Theoretical and Practical Aspects of Lance Skulling and Slag Foaming in BOF Vessels

Madhurai Malathi
Research Scholar
E-mail: malathi@iitk.ac.in
Ajay Kumar Shukla
Graduate Student
E-mail:shukla@iitk.ac.in
Nishant Singh
Under-Graduate Student
E-mail:nsingh@iitk.ac.in
Brahma Deo
Professor
Department of Materials and Metallurgical Engineering
Indian Institute of Technology, Kanpur 208016, India
Tel.:91 512 2598790
Fax: 915122597505
E-mail: bdeo@iitk.ac.in

Rob Boom
Professor, TU Delft and Director CORUS R&DT,
Ijmuiden, The Netherlands.
E-mail:rob.boom@corusgroup.com
Tel: +31 251491872
Fax: +31 251 470486

Key words: Lance skulling, Slag foaming, BOF, Morphological studies, Heat transfer, Hot spot, Iron oxide reduction, Lime dissolution

INTRODUCTION

In a BOF vessel, the supersonic jet is impinges on the slag and metal surfaces and the lance can become coated with the splashed materials. This leads to an increase in the outer diameter of the lance. This phenomenon of increase in the diameter of the lance due to deposition of slag is called 'lance skulling'. The skulling can progress layer by layer, leading to a gradual increase in the diameter of the lance. Lance skulling in BOF vessels is undesirable both from the point of view of the control of the slag formation process and for the productivity of the shop. Whereas a lance with a heavy skull has to be replaced and cleaned, heavy slopping results in the loss of material form the vessel. Skulling (due to solid slag formation) precedes slopping. Solid slag formation often results in a high phosphorus and high carbon content of metal and low steel temperature at tap. Lance height and oxygen flow rate, during the progress of the blow, should be so adjusted that the content of FeO and the activity of FeO in the slag are optimally controlled. If the FeO in the slag is reduced to a level below 5-10%, then the slag starts to become solid and the lance skulling begins. This is also manifested by spitting and the consequent changes in exhaust gas composition, and a rise in the temperature and the flow rate of the waste gases. In the present work, the morphological aspects of the lance skulls obtained from five steel plants have been investigated. The phases of varying composition are formed and ejected as droplets from/around the jet impact zone. The study of skulled samples has provided an insight into an alternative mechanism of lime dissolution occurring in the neighborhood of the jet impact region in the BOF process. Skulled samples collected from a co-jet lance have also been investigated. In addition to the morphological studies carried out in the present work, a heat transfer model has been developed to correlate the changes in the lance exit cooling water temperature with the changes in the lance height and the thickness of the lance skull. For the first time, the effect of radiation from hot spot has been considered in the heat transfer model with an objective to predict the start of lance skulling as well as the progress of the formation of skull during the progress blow in a BOF. Post combustion calculations are presented for the actual heats in a 150 ton vessel. The post combustion model can be used to control the slag formation by dynamically changing the lance height and the oxygen flow rate.

MORPHOLOGY OF SLAG SAMPLES OBTAINED FROM THE LANCE SKULL AND ITS RELATION TO THE MECHANISM OF LIME AND DOLOMITE DISSOLUTION

The results of study of skull samples collected from the body of lance in five different steel plants are presented here. In the case of Rourkela Steel Plant, it was also possible to collect a sample of material deposited around the nozzle tip. The skull material primarily consists of di-calcium silicates, tri-calcium silicates, di-calcium ferrite, calcium-magnesium iron oxides, pure iron oxides and a number of other phases containing varying amounts of MgO, P_2O_5 and S. All the specimens were prepared using the standard grinding and polishing procedures and then examined by Scan Electron Microscopy (SEM). The Energy-Dispersive X-ray spectrometer of the SEM was used to generate the element maps to determine the chemical composition. SEM analysis for the lance skulls, when a co-jet is used for refining process in the BOF vessels, has also been investigated. The ternary diagrams, consolidated in Figure 1, show the composition of skull material at different plants. The compositions of skull at different steel plants are also summarized in Table-1 in terms of the following phases: **Phase A**: Pure –FeO; **Phase B**: FeO(60-98),CaO(2-40); **Phase C**: FeO(93-98),MgO(2-7); **Phase D**: FeO(85-98),SiO2(2-15); **Phase E**: FeO(76-91),MgO(4-8),SiO2(4-17); **Phase F**: FeO(43-95),CaO(2-36),SiO2(4-47); **Phase G**: FeO(3-91),CaO(6-92),MgO(2-9); **Phase H**: FeO(25-87),MgO(1.4-15),CaO(6.6-38),SiO2(2-29); **Phase I**: the different phases observed in the skull formed at the nozzle tip in the case of RSP: CaO(41-48)-CaS(42-52)-FeO(0-17); MgO(88-97),CaO(11-3); CaO(47-64),SiO2(13-20), FeO(5-32) with P2O5(6-11).

The following specific observations can be made about lance skull at each steel plant:

Bokaro Steel Plant (BSP), India: The bulk phase is FeO rich phase containing (70-90%)FeO and the rest is (25-27%)CaO; (70-90%)FeO, (7-17%)SiO_2; (70-90%)FeO, (4-8%)MgO and the rest CaO or SiO_2. Inside the bulk phase the various shapes are present in the form of droplets, plates and acicular structure.

Jindal Steel Plant (JSW, Belari), India: Morphology is **s**imilar to BSP, the FeO rich phase is dominating (80-90% in area; the remaining area (10-20%) contains (5-56%)CaO, (2-34%) SiO_2, (2-15%)MgO and the rest is FeO. This plant has the highest refractory lining life (>8000 heats); this slag has a larger proportion of the droplets compared to the other plants.

Usiminas, Brazil: The bulk phase (>98% in area) is FeO rich (>95% FeO with some CaO, SiO_2, MgO) phase. However, next to the lance surface (0.2%skull), the phase contains about 40% CaO and 8% SiO_2 and the rest FeO. The area occupied by this phase (containing 40% CaO) is approximately 20%.

Vallourec & Mannesmann Tubes, Brazil: A detailed analysis was not carried out; only one sample was examined and it showed a phase containing >95%FeO. It is possible that the phase containing CaO was hidden below the FeO, as seen in the case of Usiminas, Brazil and other plants.

Rourkela Steel Plant (RSP), **India:** Two different samples were examined one sticking around the nozzle exit (bottom surface of the nozzle) and the other on the lance surface

-Sample near the nozzle tip: Here the CaO rich phase (75% by area) has the composition range CaO(51-68), SiO_2(2-17), FeO(23-44); the remaining phases (20% in area) is a FeO rich phase, FeO(60-98),CaO(40-2)); in addition to this phase a small amount of the other phases are also present. Calcium ferrite phase is seen.

At RSP, about 5% of the phases have very unexpected compositions,

- MgO rich phase containing: (MgO(88-97),CaO(11-3))
- A phase containing high amount of sulphur: CaO(41-48)-CaS(42-52)-FeO(0-17), it is assumed here that sulphur is in the form of CaS only
- A phase containing high amount of P_2O_5: CaO(51-64),SiO_2(13-20), FeO(5-22) with P_2O_5 (9-11); it has a composition close to tri-calcium silicate with some dissolved FeO; in the earlier work a maximum of 4-6% P_2O_5 was observed in dicalcium silicate, present in the quenched slag sample collected from BOF slag at tap.

-Sample from the lance surface: the bulk phase (90 % in area) is a CaO rich phase containing CaO(47-54),SiO_2(15-26),FeO(28-32) with P_2O_5(6-9). The remaining (10% in area) is the FeO rich phase of two different compositions, (a)

($FeO(\sim76), MgO(\sim8), SiO_2(\sim16)$), (b) $FeO(\sim78), CaO(\sim20), MgO(\sim2)$. Dicalcium silicate and calcium ferrite phases are also present.

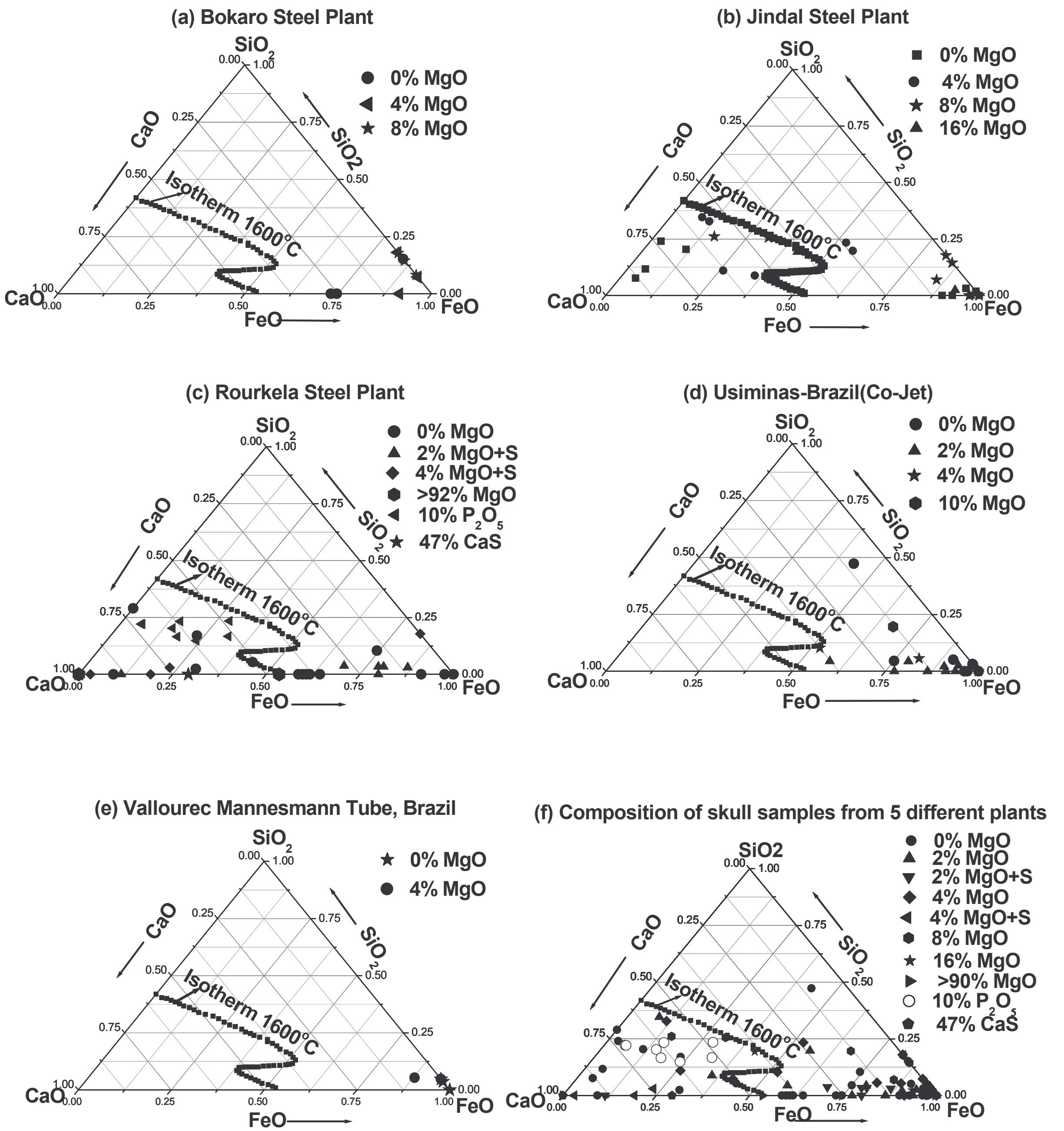


Figure 1 The analysis of phases appearing in BOF lance skull at different steel plants: (a) Bokaro Steel Plant, India, bottom stirred (b) JSW Belari, India, no stirring (c) Rourkela Steel Plant, India, no stirring (d) USIMINAS, Brazil, with CO-JET, no stirring (e) Vallourec & Mannesmann Tubes, Brazil, no stirring (f) Summary of composition of skull samples from the five steel plants

The compositions of all the skull samples are summarized in Fig. 1(f). It is clear that the phases are primarily located in two regions of the ternary diagram: near the FeO apex and near the CaO apex but below the liquidus line of 1600^{o}C. The FeO rich phase has a low melting point. The mixture of FeO rich slag (low melting) and the lime rich slag (high melting) has the capability to stick onto the lance and form skull.

Table I: Summary of analysis of different skull samples from BSP, JSW, RSP, Usiminas, and Vallourec & Mannesmann Tubes, Brazil; **Composition of the phases A-I are described above in the text.

Plant Name	Phases** → composition ↓	A	B	C	D	E	F	G	H	I
BSP	**B,D,E,F,G**		Y		Y	Y		Y		
JSP-Belari	**A,B,C,D,F,G,H**	Y	Y	Y	Y		Y	Y	Y	
RSP	**A,E,F,G,H**	Y				Y	Y	Y	Y	
RSP & near nozzle tip	**B,C,F,I**		Y	Y			Y			Y
USIMINAS-Brazil (co-jet)	**A,B,C,D,F,G,H**	Y	Y	Y	Y		Y	Y	Y	
Vallourec & Mannesmann TubesBrazil	**A,D,E,H**	Y			Y	Y			Y	

The variety of phases, present in the skull, shows the non-equilibrium nature of the slag formation process taking place around the jet impact region. Conventionally, we are used to thinking in the terms of the CaO'-FeO'-SiO_2' quasi-ternary diagram for the slag compositions obtained at the end of heat in a BOF. The non-equilibrium slag phases which appear during the progress of the blow are, however, very inhomogeneous and different from the slag that we see at the end of the blow. The variability or the stochastic nature of the slag formation process, during the progress of blow, is so large that it is difficult to propose a single model of lime dissolution and iron oxide reduction actually taking place in the BOF vessel. The skull samples indicate that both lime and dolomite are directly attacked by the FeO formed in and around the area of the jet impact region and that this is one of the mechanisms of lime and dolomite dissolution.

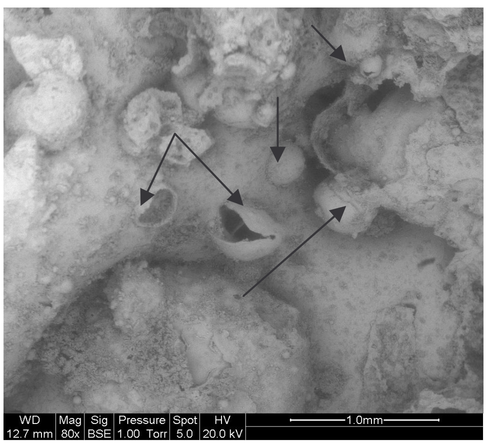
The jet penetration affects the FeO formed around the jet impact zone; in the case of deeper penetration of jet, as expected in the case of Co-jet, FeO is ejected in the form of droplets, Figure 2 (a), giving an appearance of exploded bubbles at some places. The converter mouth lip burning is enhanced due to deposition of FeO on the refractory in the lip area. Lip burning becomes serious if dry slag formation is frequent. Figure 2(b) shows the droplets in a normal BOF. The droplets in Figure 2(b) have a variable composition: some are FeO rich and some are CaO rich. Typical compositions seen are : (i)CaO(54.5),FeO(34.8),SiO_2(8.6),MgO(2.2); (ii)CaO(32.3),FeO(34.6),MgO(17.0), SiO_2(16.0); (iii) FeO(90.0), CaO(9.9); (iv) FeO(92.8), CaO(7.2)

The predicted surface temperature of skull (for different thicknesses) is shown in Figure 3, reaching as high as 1400^{o}C. Thus, when the thickness of the skull increases beyond a limit then the deposition of slag becomes difficult due to rise in surface temperature. In the calculation of surface temperature, the effect of radiation from hot spot has been taken into account. The change in view factor of hot spot due to the change in thickness of skull is shown in Figure 4 (when lance height is about 2.5 m in a 300 ton vessel at BSP). View 1 is from bottom surface of the lance and view 2 is side surface of the lance; with an increase in skull thickness there is increase in view 2 because of change in surface area. The predicted and actual changes in lance exit in water temperature, for the case of no-skulling, are shown in Figure 5(a) and Figure 5(b), respectively. The predicted change in water temperature is not significant with increase in skull thickness (Figure 6). In actual practice, however, the change in water temperature is sensitive (but erratic and hence not dependable) to the occurrence of dry slag formation and also skulling. It has not yet been possible to correlate (with confidence) the dry slag formation with the change in water temperature. This is because of the simultaneous changes in exhaust gas temperature and flow rate as well; the gas temperature and gas flow rise when the dry slag formation starts, but the water temperature does not change in the same proportion in all the cases.

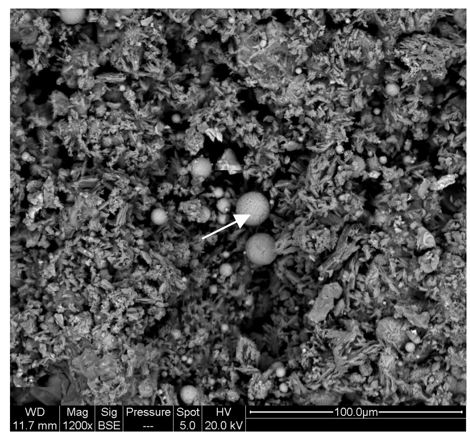
ANALYSIS OF POST COMBUSTION DURING THE PROGRESS OF BLOW AND THE CONTROL OF SLAG FORMATION

A post combustion model has been developed with the help of which the ratio of actual to theoretical post combustion ratio (called β (beta) factor) can be calculated. This β factor for, two typical heats (150 ton BOF) at RSP, is plotted in Figure 7. The shape of curve is typically convex and from the pattern of curve (rate of change of slope with time) the progress of slag formation can be controlled by adjusting the lance height and/or oxygen flow rate. The period of dry slag formation can be predicted well in advance to take a proper a corrective action. The calculated values of gas accumulated in slag at intervals of one minute are plotted in Figure 8. The change in oxygen added to the slag at intervals of one minute is plotted in Figure 9. These are not a cumulative plots but only a difference between last moment and the current moment values. A dOs/dt (oxygen accumulated in slag) value approaching zero (viz during 8-10 mins in Figure 9) indicates that less FeO is being added to the slag; most of the oxygen supplied from the lance is escaping in the gas phase (in the form of CO and CO_2 in the exhaust gas).

The continuous addition of FeO to slag has to compete with the rate of lime dissolution to keep the percentage of FeO in the total slag mass at a given level. If the lime dissolution rate is faster (than the rate at which FeO is being added to the slag) then the percentage of FeO in the slag will decrease with time. The implication of this aspect is that the lime quality from one heat to another must be kept same. Other wise, for example, a good quality lime will tend to dissolve faster and this can eventually lead to dry slag formation. In the case of a relatively poorer quality lime, the slag will have a higher percentage of FeO (because of lower lime dissolution rate). Contrary to the popular belief, the retained slag (retained from the last heat, depending on its mass) actually slows down the lime dissolution rate (for the same quality of lime) and this often promotes dry slag formation. The reason is that the retained slag is already saturated with lime and MgO and offers little scope for further lime and dolomite dissolution in itself. Perhaps it only facilitates an early ignition and, to some extent, the dissolution of MgO from the lining in the early stages of the blow. It has been practically observed at CORUS IJmuiden that the problem of dry slag formation is enhanced if the mass of retained slag is increased. The slag splashing, though favorable to vessel lining life, is well known for its adverse effects on slag formation and it actually leads to "inconsistent blowing".



(a)



(b)

Figure 2 (a) Sample from the lance skull at Usiminas-Brazil, BOF with CO-JET; the arrows show FeO rich droplets/broken bubbles embedded in the matrix of slag; Fig. 2 (b) droplets are seen in normal BOF as well, (150 ton BOF at RSP).

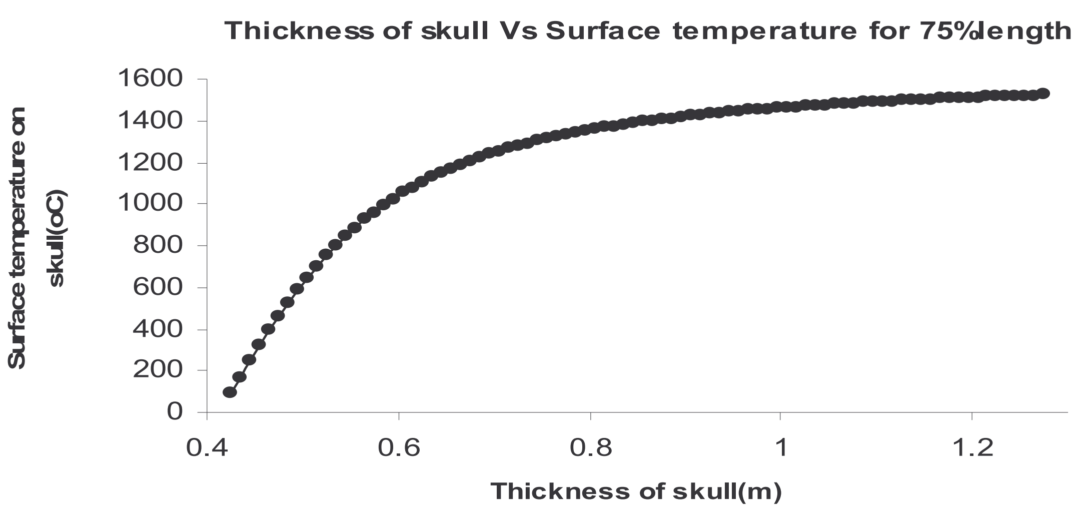


Figure 3 The predicted surface temperature of skull with different thicknesses

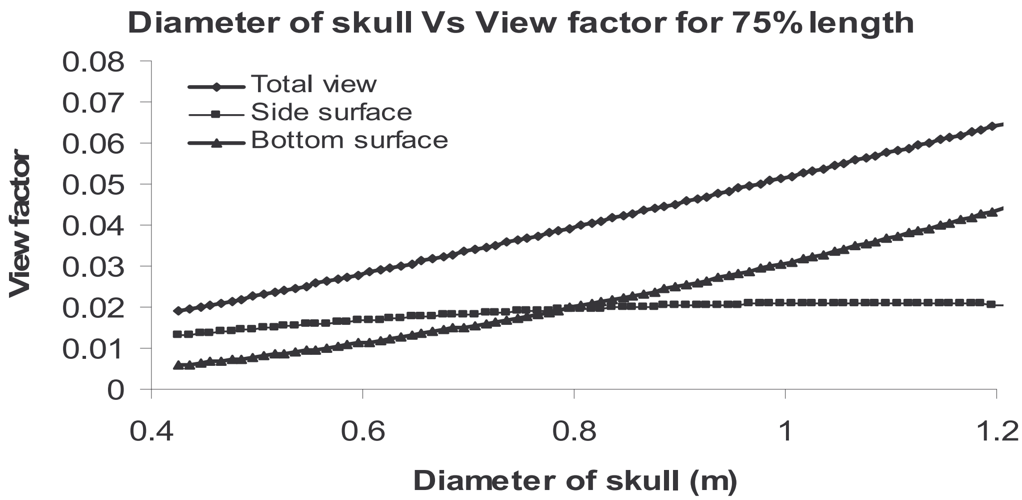


Figure 4 View factors for different skull thicknesses

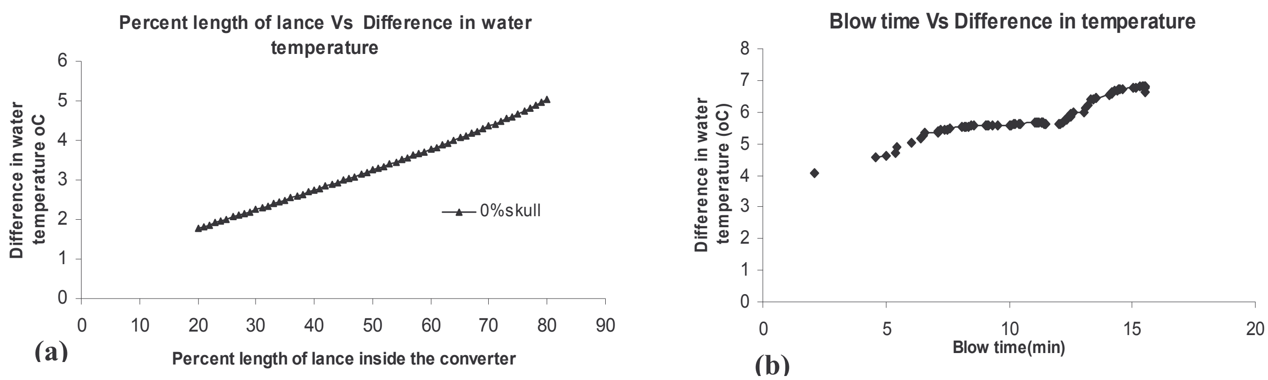


Figure 5 (a) Predicted difference in water temperature, (b) Actual difference in water temperature during a blow

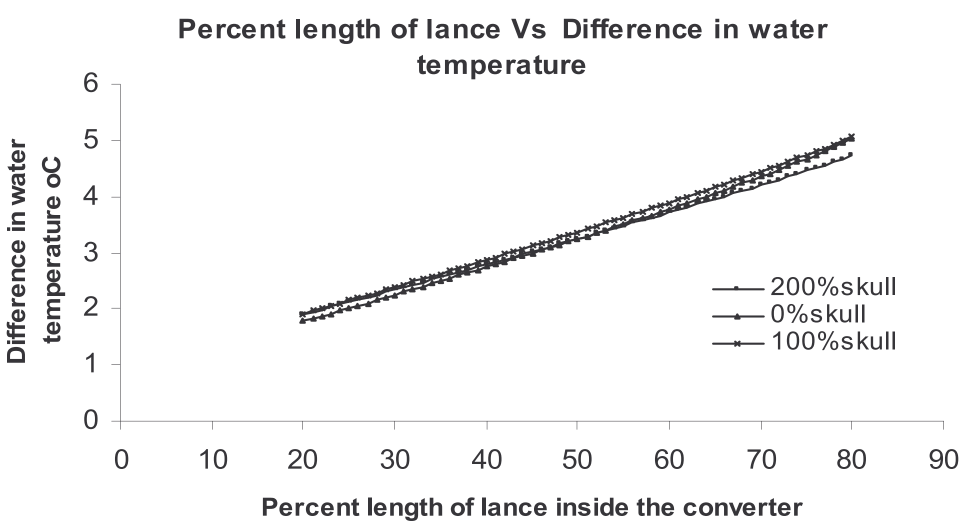


Figure 6 The predicted change in water temperature versus percentage length of lance inside the converter for an assumed thickness(0, 100%, 200%) of skull

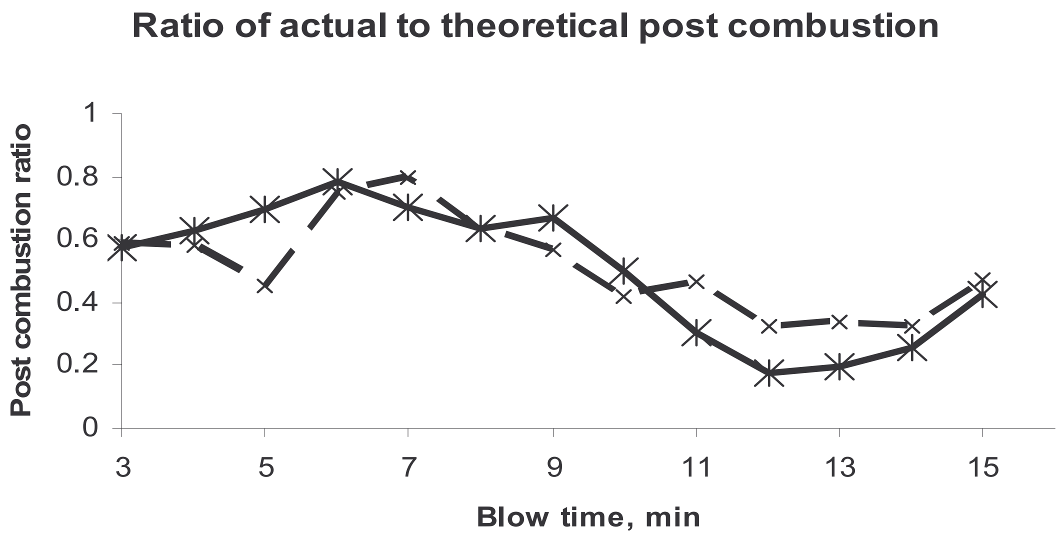


Figure 7 Ratio of actual to theoretical post combustion (β factor) observed during the progress of blow of two typical heats in the 150 ton BOF at RSP

A dynamic slag foaming model was published earlier[1]. From the gas entrapped in slag (Figure 8), the foam height can be calculated if the approximate slag mass is estimated from the lime dissolution model[2]. As an improvement of the earlier slag foaming model, the new dynamic slag foaming model, developed at IITK, controls the post combustion and the amount of FeO added to the slag by dynamically adjusting the oxygen flow rate and the lance height (at intervals of one minute or more depending upon the requirement of the process), as determined by continuous changes (with time) in the post combustion ratio, dOs/dt value and gas accumulated in the slag at the previous time steps. The model thus dictates the required changes in the lance height and/or the oxygen flow rate. In this model it is possible to calculate the foam height at each time step. The calculation of foam height from the model is, however, subject to several assumptions, including the viscosity of slag-gas-metal droplet-solid slag mixture, residence time of bubbles and droplets and the reduction rate of FeO by the droplets and rising gases. Detailed shop floor investigations have revealed that, for the control of BOF, all the slag formation effects are ultimately manifested in by the dynamic changes in the post combustion ratio, exhaust gas flow rate and temperature, which are measurable parameters.

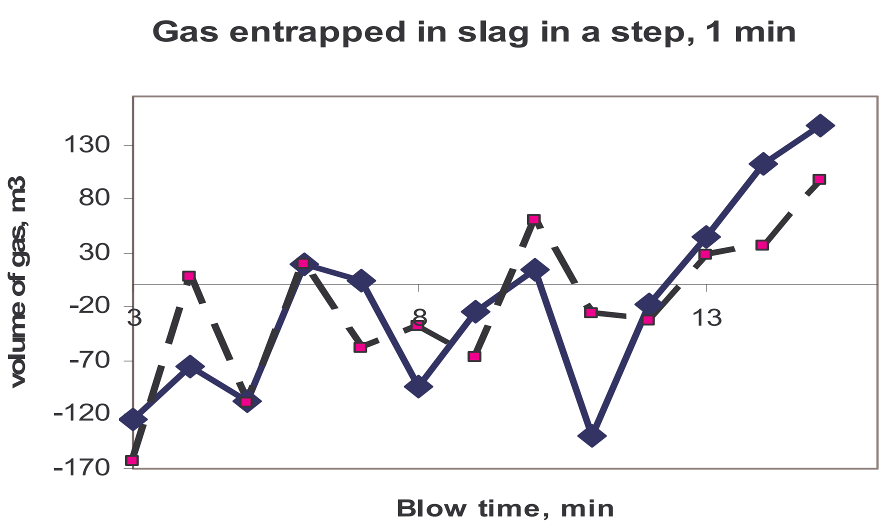


Figure 8 The calculated values of gas accumulated in slag at intervals of one minute, for two typical heats in 150 ton BOF at RSP

The best blow control is thus exercised though the timing of addition of coolants, adjustment in lance height and the oxygen flow rate, as guided by the dynamic slag evolution (based on Figure 7-9). At CORUS IJmuiden, an additional information on the progress of slag formation is made available to the operator to judge the progress of slag formation through the sound measurement probes installed for each BOF.

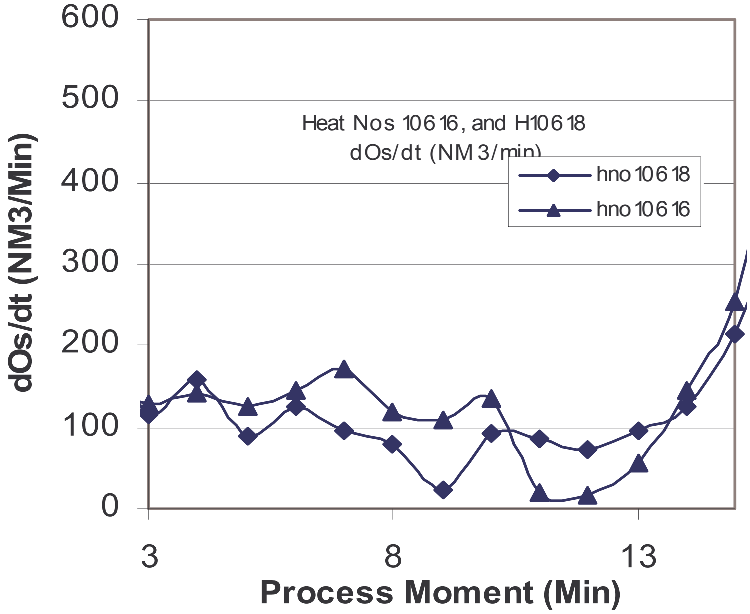


Figure 9 The change in oxygen added to the slag at intervals of one minute for the two typical heats in 150 ton BOF at RSP

REFERENCES

1. P.Misra, B.Deo and R.P.Chhabra, "Dynamic Model of Slag Foaming in Oxygen Steelmaking Converters", *ISIJ Int*. Vol. 38,1998, pp.1125-1132.

2. B.Deo, Pramod Kumar Gupta, M. Malathi, P.Koopmans, A.Overbosch, R.Boom, "Theoretitcal and Practical Aspects of Lime Dissolution in Laboratory Experiments and in BOF",*5th Eurpoean Oxygen Steelmaking Congress 26-28 June 2006", Steel Institute VDEH*, pp. 202-209.