

Optimization of Haematite Mass-Input for Minimum Remnant Sulphur Content in Iron Ore Beneficiated with Powdered Potassium Chlorate

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ABSTRACT

A model was derived for optimization of haematite mass-input during its beneficiation with powdered potassium chlorate in order to ensure a minimum remnant sulphur condition in the ore. The polynomial model;

$$S = 0.1233\alpha^2 - 0.8042\alpha + 18.823$$

is rooted in the expression

$$5.3126 \times 10^{-2} S = 6.5505 \times 10^{-3} \alpha^2 - 0.0427\alpha + 1 \quad \text{where}$$

both sides of the expression are correspondingly approximately equal to 1. The maximum deviation of the model-predicted concentration of remnant sulphur (during the beneficiation process) from the concentrations obtained from regression model and experiment were less than 3 and 2% respectively. These translate to confidence levels of 97 and 98% respectively. The remnant sulphur content of the ore per unit mass-input of iron oxide ore beneficiated as obtained from experiment, derived model and regression model are 0.4920, 0.5520 and 0.5335 mg/kg g⁻¹ respectively. The standard errors in predicting the remnant ore sulphur for each mass-input value of the iron oxide ore beneficiated (STEYX) is 0.3778 compared to experimental (0.4920) and regression model (2.805 x 10⁻⁵). The measure of variability (AVEDEV) in the results of concentrations of remnant ore sulphur from regression model, experimental and model-predicted are 6.6625, 6.6625 and 6.6430% respectively. The F-test between the derived and regression model is 0.8234 and then 0.9814 between the derived and experimental results. Evaluations from experimental results and optimization of mass-input of the iron oxide ore as well as predictions by derived model (D-Model) and regression model (R-Model) indicate that a minimum remnant sulphur content of the ore \approx 18 mg/kg would be achieved at an optimum ore mass-input of 3.2616g during the beneficiation process providing the mass-input of oxidant (KClO₃) and treatment temperature remained constant.

Keywords: Model, Optimization, Haematite Mass-input, Minimum Remnant Sulphur.

1. INTRODUCTION

The growing need for defect free engineering materials or engineering materials that can serve in very stressful and red-hot environment without failure (due to hot-shortness) has necessitated various researches aimed at reducing to a bearest minimum the sulphur content of the iron oxide ore put into use as a primary raw material. The highlighted failure is attributed to the presence of a membrane of high concentration of sulphur as iron sulphide in the steel crystals [1].

During heating of ingots before rolling or forging, the inter-granular sulphur-rich layers within the metal microstructure soften resulting to the destruction of the bonds between the grains and invariably crack formation during plastic working [2]. This defect is also called hot or red shortness.

Based on the foregoing, several studies on effective desulphurization of iron oxide ores before use for iron and steel making have been embarked on with the aim of reducing sulphur present in steels and iron to a deleterious level.

Studies [3,4] on desulphurization of Agbaja iron oxide ore concentrates using solid potassium trioxochlorate (V) (KClO₃) as oxidant has been carried out. The concentrate was treated at a temperature range 500 – 800^oC. 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^oC) 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^oC) are high. The mechanism of the process was found [4] to be gaseous state interaction between oxygen and sulphur through molecular combination. Oxygen required for the desulphurization process was produced following decomposition of KClO₃ within a temperature range 375-502^oC, which 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. Models [5-8] have been derived to predict the concentrations of sulphur removed during the

processes [3, 4] relative to mass-input of potassium chlorate and treatment temperature.

Models predicting the concentrations of removed sulphur relative to the mass-input of potassium chlorate [5, 7] shows that the percentage of removed sulphur is inversely proportional to the log of mass-input of $KClO_3$. Model derivation for sulphur removal relative to the treatment temperature [6, 8] shows that the percentage concentration of sulphur removed is also inversely proportional to the log of the treatment temperature. The possibility of taking a model-aided computational analysis of the concentration of sulphur removed during oxidation of iron oxide ore with powdered potassium chlorate by considering the mass-input of $KClO_3$ as well as treatment temperature has made it amply possible for a metallurgist to predict directly and successfully (within the experimental range) when desulphurization would be maximum and the likely sulphur content of the iron oxide ore for any change in the process parameters without carrying out any chemical analysis on the reaction residue.

The purpose of this present work is to derive a model for optimization of haematite mass-input for its minimum remnant sulphur condition during beneficiation with powdered potassium chlorate. The desulphurized iron oxide ore was mined from Itakpe (Nigeria).

2. Model

The solid phase (ore) is assumed to be stationary, contains the un-leached iron remaining in the ore. It is strongly believed that hydrogen peroxide gas produced from the reaction between KOH and Fe_2O_3 decomposed to produce oxygen gas (in agreement with past findings [9]) which oxidized sulphur, hence removing it from the ore in the form of SO_2 respectively. Equations (10-12) show this.

2. MATERIALS AND METHODS

Iron oxide ore obtained from Itakpe, Nigeria (figures 1 and 2) was crushed to $60 \mu m$ and a weighed mass (2g) (using a Triple Beam balance at National Metallurgical Development Center (NMDC)) Jos, was mixed with 25g of powdered potassium chlorate ($KClO_3$) obtained from Fisher scientific company, Fair Lawn, New Jersey, U.S.A. The mixed sample contained in an iron crucible was then heated at a temperature of $500^\circ C$ in a Gallenkamp Hotpot electric furnace at NMDC laboratory for 10 minutes and thereafter emptied on a white steel pan for observation. The experiment was repeated three times with iron oxide ore mass-input: 3, 3.5, 4, 5, 6 and 8g and the average values taken. A weighed quantity of the treated ore concentrate was taken in each case for chemical analysis (to determine concentration of sulphur left in the ore) using wet chemical analysis method.



Figure 1: Lumps of Itakpe iron ore



Figure 2: Pulverised Itakpe iron ore

2.1 Model Formulation

Experimental data obtained from research work were used for this work. Computational analysis of the experimental data shown in Table 1, gave rise to Table 2 which indicate that;

$$S \beta = N \alpha^2 + K \alpha - N_e \quad (\text{approximately}) \quad 1$$

Introducing the values of S , N , K and N_e into equation (1) reduces it to;

$$5.3126 \times 10^{-2} \beta = 6.5505 \times 10^{-3} \alpha^2 - 4.2730 \times 10^{-2} \alpha + 1 \quad 2$$

$$\beta = \frac{6.5505 \times 10^{-3} \alpha^2 - 4.2730 \times 10^{-2} \alpha + 1}{5.3126 \times 10^{-2}} \quad 3$$

$$\beta = 1.2330 \times 10^{-1} \alpha^2 - 0.8043 \alpha + 18.823 \quad 4$$

$$\beta = 0.12330 \alpha^2 - 0.8043 \alpha + 18.823 \quad 5$$

Where

(β) = Sulphur content of the ore (mg/kg)
 $S = 5.3126 \times 10^{-2}$; Sulphur concentration coefficient
 (determined using C-NIKBRAN [10])

(α) = Mass-input of ore (g)
 $N = 6.5505 \times 10^{-3}$; Second order ore-mass-input
 coefficient (determined using C- NIKBRAN [10])

$K = 4.2730 \times 10^{-2}$; First order ore-mass-input
 coefficient (determined using C-NIKBRAN [10])

$N_e = 1.0$; Decomposition coefficient of $KClO_3$ at a
 temperature $500^\circ C$ (determined using C-
 NIKBRAN [10])

Table 1: Variation of sulphur content of the ore (after beneficiation) with Mass-input of iron oxide ore

(α) g	S (mg/kg)	T ($^{\circ}$ C)
3	17.83	500
3.5	17.60	500
4	17.38	500
5	17.91	500
6	18.44	500
8	20.29	500

Table 2: Variation of $5.3126 \times 10^{-2} \beta$ with $6.5505 \times 10^{-3} \alpha^2 - 4.273 \times 10^{-2} \alpha + 1$

$5.3126 \times 10^{-2} \beta$	$6.5505 \times 10^{-3} \alpha^2$	$4.273 \times 10^{-2} \alpha + 1$	$6.5505 \times 10^{-3} \alpha^2 - 4.273 \times 10^{-2} \alpha + 1$
0.9472	0.0590	0.8718	0.9308
0.9350	0.0802	0.8504	0.9306
0.9233	0.1048	0.8291	0.9339
0.9515	0.1638	0.7864	0.9502
0.9796	0.2358	0.7436	0.9794
1.0779	0.4192	0.6582	1.0774

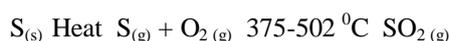
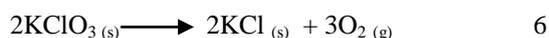
2.1.1. Boundary and Initial Condition

Consider iron ore (in a furnace) mixed with potassium chlorate (oxidant). The furnace atmosphere is not contaminated i.e (free of unwanted gases and dusts). Initially, atmospheric levels of oxygen are assumed just before the decomposition of $KClO_3$ (due to air in the furnace). Mass-input of iron oxide ore used (2g), and treatment time of 10 minutes were used. Treatment temperature range; 500-700 $^{\circ}$ C, ore grain size; 60 μ m, and mass of $KClO_3$ (oxidant); 25g were also used. The boundary conditions are: 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 sides of the particles are taken to be symmetries.

4. RESULTS AND DISCUSSION

4.1 Desulphurization process

Oxygen gas from the decomposition of $KClO_3$ attacked the ore in a gas-solid reaction in accordance with previous work [2], hence removing (through oxidation) the sulphur present in the ore in the form of SO_2 as shown in equations (6) and (7).



Equation (6) [2] shows that sulphur turns to vapour at a temperature range 375-502 $^{\circ}$ C and this corresponds to the Gas Evolution Temperature Range (GETR). Therefore, at a temperature of 500 $^{\circ}$ C, the sulphur inherent in the ore has a greater tendency as vapour to combine with oxygen. Table 1 shows that the concentration of remnant sulphur in the ore (following the desulphurization process) decreases with increase in the mass-input (up to 4g) of iron oxide ore. This implies that the concentration of sulphur removed (at this particular ore mass-input) increases with increase in the mass-input of the ore. It was observed that beyond the iron oxide ore mass-input of 4g i.e 5-8g, the remnant sulphur content of the ore increases with increase in the mass-input of the iron oxide ore. This implies that the concentration of sulphur removed (within this ore mass-input range) decreases with increase in the mass-input of the ore. At exactly 5g mass-input of the ore, the remnant sulphur content of the ore drops to a concentration of 17.91 mg/kg which from Table 1 is the minimum remnant sulphur content of the ore. This indicates that at this ore mass-input and remnant sulphur concentration of the ore, maximum sulphur removal from the iron oxide ore was achieved.

4.2 Model Validation

The model was validated by comparing results of standard error (STEYX), correlation

(CORREL), measure of variability (AVEDEV), confidence level, and F-test obtained from experiment, derived model and regression model which is applied as a standard model. All these were evaluated using [11].

Standard Error (STEYX)

This gives the error incurred in predicting y value for any x value considered and substituted in the derived model. This could be calculated using the equation [11]:

$$SE = \frac{1}{(n-2)} \left[\sum (\bar{y} - y)^2 - \frac{[\sum (\bar{x} - x)(\bar{y} - y)]^2}{\sum (\bar{x} - x)^2} \right] \quad 8$$

Where

\bar{x} and \bar{y} = Mean; average of x (mass-input of ore) and y (conc. of remnant sulphur in ore) values.

n = No. of samples

Equation (1) translates to the error in predicting the remnant sulphur content of the ore for each mass-input value of the iron oxide ore. The standard error incurred by the derived model in predicting the remnant sulphur content of the ore is 0.3778 compared to experimental (0.4920) and regression model (2.805×10^{-5}) respectively.

Correlation (CORREL)

Correlation coefficient determines the relationship between two properties. The correlation between mass-input of iron oxide ore and the concentration of remnant sulphur in the ore as obtained from derived model, experiment and regression model are 0.9924, 1.0000 and 1.0000 respectively. These values could be evaluated using the equation (9)

$$Correl (X,Y) = \frac{\sum (\bar{x} - x)(\bar{y} - y)}{\sum (\bar{x} - x)^2 (\bar{y} - y)^2} \quad 9$$

Where

\bar{x} and \bar{y} = Mean; average of x (mass-input of ore) and y (conc. of remnant sulphur in ore) values.

Measure of Variability (AVEDEV)

of data points from the mean. The variability of the concentrations of remnant ore sulphur (from the mean value) as obtained from derived model, experiment and regression model are 6.6430, 6.6625 and 6.6625% respectively. These values could be evaluated using the equation (10):

$$AVEDEV = \frac{1}{n} \sum |\bar{x} - x| \quad 10$$

Deviation (Dv) (%) of D-model predicted remnant sulphur contents of the ore from the corresponding values obtained from experimental is given by

$$Dv = \left[\frac{Dm - Ex}{Ex} \right] \times 100 \quad 11$$

While deviation of D-model predicted remnant sulphur contents of the ore from the corresponding values obtained from regression model is given by

$$Dv = \left[\frac{Dm - Rm}{Rm} \right] \times 100 \quad 12$$

Where

Dm = D-Model predicted remnant sulphur content of the ore

Ex = Remnant sulphur content of the ore as obtained from experiment

Rm = R-Model predicted remnant sulphur content of the ore

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

$$Cf = -Dv \quad 13$$

Therefore correction factor for equation (13) is given by;

$$Cf = \left[\frac{Dm - Ex}{Ex} \right] \times 100 \quad 14$$

And for equation (14) is given by;

$$Cf = \left[\frac{Dm - Rm}{Rm} \right] \times 100 \quad 15$$

Introduction of the corresponding values of Cf from equations (14) and (15) in each case into the D-model gives exactly the corresponding values of remnant sulphur as obtained from experiment and regression model respectively.

Comparative analysis of Tables 3 and 4 shows that the maximum deviation of the model-predicted (D-Model) remnant sulphur concentration from the regression model (R-Model) and experiment were less than 3 and 2% respectively.

Tables 3 and 4 show that the least and highest magnitudes of deviation of the model-predicted (D-Model) remnant sulphur concentration (from the corresponding experimental values) are - 0.02 and -1.74 % which corresponds to remnant sulphur concentrations: 18.436 and 17.5198 mg/kg as well as ore mass-inputs: 6 and 3g respectively. Furthermore, the least and highest magnitudes of deviation of the model-predicted (D-Model) remnant sulphur concentration (from the corresponding R-Model values) are + 0.10 and -2.19 % which corresponds to remnant sulphur concentrations: 17.5075 and 18.2852 mg/kg as well as ore mass-inputs: 3.5 and 5g respectively.

Tables 3 and 4 also indicate that values of the evaluated deviations are opposite that of the correction factors. This is because correction factor is the negative of the deviation as shown in equation (13). 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 added oxidant which (affected experimental results) were not considered during the model formulation.

Figures 6 and 7 show that the highest and least confidence levels of D-Model predicted results relative to experimental results are 99.98 and 98.26%, corresponding to remnant sulphur concentrations: 18.436 and 17.5198 mg/kg as well as ore mass-inputs: 6 and 3g respectively. Furthermore, the highest and least confidence levels of D-Model predicted results relative to R-Model results are 99.90 and 97.81%, corresponding to remnant sulphur concentrations: 17.5183 and 17.8840 mg/kg as well as ore mass-inputs: 3.5 and 5g respectively.

Table 5 indicates that the highest and least significant levels of D-Model predicted results relative to experimental results are 0.0174 and 0.0002, at ore mass-inputs: 3 and 6g respectively. However, the highest and least significant levels of D-Model predicted results relative to R-Model predicted results are 0.0219 and 0.0001 at ore mass-inputs: 5 and 3.5g respectively.

Table 3: Deviation of D-Model results from experimental results; varying with Mass-input of iron oxide ore

(α) (g)	$D_{Dmodel-Ex}$ (%)	Cv (%)
3	-1.74	+1.74
3.5	-0.46	+0.46
4	+1.14	-1.14
5	-0.15	+0.15
6	-0.02	+0.02
8	-0.05	+0.05

Table 4: Deviation of D-Model results from R-Model results; varying with Mass-input of iron oxide ore

(α) (g)	$D_{Dmodel-Rmodel}$ (%)	Cv (%)
3	+1.62	-1.62
3.5	+0.10	-0.10
4	+1.04	-1.04
5	-2.19	+2.19
6	-1.98	+1.98
8	+2.15	-2.15

Table 5: Significant levels of D-Model predicted results relative to R-Model and experimental results

(α) (g)	$D-Model_{ExD}$	$D-Model_{R-Model}$
3	0.0174	0.0162
3.5	0.0046	0.0001
4	0.0114	0.0104
5	0.0015	0.0219
6	0.0002	0.0198
8	0.0005	0.0215

F-test

This is a one tailed probability that the variance between two data sets is not significantly different. The probability that the variance between derived model (D-Model) and regression model (R-Model) is not significantly different is 0.8234 while between derived model and experiment gave 0.9814.

The validity of the model is strongly rooted on equation (2) where both sides of the equation are correspondingly approximately equal. Table 2 also agrees with equation (2) following the values of $5.3126 \times 10^{-2} \beta$ and $6.5505 \times 10^{-3} \alpha^2 - 4.2730 \times 10^{-2} \alpha + 1$ evaluated from the experimental results in Table 1. Furthermore, the n^{th} Degree Model Validity Test Techniques (n^{th} DMVTT), using computational and graphical analysis [10] also indicate proximate agreement between D-Model, R-Model and experimental data and invariably validity of the derived model; D-model.

4.3 Computational Analysis

A comparative analysis of the results computed from the experiment, D-Model and R-Model on the remnant sulphur content of the ore was carried out to ascertain the degree of validity of the derived model. This was done by comparing the remnant ore sulphur content per unit mass-input of iron oxide ore as obtained through experiment, D-Model and R-Model predicted results.

Remnant ore sulphur content per unit mass-input of the ore S_m (mg/kg/g) was calculated from the equation:

$$S_m = S / m \quad 16$$

Therefore, a plot of remnant ore sulphur content against mass-input of iron oxide ore as in Figure 3 using experimental results in Table 1, gives a slope, Se at points (3, 17.83) and (8, 20.29) following their substitution into the mathematical expression;

$$S_m = Se = \Delta S / \Delta m \quad 17$$

Equation (17) is expressed as

$$Se = S_2 - S_1 / m_2 - m_1 \quad 18$$

Where ΔS = Change in the remnant ore sulphur contents S_2, S_1 at two ore mass-input values m_2, m_1 . Considering the points (3, 17.83) and (8, 20.29) for (m_1, S_1) and (m_2, S_2) respectively, and substituting them into equation (18), gives the slope as 0.4920 (mg/kg / g) which is the remnant ore sulphur content per unit mass-input of iron oxide ore during the actual experimental process. A plot (as in Figure 4) using D-Model predicted results gives a slope. Considering points (3, 17.5198) and (8, 20.2798) for (m_1, S_1) and (m_2, S_2) respectively and substituting them into equation (18) gives the value of slope, S_e as 0.5520 (mg/kg / g). This is the D-Model predicted remnant ore sulphur content per unit mass-input of iron oxide ore. Similarly, a plot (as in Figure 5) using R-Model predicted results gives a slope 0.5225 (mg/kg / g) on substituting points (3, 17.2403) and (8, 19.8526) for (m_1, S_1) and (m_2, S_2) respectively into equation (18). A comparison of these three values of the remnant ore sulphur content per unit mass-input of iron oxide ore shows proximate agreement and validity of the model.

4.4 Graphical Analysis

Graphical analysis of Figures 8-11 shows very close alignment of the curves from the experimental (ExD), D-Model and R-Model predicted remnant ore sulphur content per unit mass-input of iron oxide ore. Furthermore, the degree of alignment of these curves is indicative of the proximate agreement between experimental and D-Model and R-Model predicted remnant ore sulphur content.

4.5 Model-aided determination of optimum mass-input of iron oxide ore for achieving minimum remnant sulphur content of the ore

The concentration of remnant sulphur in the ore β predicted by the D-Model (equation (5)); $\beta = 0.1233 \alpha^2 - 0.8042 \alpha + 18.823$ is based on the mass-input of the iron oxide ore α . Optimization of the iron oxide ore mass-input was achieved by differentiating the D-Model (equations (5)) with respect to the mass-input of the iron oxide ore α (and equating to zero) in order to determine the value of α at which β is minimum.

$$d\beta/d\alpha = 0.1233 \alpha^2 - 0.8043 \alpha + 18.823 \quad 19$$

Differentiation of equations (19) with respect to α reduces it to;

$$0.2466 \alpha - 0.8043 = 0 \quad 20$$

$$0.2466 \alpha = 0.8043 \quad 21$$

Evaluating equation (21) gives the value $\alpha = 3.2616$ g. This is the optimum mass-input of iron oxide ore which invariably gave the minimum remnant sulphur content of the ore, β as 17.5114

mg/kg on substituting the value of $\alpha = 3.2616$ g into the D-Model in equation (5).

Confirmation of the minimum and optimum values of β and α respectively was achieved by including $\alpha = 3.2616$ g as well as $\beta = 17.5114$ mg/kg and re-plotting remnant sulphur concentration (as predicted by the D-Model) against mass-input of iron oxide ore as shown in Figure 9.

Comparative analysis of Figures 8-11 indicates that experiment conducted gave minimum sulphur content of the ore (17.91 mg/kg) at an optimum ore mass-input of 5g while at the same mass-input (Figures 8 and 9); the D-Model predicted 17.8840 mg/kg which is in proximate agreement with the minimum value of remnant sulphur obtained from experiment (a deviation less than 0.2%). However, evaluation of the D-Model to determine the actual optimum ore mass-input that would possibly result to minimum remnant sulphur content of the ore gives $\alpha = 3.2616$ g and $\beta = 17.5114$ mg/kg as the optimum ore mass-input and minimum remnant sulphur content of the ore respectively (Figure 11). Furthermore, R-Model predicted minimum remnant sulphur content of the ore as 18.2852 mg/kg (a deviation less than 2.5% from D-Model and 2.1% from experiment result) at 5g input of iron oxide ore (Figures 10 and 11). Based on the foregoing, the minimum remnant sulphur content of the ore at 5g input of the ore as obtained from the experiment, D-Model and R-Model; 17.91, 17.884 and 18.2852 mg/kg respectively show proximate agreement. This implies that within this haematite mass-input range, sulphur removal from the ore is likely to have reached maximum providing the mass-input of oxidant ($KClO_3$) and treatment temperature remained constant. Based on the following, it is strongly conceived that 3.2616g input of iron oxide ore is the ideal optimum mass-input for achieving minimum remnant sulphur content of the ore for economic reason. This is so because 5g input of the ore gave a minimum remnant sulphur content of the ore: 17.91, 17.884 and 18.2852 mg/kg as obtained from the experiment, D-Model and R-Model respectively (approximately the same result as in the case of using 3.2616g of iron oxide ore; 1.7384g short of the 5g input). It is therefore believed that ore mass-input of 3.2616g would likely give a reduced overall cost of production, resulting to increased profit and same level of productivity as associated with using 5g of iron oxide ore.

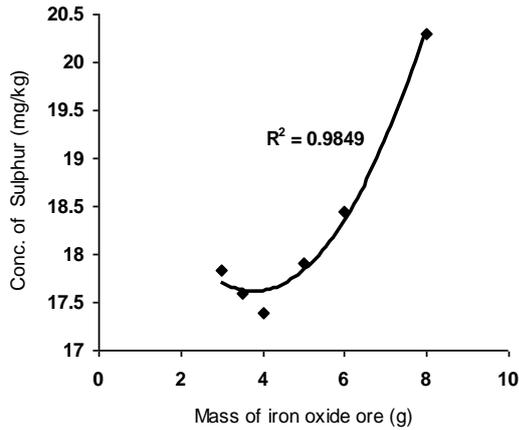


Figure 3: Coefficient of determination between mass-input of iron oxide ore and remnant sulphur content of the ore as obtained from the experiment (ExD).

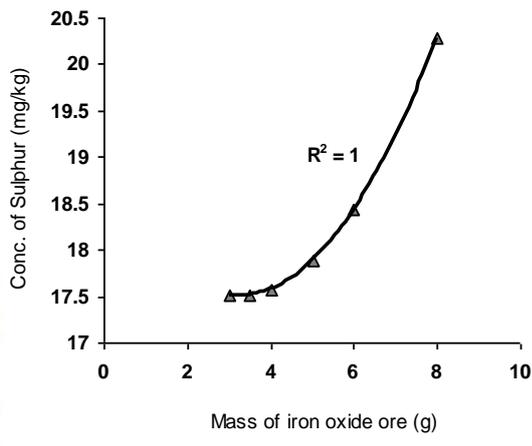


Figure 4: Coefficient of determination between mass-input of iron oxide ore and remnant sulphur content of the ore as obtained from derived model (D-Model).

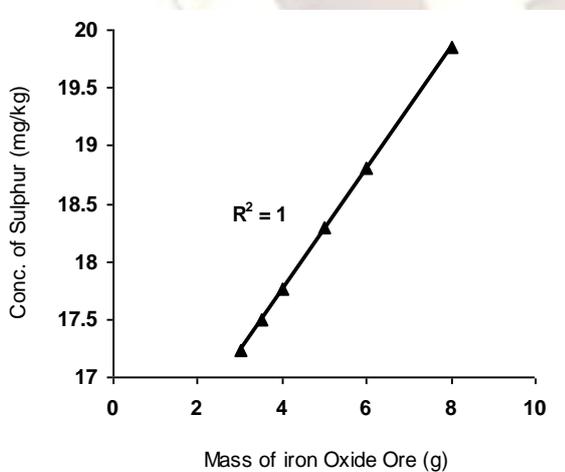


Figure 5: Coefficient of determination between mass-input of iron oxide ore and remnant sulphur content of the ore as obtained from regression model (R-Model).

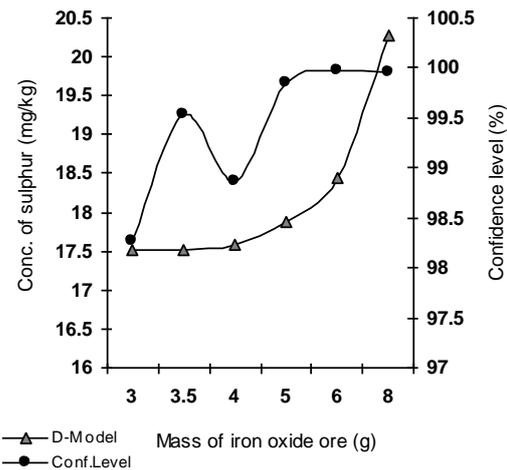


Figure 6: Variation of D-Model predicted concentration of remnant sulphur and confidence level (relative to experimental results) with mass-input of iron oxide ore.

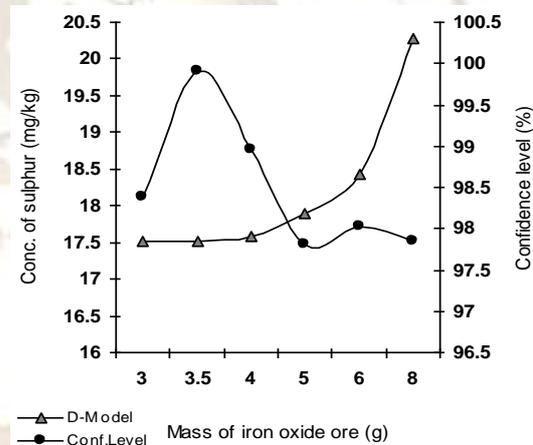


Figure 7: Variation of D-Model predicted concentration of remnant sulphur and confidence level (relative to R-Model predicted results) with mass-input of iron oxide ore.

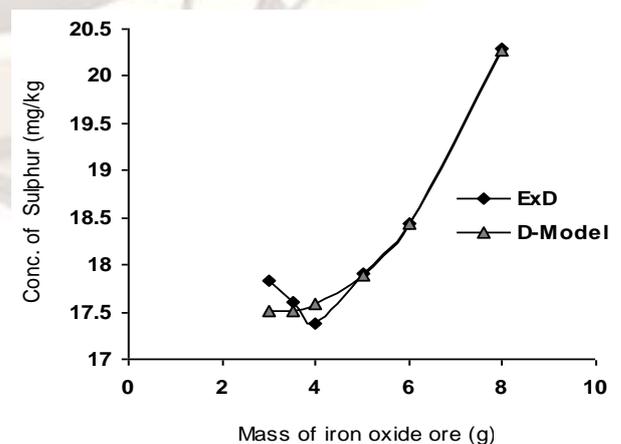


Figure 8: Comparison of the remnant sulphur concentrations per unit ore mass-input as obtained from experimental results (ExD) and the D-Model.

from experiment (ExD) and derived model (D-Model).

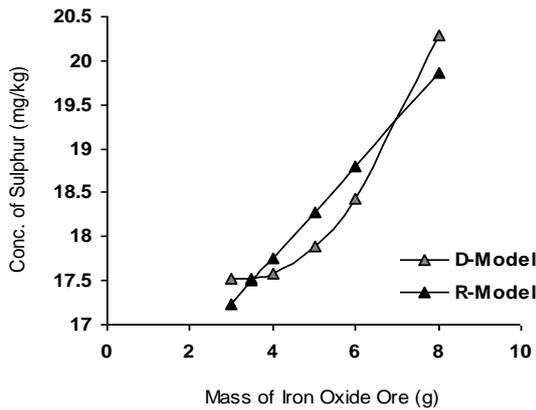


Figure 9: Comparison of the remnant sulphur concentrations per unit ore mass-input as obtained from derived model (D-Model) and regression model (R-Model).

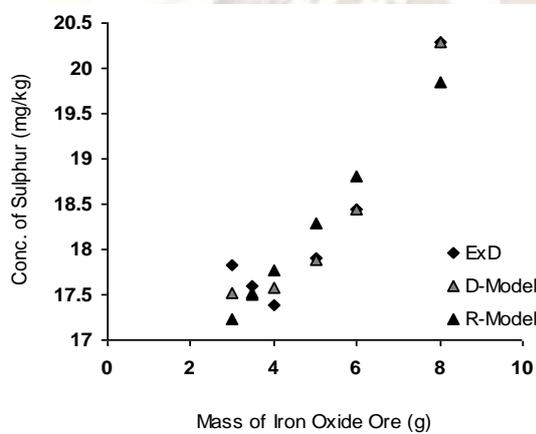


Figure 10: Comparison of the remnant sulphur concentrations per unit ore mass-input as obtained from experiment (ExD), derived model, (D-Model) and R-Model.

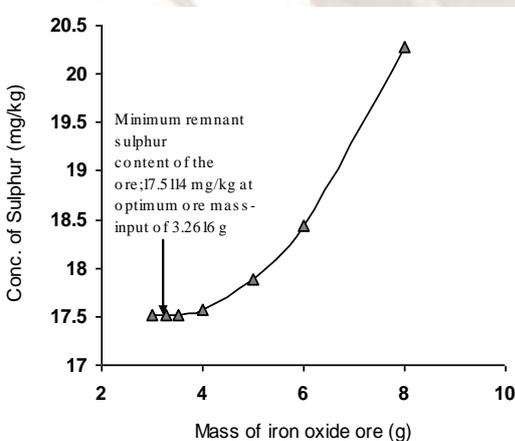


Figure 11: Predicted minimum remnant sulphur content of the ore at predicted optimum mass-input of iron oxide ore

CONCLUSION

The derived model was used to optimize haematite mass-input during its beneficiation with powdered potassium chlorate in order to ensure a minimum remnant sulphur condition in the ore. The derived model is polynomial nature. The model was rooted in the expression $5.3126 \times 10^{-2} S = 6.5505 \times 10^{-3} a^2 - 0.0427 a + 1$ where both sides of the expression are correspondingly approximately equal to 1. The maximum deviation of the model-predicted concentration of remnant sulphur (during the beneficiation process) from the concentrations obtained from regression model and experiment were less than 3 and 2% respectively. These translated into confidence levels of over 97 and 98% respectively. The remnant sulphur content of the ore per unit mass-input of iron oxide ore as obtained from experiment, derived model and regression model are 0.4920, 0.5520 and 0.5335 mg/kg g⁻¹ respectively. The standard errors in predicting the remnant ore sulphur for each mass-input value of the iron oxide ore (STEYX) is 0.3778 compared to experimental (0.4920) and regression model (2.805×10^{-5}). The measure of variability (AVEDEV) in the results of concentrations of remnant ore sulphur from regression model, experimental and model-predicted are 6.6625, 6.6625 and 6.6430% respectively. The F-test between the derived and regression model is 0.8234 and then 0.9814 between the derived and experimental results. Evaluations from experimental results and optimization of ore mass-input as well as prediction by derived model (D-Model) and regression model (R-Model) indicate that the minimum remnant sulphur content of the ore; ≈ 18 mg/kg would be achieved at an optimum ore mass-input of 3.2616g during the beneficiation process providing the mass-input of oxidant (KClO₃) and treatment temperature remained constant.

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