

Model for Predicting the Upgraded Concentration of Iron during Solid-State Beneficiation of Iron Oxide Ore Pelletized with Powdered Potassium Chlorate

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Abstract: Model for predicting the upgraded concentration of iron during solid-state beneficiation of iron oxide ore has been derived. The model-predicted %Fe upgrades were found to agree with a direct relationship between %Fe values and weight input of KClO₃ as exhibited by %Fe upgrades obtained from the experiment. It was found that the model; %Fe = 1.57[(ln(T/γ))^{2.58}] is dependent on the weight input of KClO₃ and the range of treatment temperature used (500-800°C). It was found that the validity of the model is rooted in the expression (%Fe/α)^N = ln(T/γ) where both sides of the expression are correspondingly approximately equal to 4. The maximum deviation of the model-predicted values of %Fe from those of the corresponding experimental values was found to be less than 13% which is quite within the range of acceptable deviation limit of experimental results. Upgraded concentration of iron per unit increase in the treatment temperature evaluated from experimental and model-predicted results are 0.0545 and 0.0629%/°C respectively, indicating proximate agreement. [Nature and Science. 2009;7(7):8-14]. (ISSN: 1545-0740).

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1. Introduction

Nigeria's largest known iron ore deposit estimated at 1250 metric tonnes have been found at Agbaja. It consists of oolitic and pisolitic structures rich in iron oxides, in a matrix that is predominantly clay [1]. Uwadielle [1] also found that the principal constituent of the ore is goethite, with minor hematite, maghemite, siderite, quartz, kaolinite pyrite and an average of 0.09%S.

It has been reported [2] that one of the most important factors influencing the desulphurization process during iron making is the state of oxidation of the bath.

Desulphurization of Agbaja iron oxide ore concentrate using solid potassium trioxochlorate (v) (KClO₃) as oxidant has been carried out [3]. The concentrate was treated at a temperature range 500–800°C. The results of the investigation revealed that simultaneous increase in both the percentage of the oxidant added (up to 15g per 50g of ore) and treatment temperature (maximum 800°C) used give the ideal conditions for increased desulphurization efficiency. This translates into high desulphurization efficiency when both oxidant concentration (up to 15g per 50g of ore) and treatment temperature (maximum 800°C) are high.

The mechanism and process analysis of desulphurization of Agbaja iron ore concentrate using powdered potassium trioxochlorate (v) (KClO₃) as oxidant has been reported [4]. Concentrates were treated at a temperature range 500 – 800°C. Results of the process analysis indicate that oxygen required for the desulphurization process was produced following decomposition of KClO₃ within a temperature range 375-502°C. It was observed that this temperature range is the Gas Evolution Temperature Range (GETR) for sulphur present in Agbaja iron ore. Sulphur vapour and oxygen gas produced at this temperature range were believed to have reacted to form and liberate SO₂. The process analysis suggests that the mechanism of the desulphurization process involves gaseous state interaction between oxygen and sulphur through molecular combination. The results for the extent of desulphurization reveal that simultaneous increase in both the percentage of the oxidant added and treatment temperature used (up to 15g KClO₃ per 50g of ore and maximum of 800°C respectively) are the ideal conditions for the best desulphurization efficiency.

Previous study [5] indicates that Agbaja oolitic iron ore, which has not been responsive to so many upgrading processes, has been upgraded to 73.4% Fe assay (starting from as-received concentrate assaying 56.2%Fe) by pyrometallurgical-oxidation method. Main parameters investigated were the effects of treatment temperature and oxidant (KClO₃) on the upgrading process. It was established that 800°C is the optimum temperature for the upgrading step considering the range of temperature used (500-800°C). It was observed from results of the investigation that both oxidant and temperature increase (up to 12g per 50g of iron ore and maximum of 800°C respectively) during the process are vital conditions for improving on the grade of the ore concentrate.

Following an intensive study [6] on selective oil agglomeration of Agbaja iron ore, the crude ore of Fe content (45.6%), was concentrated by oil agglomeration technique to 90% Fe recovery and 65% Fe assay. The researcher stated that the ore require grinding to minus 5µm to effect adequate liberation. These results were obtained at optimum pH 9. It was found [7] following studies on the effect of temperature on magnetizing reduction of Agbaja iron ore that the fine-grained oolitic Agbaja iron ore, which is not responsive to conventional processing techniques, can be upgraded by the magnetizing reduction method with an Fe recovery of 87.3% and Fe assay of 60% at 600°C.

It has been found [8] that oleate can be used to enhance concentrate Fe recovery. The researchers stated that concentrate Fe recovery decreases progressively below pH 8. In this pH region, oleate used is present as dispersion of oleic acid, and its adsorption on the surface of the iron oxides is similar to the process of hetero-coagulation involving positively charged iron oxide particles and negatively charged oleic acid droplet.

Model for predictive analysis of the concentration of sulphur removed by molecular-oxygen-induced desulphurization of Agbaja (Nigeria) iron oxide ore has been derived [9]. The model is expressed as;

$$\%S = \text{Log}T - \text{Log} \alpha - \text{Log}k_n \quad (1)$$

Where

%S = Concentration of sulphur removed during the pyrometallurgical-oxidation process.
 $k_n = 9.75$ (Decomposition coefficient of KClO_3 at the treatment temperature (600°C) determined in the experiment [9].

$(\mu) = 2.1739$ (Oxidation coefficient of KClO_3 relative to the treatment temperature (600°C) determined in the experiment[9]

$(\alpha) =$ Weight of iron oxide ore added (g)

T = Treatment temperature used for the process (°C)

$(\gamma) =$ Weight of KClO_3 added (g)

$D_e = 0.0415$ (Assumed Desulphurization Enhancement Factor)

Substitution of these parameters into the model in equation (1) reduced it to ;

$$\%S = \frac{0.0415}{\text{Log} \gamma} \quad (2)$$

The model was found to predict the concentration of sulphur removed, very close to the corresponding %S values obtained from the actual experimental process. It was found that the model is dependent on the values of the weight input of the oxidant (KClO_3) during the desulphurization process. The validity of the model was rooted in the expression $k_n[(\gamma)^{\mu\%S}] = T/\alpha$ where both sides of the expression were correspondingly almost equal.

The aim of this work is to derive a model for predicting the upgraded concentration of iron during solid-state beneficiation of Agbaja (Nigeria) iron oxide ore pelletized with powdered potassium chlorate. The powdered potassium chlorate was used in the preceding work [9] as oxidant.

2. Model

The solid phase (ore) is assumed to be stationary, contains some unreduced iron remaining in the ore. It was found [4] that oxygen gas from the decomposition of KClO_3 attacked the ore in a gas-solid reaction, hence removing (through oxidation) the sulphur present in the ore in the form of SO_2 . Equations (3) and (4) show this.



Nwoye [4] posited that when sulphur inherent in the iron ore is removed in this stance, the concentration of iron present in the ore is upgraded since sulphur is an impurity element and leaves as SO_2 .

2.1 Model Formulation

Experimental data obtained from research work [10] carried out at SynchroWell Research Laboratory, Enugu were used for this work.

Results of the experiment as presented in report [10] and used for the model formulation are as shown in Table 1. Computational analysis of the experimental data [10] shown in Table 1, gave rise to Table 2 which indicate that;

$$(\%Fe/\alpha)^N = \ln(T/\gamma) \quad (\text{approximately}) \quad (5)$$

Introducing the value of N and γ into equation (5);

$$(\%Fe/1.57)^{0.3876} = \ln(T/\gamma) \quad (6)$$

Since the inverse of 2.58 = 0.3876

$$(\%Fe/1.57)^{1/2.58} = \ln(T/\gamma) \quad (7)$$

Multiplying the indices of both sides by 2.58;

$$\%Fe/1.57 = (\ln(T/\gamma))^{2.58} \quad (8)$$

$$\%Fe = 1.57[(\ln(T/\gamma))^{2.58}] \quad (9)$$

Where

%Fe = Upgraded concentration of iron during the beneficiation process

N = 0.3876 (Decomposition coefficient of $KClO_3$ during the beneficiation process at the treatment temperature range 500-800°C) determined in the experiment [10].

(γ) = Weight of $KClO_3$ added as oxidant during the beneficiation process (g).

(α) = 1.57(Oxidation coefficient of $KClO_3$ relative to its weight-input during the beneficiation process) determined in the experiment[10]

I_f = 2.58 (Assumed Temperature-Oxidant Interaction Factor)

T = Treatment temperature (°C)

Equation (9) is the derived model

Table1:Variation of upgraded concentration of iron with treatment temperature.[10]

%Fe	T(°C)	(γ) (g)
57.60	500	50
62.80	550	50
68.00	600	50
68.18	650	50
68.50	700	50
68.72	750	50
69.00	800	50

Table 2: Variation of $(\%Fe/\alpha)^N$ with $\ln(T/\gamma)$

$(\%Fe/\alpha)^N$	$\ln(T/\gamma)$
4.0403	3.9120
4.1779	4.0073
4.3089	4.0943
4.3132	4.1744
4.3210	4.2485
4.3264	4.3175
4.3332	4.3820

3. Boundary and Initial Condition

Iron oxide ore (in a furnace) pelletized with potassium chlorate (oxidant) is considered. The furnace atmosphere was not contaminated i.e (free of unwanted gases and dusts). Initially, atmospheric levels of oxygen were assumed just before the decomposition of $KClO_3$ (due to air in the furnace). Weight of iron oxide ore; (50g), and treatment temperature range; 500-800⁰C were used. Treatment time; 360 secs., average ore grain size; 150 μ m, and weight-input of $KClO_3$ (oxidant); 10g were also used. These and other process conditions are as stated in the experimental technique [10].

The boundary conditions were: furnace oxygen atmosphere due to decomposition of $KClO_3$ (since the furnace was air-tight closed) at the top and bottom of the ore particles interacting with the gas phase. At the bottom of the particles, a zero gradient for the gas scalar are assumed and also for the gas phase at the top of the particles. The reduced iron was assumed to be stationary. The sides of the particles were taken to be symmetries.

4. Model Validation

Direct analysis and comparison of %Fe values predicted by the model and those obtained from the experiment were carried out to ascertain the validity of the formulated model.

Computational analysis and comparison between these %Fe values reveal deviations of model-predicted %Fe values from those of the experiment. This was attributed to the fact that the surface properties of the ore and the physiochemical interactions between the ore and the oxidant (under the influence of the treatment temperature) which were found to have played vital roles during the oxidation-beneficiation process [10] were not considered during the model formulation. This necessitated the introduction of correction factor, to bring the model-predicted %Fe values to those of the experimental %Fe values.

Deviation (Dv) (%) of model-predicted %Fe values from experimental %Fe values is given by

$$Dv = \frac{M_D - E_D}{E_D} \times 100 \quad (10)$$

Where M_D = Model-predicted %Fe value
 E_D = Experimental %Fe value

Correction factor (Cr) is the negative of the deviation i.e

$$Cr = -Dv \quad (11)$$

Therefore

$$Cr = - \frac{M_D - E_D}{E_D} \times 100 \quad (12)$$

Introduction of the corresponding values of Cr from equation (12) into the model gives exactly the corresponding experimental %Fe values [10].

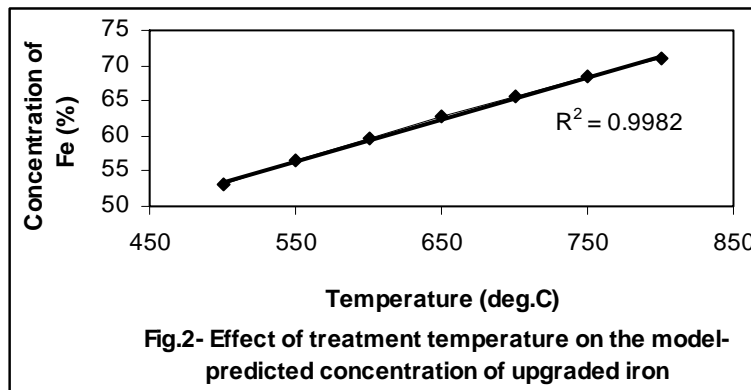
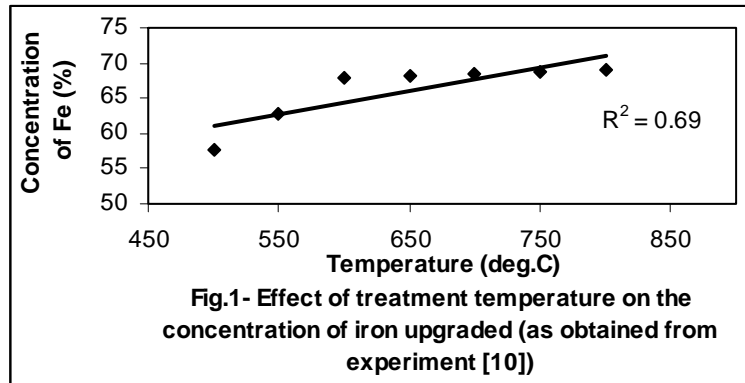
5. Results and Discussion

The derived model is equation (9).

Equations (8) and (9) show that since 2.58 is the index of the expression $\ln(T/\gamma)$, the values of the process parameters; T and γ as applied to the beneficiation process are simultaneously affected by the constant 2.58 towards iron upgrade. The constant is therefore assumed to be the interaction factor between treatment temperature and the oxidant (Temperature-Oxidant Interaction Factor) I_f since it is common to both T and γ mathematically. It was found that the model-predicted %Fe upgrades show a direct relationship with the treatment temperature, in agreement with %Fe upgrade from the experiment as in Table 1.

An ideal comparison of the quantity of water evaporated as obtained from experiment and as predicted by the model for the purpose of testing the validity of the model is achieved by considering the R^2 values. The values of the correlation coefficient, R calculated from the equation; using the r-squared values (coefficient of determination) from Figs.1 and 2 show a better correlation (0.9982) with model-predicted quantity of water evaporated than that obtained from experiment (0.69). This suggests that the model predicts more accurate, reliable and ideal quantity of evaporated water than the actual experiment despite its deviations from the experimental values.

$$R = \sqrt{R^2} \quad (13)$$



The concentration of iron upgraded per unit increase in the treatment temperature resulting from the reaction between the iron oxide ore and KClO_3 (oxidant) at a temperature range $500\text{--}800^\circ\text{C}$ was determined following comparison of the iron upgrade per unit increase in the treatment temperature obtained by calculations involving experimental results[10], and model-predicted results obtained directly from the model.

Iron upgrade per unit increase in treatment temperature, $I_U (\% / ^\circ\text{C})$ is calculated from the equation;

$$I_U = I/T \quad (14)$$

Therefore, a plot of concentration of iron upgraded I , against treatment temperature T , (as in Fig. 1) using experimental results gives a slope, S at points (57.6, 500) and (68.5, 700) following their substitution into the mathematical expression;

$$I_U = \Delta I / \Delta T \quad (15)$$

Eqn. (15) is detailed as

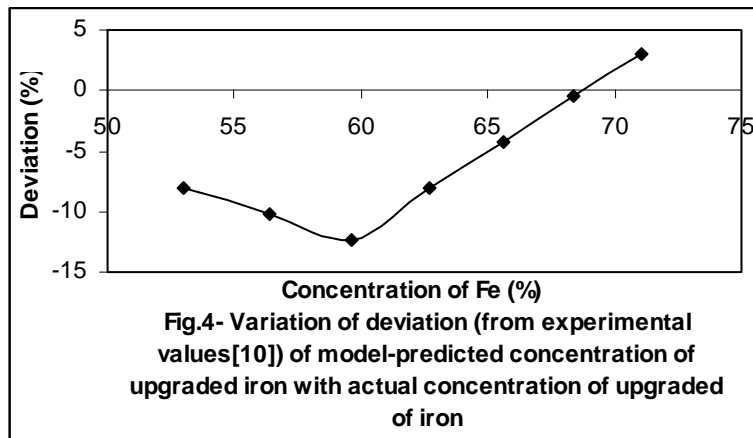
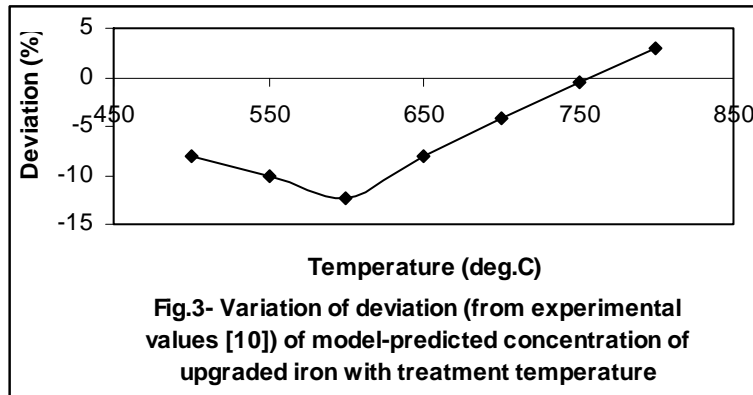
$$I_U = I_2 - I_1 / T_2 - T_1 \quad (16)$$

Where

ΔI = Change in the concentrations of upgraded I_2, I_1 at two treatment temperature values T_2, T_1 . Considering the points (57.6, 500) and (68.5, 700) for (I_1, T_1) and (I_2, T_2) respectively, and substituting them into eqn. (16), gives the slope as $0.0545\% / ^\circ\text{C}$ which is the concentration of iron upgraded per unit increase in the treatment temperature during the actual experimental process. Also similar plot (as in Fig. 2) using model-predicted results gives a slope. Considering points (53, 500) and (65.58, 700) for (I_1, T_1) and (I_2, T_2) respectively and substituting them into eqn. (16) gives the value of slope, I_U as $0.0629\% / ^\circ\text{C}$. This is the concentration of iron upgraded as predicted by the model. A comparison of these two concentrations of iron upgrade shows proximate agreement. Based on the foregoing, the model is believed to be very valid as a predictive tool.

A comparison of the values of %Fe from the experiment and those from the model shows very minimum positive and negative deviations less than 13% which is quite within the acceptable range of deviation limit of experimental results hence depicting the reliability and validity of the model. The validity of the model

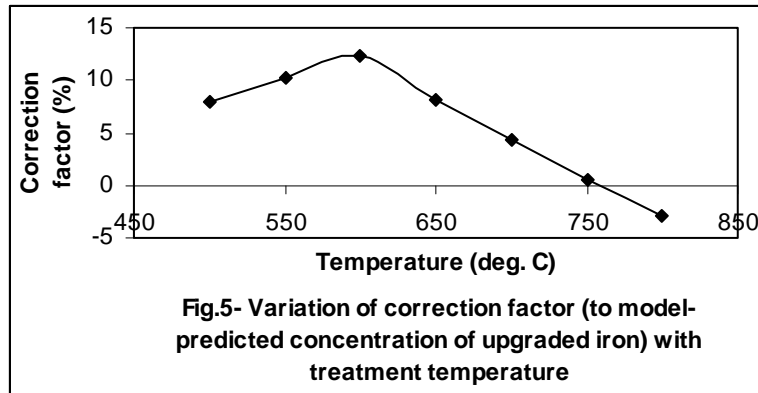
is rooted in the expression $(\%Fe/\alpha)^N = \ln(T/\gamma)$ where both sides of the expression are correspondingly approximately equal to 4. Results in Table 2 show proximate agreement with equation (5) following the values $(\%Fe/\alpha)^N$ and $\ln(T/\gamma)$ evaluated from Table 1 as a result of corresponding computational analysis.



Comparison of Figs. 3 and 4 show that the positive and negative deviations (of the model-predicted concentration of iron upgraded) from actual experimental values show an undulating relationship with both the treatment temperature and concentration of iron upgraded. These curves indicate that the highest and least deviations; -12.34 and -0.52% are associated with treatment temperatures; 600-750°C and iron upgrade; 59.61 and 68.36% respectively. This is so because the extent of deviation is a function of just the magnitude of the value while the sign (positive or negative) preceding the value indicates whether the deviation is deficit or surplus.

Correction factor to (in Fig. 5) also shows an undulating relationship with the concentration of iron upgraded. However, the orientation of the curve of correction factor against concentration of iron upgraded (Fig.5) is opposite that of the deviation against treatment temperature and concentration of iron upgraded (Figs. 3 and 4).

This is attributed to the fact that correction factor is the negative of the deviation as shown in eqns. (11) and (12). It is believed that the correction factor takes care of the effects of the surface properties of the iron oxide ore and the physiochemical interaction between the ore and the leaching solution which (affected experimental results) were not considered during the model formulation.



6. Conclusion

The model predicts the concentration of upgraded iron during solid-state beneficiation (at a temperature range 500-800°C) of iron oxide ore pelletized with powdered potassium chlorate. The validity of the model is rooted in the expression $(\%Fe/\alpha)^N = \ln(T/\gamma)$ where both sides of the expression are correspondingly approximately equal to 4. The maximum deviation of the model-predicted concentration of iron upgraded from the corresponding experimental value is less than 13% which is quite within the acceptable deviation range of experimental results. Upgraded concentration of iron per unit increase in the treatment temperature evaluated from experimental and model-predicted results are 0.0545 and 0.0629%/°C respectively, indicating proximate agreement.

Further works should incorporate more process parameters into the model with the aim of reducing the deviations of the model-predicted %Fe values from those of the experiment.

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