{C_3} \qquad \dots 1$$

On taking logarithm of both the sides,

 $In M = InC_o + C_1 In P + C_2 In T + C_3 In F \qquad \dots 2$

According to Lindgren (1976), the regression model for this problem involves three variables; therefore their dependency relationship can be mathematically expressed as follows:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \varepsilon$$
...3

This is a natural extension of the simple linear regression model. In matrix notation, it can be written as:

$$Y = X\beta + \varepsilon \qquad \dots 4$$

Y - Is a linear function of *k* control variable x_1, \ldots, x_k and ε is an error term. Using sample data, model parameters can be estimated using the coefficients $\beta_0, \beta_1, \beta_2, \beta_3, \ldots, \beta_k$ of the regression equation, associating response variable *Y* with its control variables $x_1, x_2, x_3, \ldots, x_k$

3.1 Variables selection

The relationship of air blast pressure (P), melting time (T) and fuel consumed (F), all independent variables with melting rate (M)), a dependent variable, is to be derived. The specific definitions and units of measurements of these variables are defined as follows; Blast air pressure measures in bar, is the pressure of the air supplied by the blower; Melting time (T) measures in Minutes, is the melting time of metal; Fuel Consumed (F) measures in Kilogram, is the fuel consumed in melting the metals and Melting rate (M) measures in Kg/min., is the amount of metal melted per minute.

The above factors are selected as control variables influencing melting rate of iron based on;

- The presence of physical or logical influence of these factors on Melting rate. For example, as air pressure increases the velocity of the air in the tuyere increases and hence accelerates the melting of the iron in contact with the solid fuel (Olorunnishola and Anjorin, 2018).
- ii) It is predicted that as the amount of iron melted per unit time changes, it is logical to conclude that melting rate in kg/min. would change accordingly (Chastain, 2000).

To justify the presence of such informative relationships between these factors, scatter diagrams are used to clearly indicate the validity of initial selection of control variables.

3.2 Models assumptions

The following assumptions were made:

- i. There was a linear relationship between the melting rate and the related control variables (application of scatter diagrams).
- ii. That multi-co-linearity was not present among the control variables (air pressure, melting and fuel consumed).
- iii. That the random errors (o) are independent and normally distributed with constant variance and zero mean.

4.0 Formulation of multiple linear regression models (MLRM)

4.1 Models formulation.

Based on the selected variables and model assumptions, the following multiple linear regression model was formulated for a cupola furnace using hybrid fuel (OK/ES).

Model: for a cupola furnace using OK/ES as fuel.

$$Exp(M/P,T,F) = b_{oOk/es} + b_{1Ok/es}P + b_{2Ok/es}T + b_{3Ok/es}F$$
(5)

where:

 $E_{xp}(M/P,T,F)$ is the expected value of melting rate in kg/min. given the independent variables P, T and F, $b_{oOk/es}$ is intercept of model IV, $b_{1Ok/es}$ is regression coefficient associated with air pressure of the model, $b_{2Ok/es}$ is regression coefficient associated with melting time of the model and $b_{3Ok/es}$ is regression coefficient associated with fuel consumed of the model.

4.2 Hypothesis 1: Testing model validity

Model hypothesis: for a cupola furnace using OK/ES as fuel is presented as in equation 6:

$$H_0: \beta_{jOk/es} = 0, \ j = 1, 2, 3$$

If H_0 is rejected, then H_1 : at least one $\beta_{jOk/es} \neq 0$

This hypothesis is intended to test validity of the presence of a relation between melting rate of the furnace and the independent variables. If the null hypothesis is rejected, then there are some independent variables that do actually affect melting rate.

4.3 Hypothesis II: Individual testing of coefficients of the multiple linear regression models.

Hypothesis II for any independent variable is as presented in equation 7.

$$H_0: \beta_{1-3Ok/es} = 0 \ vs \ H_1: \beta_{1-3Ok/es} \neq 0$$

The null hypothesis assumed that there was no statistically significant relationship between melting rate and any of the independent variables (blast pressure, melting time and fuel consumed).

4.4 Model Validation and Discussion

SPSS (version 16.0) was used to validate the data obtained in Table 2 and the results are shown

in Table 3.

Table 3: Model Summary for a Cupola Furnace using OK/ES as Fuel

ANOVA			COLLINEARITY DIAGNOSTICS			RESIDUALS					
Parameter	Value	Paramet er	Sum of squares	Param eter	Condition index	Coefficient s	VIF	T- Statistic	Param eter	Mean (µ)	Std. Deviation (σ)
\mathbf{R}^2	0.999	Regressio n	6501.65	Consta nt (b _{00kc})	1.00	35.204	-	0.542	Predict ed value	46.973	24.312
F-Statistic	1808.8 37	Residual	9.585	P (b _{10kc})	4.332	-35.079	1.004	-0.554	Residu al	0	0.933
Significance of F-statistic	0.000	-	-	T (b _{2Okc}) F(b _{3Okc})	118.346 566.218	0.931 1.796	-	2.666 1.238	-	-	-

(6)

Scatter diagram shown in Figure 1 was plotted which clearly indicates the validity of initial selection of variables. The model summary shown in Table 3, gave a computed value for the R^2 as 0.999, thus indicating that the regression was significant as 99.9 % variation in melting rate could be accounted for by the control variables. The ANOVA analysis in the regression result, shown in Table 3, gave a computed value for the F-statistic as 1808.837 while the corresponding table value of 3.98 at 0.05 level of significance (q) and (2,11) degrees of freedom showed that the multiple linear regression models was significant and valid. Large regression sum of squares (6501.65) in comparison to the residual sum of squares (9.585) indicated that the model accounts for most of variation in the dependent variable. The coefficients b_{00kc}, b_{10kc}, b_{20kc} and b_{30kc} shown in Table 3 are 35.204, -35.079, 0.931 and 1.796 respectively; and the results of the t- test indicated that regression coefficients b_{10kc} , b_{20kc} and b_{30kc} were statistically significant and not equal to zero (as given by hypothesis ii) at 0.025 level of significance and 11 degrees of freedom (table t-value= $t_{0.025}$, 11 = 2.201) (*Neave, 1978*). Therefore, the regression equation of melting rate of iron in kg/min. can be given by equation 8. It should be noted that the assumptions made were valid for this model with respect to multi co-linearity and residuals' distribution. As seen from Table 3, the condition indexes value of 4.332, 118.346 and 566.218 are for P, T and F respectively. From Table 3 the predicted value of mean was 4.697 kg/min with standard deviation of 2.431 kg/min implying that control variables were independent. The variance inflation factor VIF of 1.004 indicated that multi co-linearity was not a problem in this application (i.e. VIF < 4) (*Neave*, 1978), which clearly demonstrated that air pressure; melting time and fuel consumed were not significantly interacting factors.

$$Exp(M_4/P,T,F) = 35.204 - 35.079P + 0.931T + 1.796F$$
(8)



Figure 1: Scatter Plot for the Model

5.0 Conclusion

Multiple linear regression Model was formulated to establish the relationship between air blast pressure, melting time, fuel consumed and iron melting rate of an hybrid fuel-fired cupola furnace. The significance of the relationship between air blast pressure, melting time, fuel consumed and iron melting rate was established. The model summary gave a computed value for the R^2 as 0.999, thus indicating that about 99.9 % of the variation in melting rate could be accounted for by the control variables.

The coefficients b_{00kc} , b_{10kc} , b_{20kc} and b_{30kc} shown in Table 3 are 35.204, -35.079, 0.931 and 1.796 respectively; and the results of the *t*- test indicated that regression coefficients b_{10kc} , b_{20kc}

and b_{30kc} were statistically significant and not equal to zero (as given by hypothesis ii) at 0.025 level of significance and 11 degrees of freedom (table t-value= $t_{0.025}$, 11 = 2.201). Also in testing hypothesis I, since no value of the regression coefficients for all the independent variables (P, T and F) was equal to zero, the null hypothesis was rejected and the alternative accepted for all the independent variables. The average variance inflation factor *VIF* of 1.004 indicated that multi co-linearity was not a problem in this application (i.e. *VIF* < 4).

The regression model developed in this work can effectively estimate the melting rate based on Air blast pressure; Melting time and Fuel consumption. The model equation when used to develop a computer software will help energy and foundry managers to significantly monitor and improve on the melting rate of a hybrid fuel-fired cupola furnace which may in turn reduce the energy consumed in iron melting.

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