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HEAT TRANSFER ANALYSIS OF LANCE SKULLING IN TOP-BLOWN OXYGEN STEELMAKING CONVERTERS

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ABSTRACT

The lance used for blowing oxygen in top blown oxygen steelmaking converters (BOF) is water-cooled. Deposition of metal on the lance surface results in an increase in the diameter and mass of the lance. If the deposition (skulling) is excessive, it may cause severe operational difficulties in taking out the lance from the vessel after the blow is over. The temperature difference of inlet and exit cooling water circulating inside the lance is a direct measure of the condition of the lance. An iterative calculation procedure using a computer program has been developed, for the case of a lance used in a 100T vessel, to study the effect of solidification of molten metal (skulling) on the lance body on the exit water temperatures. For the first time, the effect of radiation from hot spots has been taken into account and it turns out to be the most significant factor in heat transfer.

Key words: Heat transfer, Lance, Skulling, Hot Spots and View Factor.

1.0 INTRODUCTION

The lance used for injecting oxygen in the top blown steelmaking converter is made up of three concentric pipes of steel. Water (22-25 ^{o}C) is circulated through this lance at high pressure to keep the temperature of the outermost surface of the lance within 150 ^{o}C. The height of the lance inside the converter is varied at the various stages of blowing to control the slag formation and decarburization. During blowing the supersonic jet of oxygen impinges on the slag and metal surfaces and the lance may get coated with the splashed material, thereby increasing the diameter of the lance. This is called skulling. A general BOF undergoing skulling is as shown in Fig1. It is known that the possibility of deposition of metal on lance is most likely when the slag becomes dry (or solid). Also, iron loss in dust and top cone wear are maximum during the dry slag period. The amount of skulling affects the heat transfer rate to the cooling water circulating inside the lance. The diameter of hole through which lance travels in and out of the hood is fixed and therefore the skulling of lance may eventually result in an increase in the diameter of lance to an extent such that it is unable to pass through the hole and then “lance jam” occurs. Once lance jam occurs the blowing has to be stopped and effort is made to melt the skull by deep blowing, or replace the skulled lance resulting in unavoidable delays and loss of production which in turn affects the overall economy of the process. A blower therefore tries his best to avoid lance skulling. In the present work an attempt has been made to mathematically calculate the heat transferred to the lance at the different depths, by conduction, convection and radiation inside the converter and also by the radiation from the hot spots formed by the jet impact zone. The effect of hot spots on heat transfer has been considered for the first time and this turns out to be the source of maximum heat transfer to the lance.

2. CALCULATION OF HEAT TRANSFER COEFFICIENTS

The six different mechanisms of heat transfer inside the BOF vessel (Fig. 1) that we have considered in this study are:
(a) Convection between gas and lance.
(b) Conduction through steel-lance.
(c) Convection between water and steel.
(d) Radiation from refractory walls inside the converter.
(e) Radiation of heat from converter flame.
(f) Radiation from the hot spots.

(a) Convection between gas and lance
For the Reynolds number (Re) varying between 1000-50000, the heat transfer coefficient, K_1, is calculated by the empirical relation:

$$K_1 = 0.26\left(\frac{\lambda}{D}\right)(\mathrm{Re})^{0.6}\left(\frac{1}{S_t}\right)^{0.3} \tag{1}$$

D, diameter of lance =0.159m
S_t, Strantom number, assuming gas to be CO =1.35
λ, thermal conductivity of the film of CO gas = 0.05 kcal/m-h-°C
Reynolds number is calculated from mass flow rate. The viscosity of the exhaust gas, at the exhaust temperature of 90° C, is $4.5*10^{-5}$ kg/ms.
(b) Conduction through steel Lance
The effective heat transfer coefficient K_2 at external surface is given by:

$$K_2 = \left(\frac{\lambda}{e}\right)\left(\frac{D_m}{D_e}\right) \tag{2}$$

λ, thermal conductivity of mild steel (100-200°C) = 40 kcal/m-h-°C
e, thickness of external steel tube =0.0045 m
D_e, external diameter = 0.159 m
D_i, internal diameter = 0.150 m
D_m, average diameter = 0.1545 m

(c) Convection between water and steel
The heat transfer coefficient is calculated from the empirical relation

$$K_3 = 0.0025\left(\frac{\lambda}{D_H}\right)\left(\frac{\mathrm{Re}^{0.8}}{S_t^{0.4}}\right) \tag{3}$$

λ, conductivity of water (around 40°C) =0.54 kcal/m-h-°C
S_t, Strantom number =2 x 10^{-3}
D_H, Hydraulic Diameter= a_a/w_p
a_a = cross section available for flow
w_p = wetted perimeter
Re= Reynolds number

(d) Radiation of refractory wall inside the converter

If the value of 3.5 kcal/sq m-h is taken as factor of emission and absorption of heat by the lance, the heat transfer coefficient K_4, is given by the relation

$$K_4 = \left(\frac{3.5}{10^8}\right)(T_1 + T_2)(T_1^2 + T_2^2) \tag{4}$$

T_1, temperature of surface of lance
T_2, ambient temperature=1600 ^oC

(e) Radiation of heat from converter flame
The heat flux is given by

$$Q = S' \times 4.92 \times \varepsilon_s' \times \left[\varepsilon_g \left(\left(\frac{\theta_g}{100}\right)^4 - \beta_g \left(\frac{\theta_g}{100}\right)^4\right)\right] \tag{5}$$

S' = surface area of lance
ϵ_g = emissivity of gas at its temperature= 0.18
β_g = absorptivity of gas for black-body radiation
$\epsilon'_s = (\epsilon_s + \epsilon_b)/2 = 0.85$
ϵ_s = emissivity of lance surface
ϵ_b= emissivity for black body radiation = 1

The values of β_g and ϵ_g are taken to be same as an approximation.
The flux Q can also be expressed as

$$Q=K_5 \, . \, \Delta T \, . \, S \tag{6}$$

ΔT is the temperature difference. On simplification

$$K_5 = \epsilon_g \, .(T_1+T_2)\,(T_1^2+T_2^2) \tag{7}$$

(f) Radiation of heat from the hot spots
Here, as an example, we have considered four symmetrically placed hot spots (for a four-hole nozzle) and the heat transfer by radiation is calculated with the help of the view factor. The heat transfer coefficient is given by the relation

$$K_6 = \sigma\varepsilon A_1 F_{12} (T_1 + T_2)(T_1^2 + T_2^2) \tag{8}$$

Where, σ, is the Stefan's Boltzmann constant, ε is the emissivity of the hot spots, A_1F_{12} is the view factor multiplied by the area and is given by the relation

$$A_1 F_{12} = \frac{1}{\pi} \iint \frac{\cos \phi_1 \cos \phi_2}{r_{12}^2} dA_1 dA_2 \tag{9}$$

2.1 The overall heat transfer coefficient

The overall heat transfer coefficient K for two situations can now be calculated

-Lance inside the converter

$$\frac{1}{K^L} = \frac{1}{K_1 + K_4 + K_6} + \frac{1}{K_2} + \frac{1}{K_3} \tag{10}$$

-Lance inside the hood

$$\frac{1}{K^H} = \frac{1}{K_1 + K_5} + \frac{1}{K_2} + \frac{1}{K_3}$$

(11)

3. CALCULATION OF CHANGE IN WATER TEMPERATURE:

-Lance inside converter

Assume, L_i (length of lance inside the converter) = 6 m

S^L (surface area of lance inside the converter) = $\pi D_e L_i$

t_e, the exit water temperature

t_i, the inlet water temperature

$\Delta\theta = (t_e - t_i)$

$$Q^L = K^L S^L (1600 - t_i - \Delta\theta) \tag{12}$$

-Lance inside hood

Assume, L_o (length of lance inside the hood) = 3.51m

S^H (surface area of lance inside the hood) = $\pi D_e L_o$

$$Q^H = K^H S^H \left(1600 - t_i - \Delta\theta\right) \tag{13}$$

Total heat flow rate through the surface of the lance $Q = Q^L + Q^H$

Gain in heat content of water = $\rho Q_V C_p \Delta\theta$

Therefore the difference in temperature is given by

$$\Delta\theta = \frac{\left(K^L S^L + K^H S^H\right)\left(1600 - t_i\right)}{\rho Q_v C_p + \left(K^L S^L + K^H S^H\right)} \tag{14}$$

4. DISTRIBUTION OF DROP IN TEMPERATURE

-Lance inside the converter

$$^{\Delta T}W(water - lancewall) = \frac{Q^L}{S^L K_3} \tag{15}$$

$$^{\Delta T}S(lancewall) = \frac{Q^L}{S^L K_2} \tag{16}$$

Temperature of lance wall = $t_i + {}^{\Delta T}W + {}^{\Delta T}S$ (17)

-Lance inside hood

$$^{\Delta T}W(water - lancewall) = \frac{Q^H}{S^H K_3} \tag{18}$$

$$^{\Delta T}S(lancewall) = \frac{Q^H}{S^H K_2} \tag{19}$$

Temperature of lance wall inside hood = $t_i + {}^{\Delta T}W + {}^{\Delta T}S$ (20)

5. CALCULATION PROCEDURE

In the computer program, an iterative procedure is adopted to calculate lance wall temperature in the hood as well in the converter. Initially, the values of lance wall temperatures inside the hood and converter are assumed and values of Q′ and Q″ are estimated. Then from equations

(17) and (20), the wall temperatures are back calculated and compared with initial given values. The calculations are repeated with new guess values till difference is less than pre-set error limits. Once, correct lance wall temperature has been estimated, heat transferred to lance and the rise in water temperature ($\Delta\theta$) is calculated.

5.1 CALCULATION OF VIEW FACTOR

The radiation from the hot spots is dependant on the view factor of the hot spots relative to the lance. It depends on the distance of the centre of the hot spot from the central axis, which is given by

$$D/4 = h \tan \theta_1 \quad (21)$$

where θ_1 is the angle of the nozzle and is approximately equal to 12^o. The diameter of the hot spots varies with the height of the lance tip from the bath surface (h) and is given by the relation

$$d = 2 \times (\tan \theta_1 + \tan \theta_2) h \quad (22)$$

where θ_2 is the angle which the expanding supersonic jet makes with the nozzle and is approximately equal to 9^o. The parameter h is a function of percentage length (PL) of lance inside the vessel, and is given by the relation

$$h = H - \left(\frac{PL}{100} \times H \right) \quad (23)$$

H is the height of the converter mouth from the melt surface. The view factor also depends on the outer diameter of the lance (the effective diameter of the lance after skulling, r_{12}). The procedure of calculation of view factor, for the case of a lance placed inside the vessel with four hot spots are created due to the impingement of the oxygen jet issuing out from the four holes at the tip of the lance, is complex.

Figure 2 clearly shows that on increasing the percentage length of the lance inside the converter the view factor increases. This can be explained by the fact that on increasing the percentage length 'h' decreases (23) and hence heat can be radiated more effectively to the lance surface, thus the view factor increases. The value of 'D' also decreases on decreasing 'h'. As a result of lowering the lance the hot spot comes closer to the central axis and hence to the surface of the lance. This will also assist in increasing the view factor. For the same percentage length the view factor is minimum for the case of 200% skulling. This is because of the effect of r_{12} which is inversely related to the view factor. Thus an increase in the effective diameter (higher % skulling) results in a lower view factor.

6. RESULTS AND DISCUSSION

The radiation from the hot spots, which was so far neglected in the earlier works [1-3], plays a dominant role and amounts to approximately 90-95 % of the total heat received by lance (Fig 3). Also, it is clearly seen from Fig. 3 that on increasing the percentage length of the lance inside the converter the percentage contribution from the hot spots decreases. This can be explained by the fact that now more of the lance surface is available to receive heat flux from the other two mechanisms. Thus although the heat flux from the hot spots increases with increasing the percentage length, its relative contribution decreases.

As discussed earlier, the outlet water temperature is directly related to the heat received by the lance. The graph (Fig. 4) shows the variation of $\Delta\theta$ as a function of percentage lance height for a good lance (no skulling) and also for the case of 100 % and 200 % skulling, respectively. In the event of lance skulling, the heat transfer to water increases and $\Delta\theta$ rises. Also it can be observed that the outlet water temperature increases with increasing percentage length for all the cases. This can be explained by the fact that as we increase the percentage length the view factor increases and hence the heat flux from the hot spots (the most dominant mechanism as demonstrated earlier) increases. Further, when more of the lance surface is inside the converter, the radiation from the refractory walls and convection from the gas also increases. It can be seen from the figure that the change in temperature becomes fairly constant for the case of skulled lance when the percentage length inside the converter is high, thus we can say that the variation in temperature becomes independent of skull thickness after some minimum skulling has taken place.

The build up of lance skull can be monitored simply by monitoring the outlet water corresponding to a given length of lance on converter while the blow is in progress. The corrective measures can be taken as soon as $\Delta\theta$ changes from expected values; for example, as soon as $\Delta\theta$ begins to rise above the expected values, the lance can be lowered temporarily so that the skull melts (owing to increased heat transfer to lance). Through actual experimentation, the dependence of $\Delta\theta$ on thickness of lance skull can be verified. It may then be possible to back estimate skull thickness based on exit water temperature and thus avoid operational delays and difficulties owing to skulling.

7. CONCLUSIONS

1. The contribution of hot spots to the heat flux is highest.
2. The view factor is inversely related to the effective diameter of the lance and is maximum for the case of no skulling.
3. The variation in temperature due to skulling is significant and hence this technique can be employed for predicting both the lance skulling and slag formation behavior in BOF steel making.

8. REFERENCES

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FIGURES

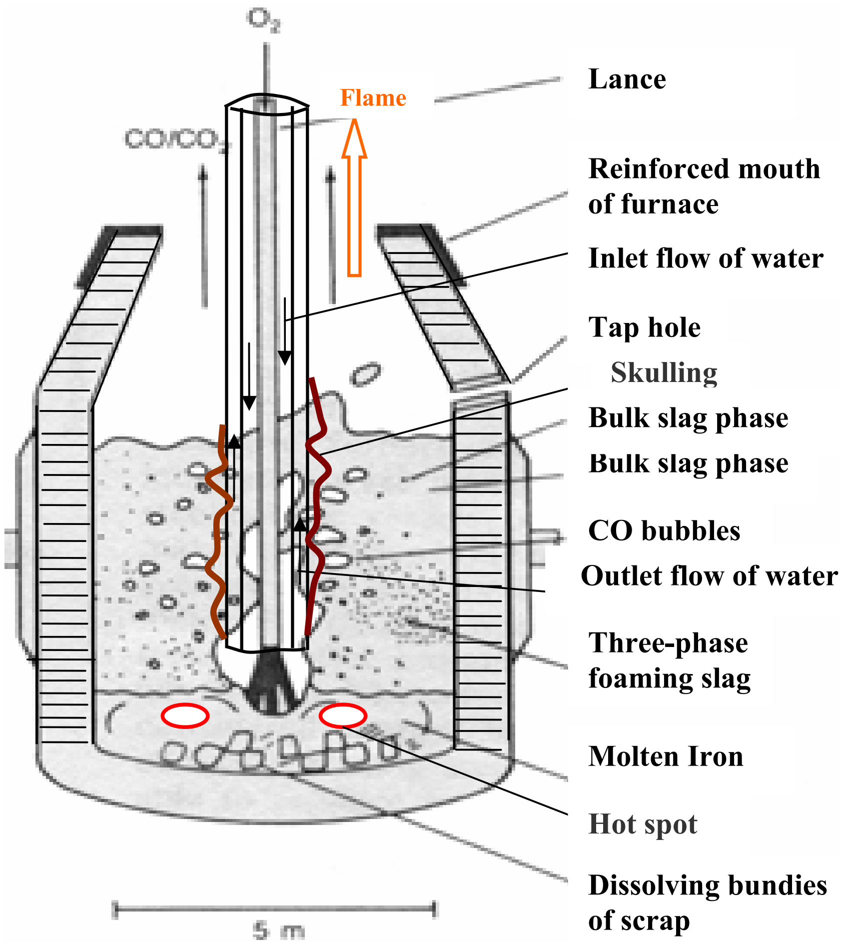

Fig 1: Basic Oxygen Furnace (BOF) in which skulling of lance has occurred.

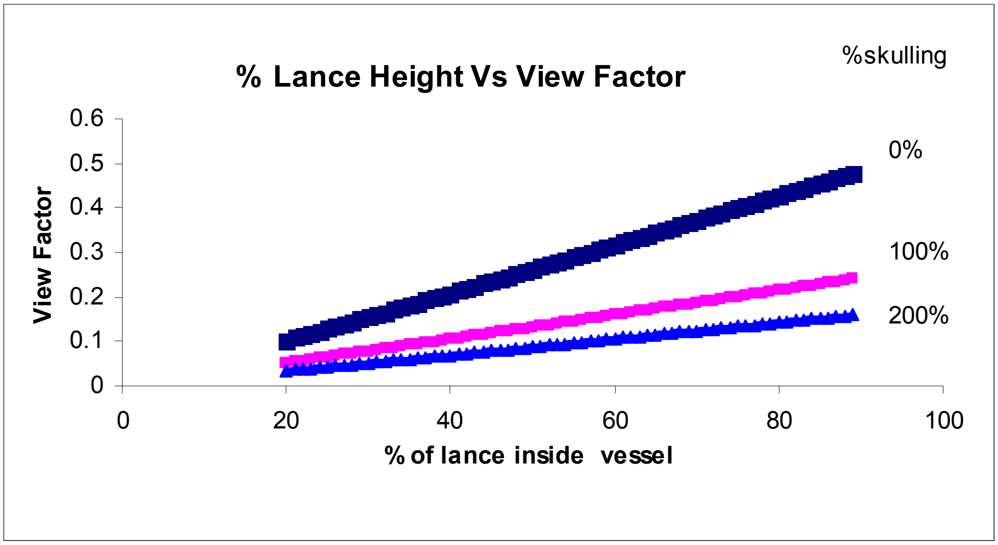

Fig 2: View factor for a single hot spot as a function of the percentage lance inside the vessel.

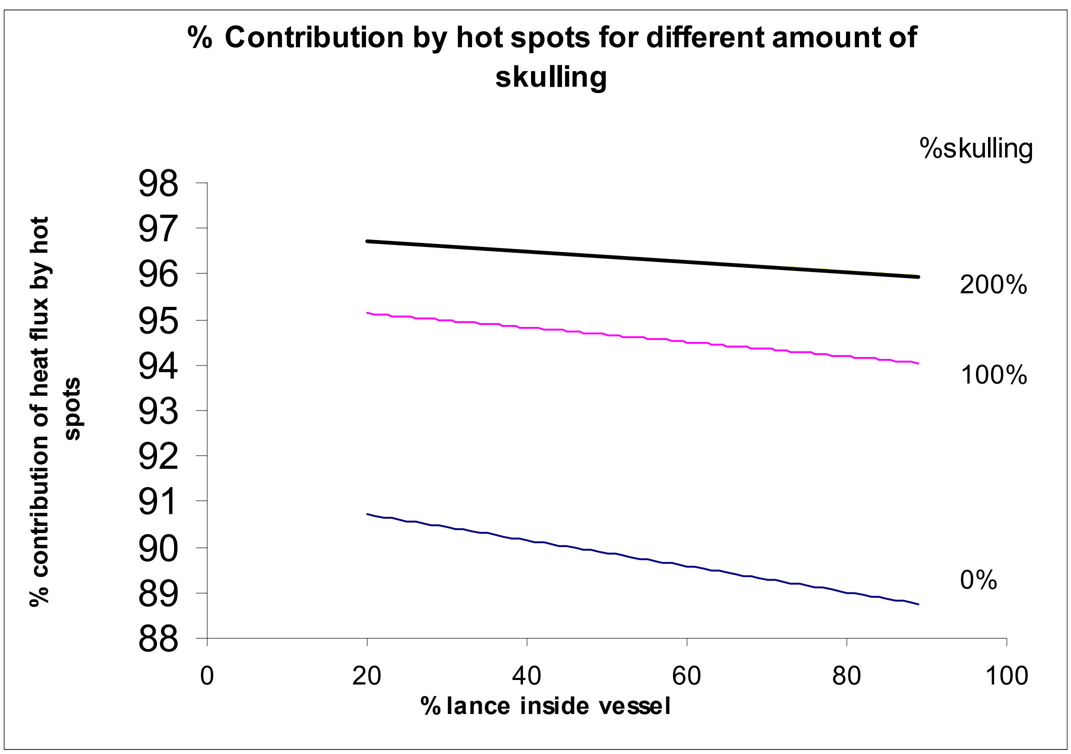

Fig 3: Percentage contribution of hot spots as a function of percentage lance inside the vessel for different amounts of skulling.

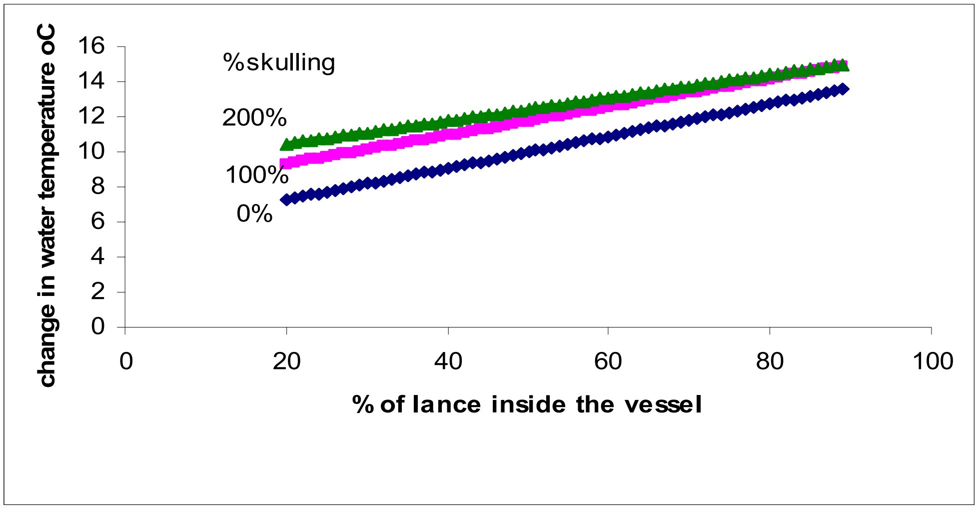

Fig 4: Change in water temperature for different percentage length of lance inside the vessel.