Mathematical Modeling of Phosphorous Prediction in BOF Steelmaking Process : A Fundamental Approach to Produce Low Phosphorous Steels and Ensure Direct Tap Practices

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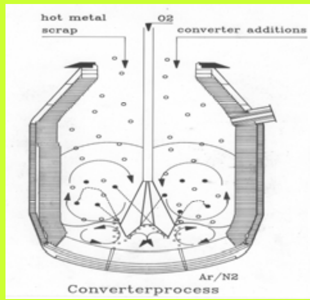
Introduction

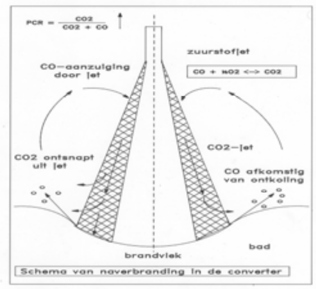
- **Phosphorous is undesirable in Steel due to poor mechanical properties (Hot shortness, temper embrittlement, poor ductility and strength).**
- **Phosphorous is entering from Iron ore, coke and recycled BOF Slag.**
- **Due to depletion of good quality iron ore and increasing demand for low phosphorous Steel, Effective Phosphorous control is essential requirement.**
- **Fundamental Study of Dephosphorization Mechanisms based upon law of Thermodynamics and Kinetics has been carried out and Dynamic Control Mathematical model in conjunction with waste gas analysis has been developed. For the first time Dephosphorization has been studied with respect to the Post Combustion and occurance of dry blow period.**

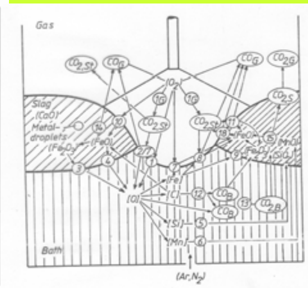
Why do We Need Low Phosphorous Steels

- **Causes hot shortness and temper embrittlement.**
- **Ductility and strength goes down if phosphorous is very high.**
- **Essential when want to have excellent mechanical properties (Ductility,Toughness and Strength).**
- **For special applications ([P] < 0.010) (Automobile Industry : EDD Grade, Petrochemical Industries : API Grade Steel).**
- **Increasing proportion of continuous cast heats where high Temperature at end point is not favorable for dephosphorisation.**
- **High phosphorous heats causes more breakouts in continuous casting.**

Reaction Mechanism inside the BOF Steelmaking converter





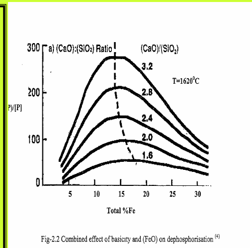


Key Factors for effective Dephosphorisation

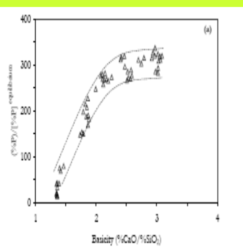
Thermodynamics of Phosphorous Distribution

$$2[P]+5(FeO)=(P_2O_5)+5Fe \qquad K_{eq}=\frac{a_{P_2O_5}}{a^5_{FeO}[\%P]^2}$$

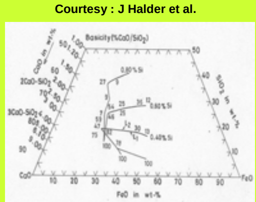
- Balajiva's Model $$\log\left(\frac{(P2O5)}{[P]^2(FeO)^5}\right)=A\log(CaO)+B(T+273)+C$$
- Turkdogan Model $$\log\frac{(P)}{[P][O]^{2.5}}=\frac{A}{T}+B(CaO+CaF_2+0.30.MgO)+C$$
- Healey's Model $$\log\frac{(\%P)}{[P]}=\frac{A}{(T+273)}+B(CaO)+C\log(Fe\_t)+D$$
- Optical Basicity Model $$\log\frac{(P)}{[P]}=A.\Lambda+\frac{B}{T}+C \qquad \Lambda=\Lambda_1X_1+\Lambda_2X_2$$
- Suito's Model $$\log\frac{(P)}{[P]}=A.[(CaO)+0.30.(MgO)+0.60.P_2O_5+0.60.(MnO)]+\frac{B}{T}+C$$
- Suito's and Inoue's Model $$\log\frac{(P_2O_5)}{[P]^2(Fe_t)^5}=A(\log(CaO)+\frac{B}{T_c+17.78}+C$$
- Molecular Slag Model $$RT\ln a_{P2O5(l)}=RT.\ln a_{P2O5(RS)}+52720-230706T$$
- Quadratic Formalism Model $$\log K_P=A.[(CaO)+0.30.(MgO)+0.60.(MnO)]+\frac{B}{T}+C \qquad K_P=\frac{a_{P2O5}}{[h_P]^2[h_O]^5}$$



Combined Influence of Basicity and FeO in Slag upon equilibrium Partion ratio at 1620 C
Courtesy : J Halder et al.



Influence of Basicity on equilibrium Partion ratio at 1923 K



Slag Path during BOF Steelmaking Process

Kinetics of Phosphorous Removal

- **Mass transfer in slag phase as a rate controlling step in first part of blow.**
- **Mass transfer in metal and slag both phases in last part of blow.**

How to enhance the kinetics of Phosphorous transfer?

$$\frac{d(P)}{dt}=\frac{k_s.\rho_s.A}{W_{Slag}}.((P)_i-(P)_b)=-\frac{W_{Steel}}{W_{Slag}}\frac{d[P]}{dt}$$

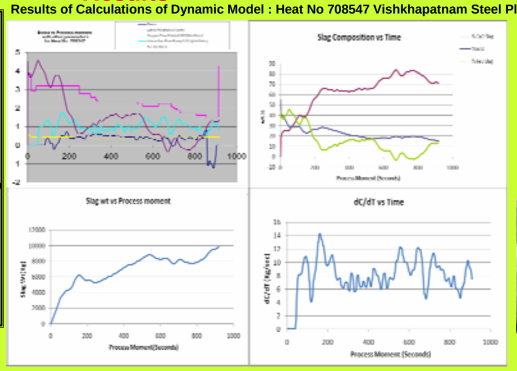
- **Create larger Interfacial area between Slag-metal interface (achieved by dispersing large number of metal droplets in slag phase and increasing their residence time by controlling the behavior of slag formation).**
- **Increasing mass transfer coefficients (By increasing total mixing energy input to the system from CO evolution, combined effect of top and bottom blowing).**
- **Ensuring proper volume of slag (controlling the Kinetics of lime dissolution, Slag retention from last heats if required).**

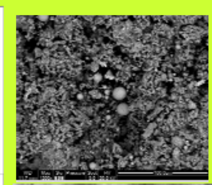
Approach

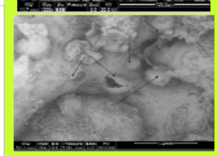
- **Development of Dynamic Control Mathematical Model in conjunction with waste gas information.**
- **Kinetics of Lime Dissolution is the function of FeO level of Slag.**
- **Estimation of transient [C] composition, d[C]/dt, Bath Temperature and Slag composition (CaO, FeO and SiO_2).**
- **Estimation of Post Combustion Ratio existing at the mouth of the converter.**
- **Coupled analysis of PCR in association with the Lance Height, Waste Gas Flow Rate , Lance Oxygen Flow Rate and estimated FeO level of the slag.**
- **The dynamic control model could be used to select the best operating strategy in order to avoid dry blow period (region corresponding to the drop in FeO level below critical level).**
- **ANN Models, Multivariate Regression models have also been developed.**
- **SEM analysis of selected slag samples have been performed.**

Results

Results of Calculations of Dynamic Model : Heat No 708547 Vishkhapatnam Steel Plant

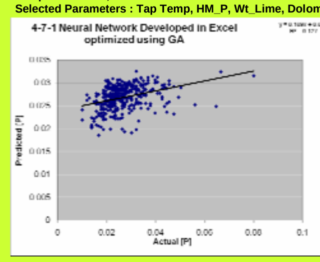




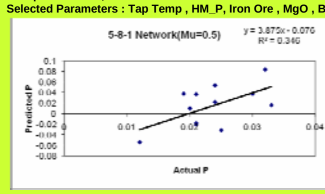


Metal droplets and high [P] containing Di-Calcium Silicate Phase in SEM Micrograph

Visakhpatnam Steel Plant (August 07):
Total No of Heats: 1084
R-Square =0.127 , SE = 0.008
Selected Parameters : Tap Temp, HM_P, Wt_Lime, Dolomite

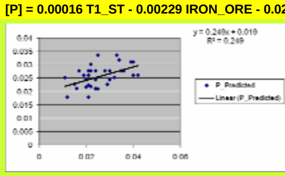


Rourkela Steel Plant (August 07):
Total No of Heats: 50
R-Square =0.347 , SE = 0.04
Selected Parameters : Tap Temp , HM_P, Iron Ore , MgO , Basicity



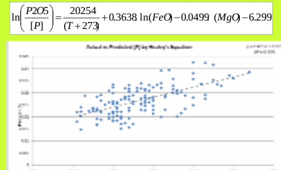
Rourkela Steel Plant (August 07):
Total No of Heats: 50
R-Square = 0.249, SE = 0.007
Selected Parameters: Tap Temp, Iron Ore

[P] = 0.00016 T1_ST - 0.00229 IRON_ORE - 0.023465



Predicted Healey's Equation for the Data of Rourkela Steel Plant (August'07)

$$\ln\left(\frac{P2O5}{[P]}\right)=\frac{20254}{(T+273)}+0.3638\ln(FeO)-0.0499\ (MgO)-6.299$$



Conclusions

- **Dynamic Control model helps to identify the dry blow period during which phosphorous reversal happens. Dry blow period is having low FeO and high PCR and in this way low availability of oxygen for dephosphorisation to take place.**
- **Retention of higher proportion of solid slag consisting of Di-Calcium Silicate gives better dephosphorisation. SEM analysis of slag sample confirms this.**
- **Linear Regression models perform better than ANN models.**

Acknowledgement:
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