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Abstract:
A system and method for determining slag coating thickness and depth of refractory erosion of high temperature metallurgical furnace has been disclosed. The system senses and records certain furnace and slag related parameters such as slag chemistry, bath temperature, shell temperature, heat loss, refractory properties, jacket inlet water temperature, jacket outlet water temperature and water mass flow rate in the jacket and processes them in order to define a temperature profile and determine slag solidus of the slag. The temperature profile and the slag solidus are further used to determine the slag coating thickness and the depth of refractory erosion.
A SOFT SENSOR BASED ON-LINE DECISION SYSTEM FOR METALLURGICAL PROCESSES

FIELD OF THE INVENTION

This invention relates to the field of metallurgy.

Particularly, this invention related to processes for smelting/converting in metallurgy.

This invention envisages a system for on-line decision of certain parameters in smelting/converting processes using a soft sensor.

BACKGROUND OF THE INVENTION

In the field of extractive metallurgy, smelting/converting is the process of obtaining a metal form its ore. Since most ores are a mix of compounds, the art of this extraction lies in formulating a chemical reaction with an oxygen source, usually air- or pure oxygen. Smelting therefore consists of using suitable oxidants that will combine with those oxidizing elements to free the metal.

The increasing need for higher and consistent production with low and varying raw material grades within a single furnace depends on robust and well-controlled pyrometallurgical furnace operation, leading to high online times. The key features of such high rate furnaces include a strong, thermally robust wall cooling system and a stable slag coating. This prevents the corrosive liquid slag from directly coming into contact with and penetrating into the sidewall refractory and eroding it. The formation and control of the slag coating is dependent on the quantity and direction of heat flow through the coating, slag chemistry, melt temperature and refractory properties. Less slag coating may lead to reduced lining life or even
break out, which results into loss of production. Excessive slag coating, on other hand, can lead to operating difficulties with magnetite and loss of smelting/converting efficiency.

A common and cost-effective way of knowing the solidified slag layer thickness in advance is by means of mathematical modeling. While number of mathematical models are present today which include the heat and fluid flow phenomena of the furnace, it is observed that a thermal conduction model is sufficient to capture the essence of the heat transfer at the furnace wall. Supplemented with plant data it is possible to reasonably predict of the frozen interface location. For instance C SCHMITZ in 1996 proposed an approach for designing furnaces for the primary aluminium industry which provided some guidelines for furnace design in the primary aluminum smelters but the approach avoids the more complex convective flow equations.

Chinese patent CN101812559A discloses the idea of developing an on-line monitoring system for the metallurgical trade balst furnace lining wear analysis. However, the method for predicting the slag coating thickness has not been described.

Hence, there was felt a need to develop an automated system to predict, monitor and control the optimum slag coating thickness and erosion profile of the refractory for high temperature pyro-metallurgical furnaces.

**OBJECTS OF THE INVENTION**

An object of the invention is to achieve stable slag coating thickness within a furnace.
Another object of the invention is to provide a system for determining the erosion profile of the furnace.

Yet another object of the invention is to improve the performance of the furnace.

SUMMARY OF THE INVENTION

The present invention envisions a system for determining slag coating thickness and depth of refractory erosion of high temperature metallurgical furnace, the system comprising first sensing means adapted to sense and record at least some of the furnace and slag related parameters selected from the group consisting of slag chemistry, bath temperature, shell temperature, and refractory properties; second sensing means adapted to sense the parameters selected from the group consisting of jacket inlet water temperature, jacket outlet water temperature and water mass flow rate in the jacket; processing means coupled with the first sensing means and second sensing means and adapted to define a temperature profile by determining oxygen potential and heat loss of the furnace and further adapted to determine slag solidus of the slag; and determining means adapted to determine the slag coating thickness and refractory erosion based on the sensed parameters, the temperature profile and the slag solidus.

Typically, the second sensing means is a distributed control system (DCS).

The system further comprises a user interface and graphical display means adapted to display the slag coating thickness and the depth of refractory erosion determined by the determining means.
The processing means is adapted to deploy a pre determined thermal model for determining the temperature profile and adapted to deploy a pre determined thermodynamic model for determining slag solidus.

Typically, the system is adapted to operate online and offline to determine the slag coating thickness and depth of refractory erosion.

The present invention also envisages a method for determining slag coating thickness and depth of refractory erosion of high temperature metallurgical furnace, the method comprising the steps of

- sensing at least some of the parameters selected from the group consisting of jacket inlet water temperature, jacket outlet water temperature and water mass flow rate in the jacket, shell temperature, bath temperature, slag chemistry, and refractory properties;

- processing the sensed parameters to define a temperature profile by determining oxygen potential and heat loss of the furnace and determine slag solidus of the slag; and

- determining slag coating thickness based on the sensed parameters, the temperature profile and the slag solidus.

Typically, the method further comprises the steps of displaying the slag coating thickness and depth of refractory erosion as determined by the determining means.

The step of processing the sensed parameters to define a temperature profile of the furnace and determine slag solidus of the slag further comprises the step of
deploying a pre determined thermal model for defining the temperature profile.

The step of processing the sensed parameters to define a temperature profile of the furnace and determine slag solidus of the slag further comprises the step of deploying a pre determined thermodynamic model for determining the slag solidus.

The step of sensing at least some of the parameters selected from the group consisting of jacket inlet water temperature, jacket outlet water temperature and water mass flow rate in the jacket, shell temperature, bath temperature, slag chemistry, and refractory properties includes the step of fetching the jacket inlet water temperature, jacket outlet water temperature and total mass flow rate of water in the jacket from a distributed control system (DCS).

The method further comprises the step of stopping the burner close to the affected jacket and stopping the lance close to the affected jacket in case the slag thickness is not appropriate

BREIF DESCRIPTION OF THE ACCOMPANYING DRAWINGS

The invention will now be described with reference to the accompanying drawings, in which:

FIGURE 1 illustrates a system for determining slag coating thickness and depth of refractory erosion of high temperature metallurgical furnace in accordance with the present invention;
FIGURE 2 illustrates meshing of the system implemented mathematical thermal equilibrium model in accordance with the present invention;

FIGURE 3 (a) illustrates a top view of converting furnace with jacket assembly in accordance with the present invention;

FIGURE 3 (b) illustrates a top view of converting furnace depicting solidified slag in accordance with the present invention;

FIGURE 4 illustrates a two dimensional configuration of a single jacket, bath and refractory in accordance with the present invention;

FIGURE 5a illustrates a temperature profile of the system with a specific consideration on slag coating thickness in accordance with the present invention;

FIGURE 5b illustrates a temperature profile of the system with a specific consideration on refractory erosion profile in accordance with the present invention;

FIGURE 6 illustrates a variation in slag coating thickness owing to variation in slag solidus in accordance with the present invention;

FIGURE 7 illustrates a variation in slag coating thickness owing to variation in heat loss in accordance with the present invention;

FIGURE 8 illustrates a variation in slag coating thickness owing to variation in thermograph measurement in accordance with the present invention;

FIGURE 9 illustrates a variation in slag coating thickness owing to variation in melt temperature in accordance with the present invention;

FIGURE 10 illustrates liquids of Converting (C) slag in accordance with the present invention; and
FIGURE 11 illustrates a method for determining slag coating thickness and depth of refractory erosion of high temperature metallurgical furnace in accordance with the present invention.

DETAILED DESCRIPTION OF THE INVENTION

In accordance with the invention a system implemented mathematical thermal equilibrium model is envisaged. The system basically determines slag coating thickness and depth of refractory erosion.

Referring to Figure 1, there is shown a system 100 for determining slag coating thickness and depth of refractory erosion. A first sensing means 105 is provided which senses and records the needed furnace and slag related parameters such as slag chemistry, bath temperature, shell temperature, and refractory properties. A second sensing means 110 is provided which senses the parameters selected from the group consisting of jacket inlet water temperature, jacket outlet water temperature and water mass flow rate in the jacket;

Further to sensing the above stated parameters, the sensed parameters are sent to a processing means 115 which defines a temperature profile by determining oxygen potential and heat loss of the furnace by deploying a pre determined thermal model and determine slag solidus of the slag by deploying a predetermined thermodynamic model.

After the temperature profile is defined and slag solidus is determined a determining means 120 determines the slag coating thickness and refractory erosion based on the sensed parameters and the slag solidus.
In order to determine the slag coating thickness and depth of refractory erosion the system takes into account different parameters associated with smelting/converting in metallurgy such as the slag chemistry (slag composition), bath temperature, heat loss and refractory properties in achieving a stable slag coating thickness for high temperature furnaces. The system predicts / determines the equilibrium slag coating thickness or the slag coating thickness and the depth of refractory erosion based on the on-line temperature of the jacket inlet water and jacket outlet water and mass cooling water flow rate data (inlet and outlet). Further, the system can also be used for online coupling with industrial automation infrastructure (distributed control systems DCS or programmable logic controller PLC).

In accordance with another embodiment of the of the invention for determination of slag coating thickness and the depth of refractory erosion the processing means uses a two-dimensional cartesian system for (depth of wall (x) and height of furnace (y)) is considered under steady state conditions. The width of the furnace (z or Θ in cylindrical coordinates) is not taken into consideration as it is expected that the copper blocks have sufficient thermal capacity to absorb the heat flow in this direction. Further, heat flow is predominantly towards the cooling elements (i.e. the jacket) and the heat flow towards the roof and hearth is neglected as it is miniscule and in most of the cases of macroscopic heat balance for a matte reverberatory furnace about 2% of the heat is lost through the sidewall, roof, bottom and hearth, respectively.

Further, the two dimensional cartesian system is used in governing transport equations for enthalpy which are also solved in two dimensions.
The governing equations are discretized into finite volume cartesian coordinates.

The tri-diagonal matrix algorithm, also known as thomas algorithm, is used to solve the set of discretized linear equations.

Referring to figure 2 there is shown an exemplary of cartesian coordinates which are used with uniform 520 by 130 cells at 10 mm cell size in a mesh representation. The convergence is satisfied by the following criteria:

(a) the sum of the residuals should continue to decrease with respect to the first iteration;

(b) the input heat flux is equal to the exit heat flux - imbalance < 0.1% ; and

(c) the spot temperature values at several critical locations are monitored to ensure that they have remained unchanged i.e. the percentage change in their value from the previous iteration is less than 0.001%.

In accordance with still another embodiment of the invention, the numerical code determinations were compared to the solution using Matlab™ PDE solver to ensure accuracy, precision and compliance.

In accordance with still further an embodiment of the invention, the thermodynamic model was deployed to determine the solidus for the converter multi-component slag system.

A thermodynamic model consists of a set of model equations for the Gibbs energies of all phases in multi-component system as a function of temperature, composition and pressure. From these equations, all the thermodynamic properties and phase diagrams of simple systems can be reproduced and those of multi-component systems can be predicted. Technically, this is realized by storing the model parameters in solution databases, which are then used along with pure
component databases by general Gibbs free energy minimization tool that incorporates the model equations to calculate multi-component and multi-phase heterogeneous equilibria. With the help of thermodynamic modeling, slag-liquidus and solidus could be predicted on several regions of compositions and temperature.

In accordance with the invention the salg system is FeOx-CaO-Cu20-SiO2 and the converting furnace slag system consists of the following constituents: FeO, Fe2O3, Fe3O4, Cu2O, Cu2S, CaO, and SiO2. The slag system is essentially calcium ferrite in nature.

Referring to Figure 3(a), there is shown a top view of furnace with jacket assembly containing a plurality of jackets represented by numeral 30, the exothermic heat of the furnace is removed by water cooled copper jacket located at the slag level. Jacket water inlet is shown by 33 and outlet is shown by 35. The blister outlet is shown by 37, the slag outlet is shown by 39, the matte inlet is shown by 43 and the gas outlet is shown by 45. Figure 3(b) shows the solidified slag is represented by reference numeral 36.

The configuration of single water cooled jacket (side view) is also shown in figure 4 wherein a water cooled pipe jacket water inlet 33 and jacket water outlet 35 is extruded through copper block. Reference numeral 56 denotes refractory, 58 denotes hearth, 52 denotes blister and 54 denotes slag. Here higher thermal conductivity of copper block ensures the efficient heat removal of heat at the slag level. Consequently, the temperature of slag in the vicinity of the jacket (copper block) tends to decrease. The slag becomes solidified (frozen) when the slag temperature attains its solidus. Once the slag solidus is known, it is then used to determine the slag coating thickness. With the help of the solution of equations for given boundary conditions and given geometry, the temperature values over each
node could be determined and hence, the isotherms at different temperatures could also be drawn.

Referring to Figure 5 (a) and Figure 5 (b) there is shown an exemplary of a temperature profile of the system with a specific consideration on slag coating thickness 65. The molten or liquid slag is shown by 67 and blister is shown by 63.

In accordance with still another embodiment of the present invention the solidified slag thickness is determined as follows: The slag solidus (e.g.:1075°C) is first determined from phase diagram as schematically shown in figure 5 (a). The slag coating thickness is measured as a distance from the refractory to the solidus. Figure 5 (a) shows the shaded area between the refractory outerface and the solidus (~1075 °C) as the solidified layer of slag.

The solidified slag layer gradually shrinks towards blister side. Therefore, slag coating thickness at the gas-slag interface has been referred as the maximum slag coating thickness \(\text{SCT}_{\text{max}}\) and at the slag blister interface as the minimum slag coating thickness \(\text{SCT}_{\text{min}}\). It should be ensured that \(\text{SCT}_{\text{min}}\) is positive in order to avoid the liquid slag coming in contact with the refractory. The process conditions such as slag chemistry, bath temperature and heat loss must be brought into the safe operating conditions which ensure \(\text{SCT}_{\text{min}}\) is positive. The negative value of \(\text{SCT}_{\text{min}}\) indicates that the slag solidus is inside the refractory and refractory tantamount to the depth of slag solidus has been eroded, as shown by reference numeral 69 in Figure 5(b).

The effect of slag chemistry, bath temperature, heat loss and thermography measurement on slag coating thickness have been analysed with the help of the model. The values of these parameters have been taken within the plant operating
range, thus ensuring that the effects of process variability on slag coating has been accounted for.

Referring to **Figure 6** there is shown a graph representing the effect of slag coating thickness (in mm) (x-axis) on slag solidus (°C) (y-axis). The slag coating thickness increases with rise in slag solidus and as the thickness becomes steep above 1090 °C for a given heat loss and other conditions. At this point the slag coating at slag-blistter interface (SCT \text{\textsubscript{min}}) vanishes, which causes liquid slag to come in contact with refractory when the slag solidus is below 1070 °C, despite the other furnace conditions being unchanged. It is also observed that the slag thickness at gas/slagn interface (SCT \text{\textsubscript{max}}) and at slag/blister interface (SCT \text{\textsubscript{min}}) attain nearly the same value at high solidus. This is because slag and blister attain the same temperature away from the jacket.

In accordance with another embodiment of the invention the Heat loss \( Q \) is calculated from the mass flow rate of jacket water and temperature difference between jacket inlet water and and jacket outlet water i.e temperature that passes through the jacket, as shown in the following equation

\[
Q = m \, C_p \, (T_{\text{out}} - T_{\text{in}})
\]

where

- \( m \) = mass flow rate of jacket water; and
- \( C_p \) = specific heat.

Keeping other furnace parameters constant, the slag coating thickness increases with a decrease in heat loss. This is also represented by the graph in **Figure 7**
where slag coating thickness (in mm) is taken on x-axis and Heat loss (in Kcal) is taken on y-axis.

The rise in slag thickness at skg-blister interface is steep when the heat loss per jacket is below 21000 Kcal/hr for a given parameters. Slag coating thickness being zero, a liquid slag-refractory contact is established when the heat loss increases above 27000 Kcal/hr.

Also, the thermography measurement (in °C) of furnace shell at the blister level has been taken as one of the boundary conditions in the model. Often, it is very difficult to estimate the refractory condition based on thermography measurements. Therefore, a correlation between thermography measurement (in °C) (y-axis) and slag coating thickness (in mm) (x-axis) is depicted in Figure 8.

As shown in Figure 8, the refractory at slag level is safe for a thermography measurement below 190 °C for a given condition, as a sufficient slag thickness is maintained below 190 °C. Furthermore, the rise in slag thickness is steep when the thermography temperature is below 190 °C, because higher thermography measurement being the indication of high heat loss from the refractory at blister level.

The fluctuation is melt temperature of C-furnace is also observed in day-to-day operation. It is therefore useful to correlate the slag thickness with melt temperature in the range in which it varies.

Referring to Figure 9, there is shown a graph between slag coating thickness (in mm) (x-axis) and melt temperature (in °C) (y-axis) where the safe operating slag coating thickness is attained below 1210 °C of melt temperature for a given furnace conditions. Slag thickness increases steeply with a decrease in melt temperature below 1210 °C. While low melt temperature ensures sufficient slag
thickness, it is equally critical to ensure that the melt temperature should be higher than the slag liquidus in order to avoid magnetite precipitation and other operating difficulties thereof. Therefore, the slag liquidus has been calculated for a range of slag chemistry being maintained in the furnace, as shown in the graph between C Slag liquidus (in °C) (x- axis) and Fe / CaO (in wt%) (y- axis) in Figure 10. The optimum melt temperature should be maintained in such a way that it is above the liquidus as shown in Figure 9 and at the same time there should be sufficient slag coating thickness at slag-blister interface. In case it is not possible to maintain the optimum melt temperature, the slag chemistry (i.e Fe/CaO) must be varied such that the melt temperature is higher than the liquidus.

In accordance with still further an embodiment of the present invention upon online implementation, the processing means would work as a soft sensor for the continuous determination of slag coating thickness, provide continuous guidance to the plant operation on the health of the furnace and advise the optimum conditions of plant working. This would enhance the decision making ability of the operators, resulting in reduced process variations and an improved operation.

In accordance with yet another embodiment of the present invention there is shown a flowchart of the process for determining slag coating thickness and depth of refractory erosion of high temperature metallurgical furnace as shown in figure 11, the method comprising the steps of

- sensing at least some of the parameters selected from the group consisting of jacket inlet water temperature, jacket outlet water temperature and water mass flow rate in the jacket, shell temperature, bath temperature, slag chemistry and refractory properties, 405;
processing the sensed parameters to define a temperature profile of the furnace and determine slag solidus of the slag, 410; and

determining slag coating thickness based on the sensed parameters, the temperature profile and the slag solidus, 415.

The method further comprises the step of stopping the burner close to the affected jacket and stopping the lance close to the affected jacket in case the slag thickness is not appropriate, 420.

Further, the method also comprises the step of displaying the slag coating thickness and depth of refractory erosion as determined by said determining means.

The step of processing the sensed parameters to define a temperature profile of the furnace and determine slag solidus of the slag comprises the step of deploying a pre determined thermal model for defining the temperature profile.

The step of processing the sensed parameters to define a temperature profile of the furnace and determine slag solidus of the slag further comprises the step of deploying a pre determined thermodynamic model for determining the slag solidus.

The step of sensing at least some of the parameters selected from the group consisting of jacket inlet water temperature, jacket outlet water temperature and water mass flow rate in the jacket, shell temperature, bath temperature, slag chemistry, and refractory properties includes the step of
fetching the jacket outlet water temperature, jacket inlet water temperature and total mass flow rate of water in the jacket from a distributed control system (DCS).

The water inlet as well as outlet temperature of a jacket and total mass flow rate of water can be measured online is fetched directly from the distributed control system DCS. The bath temperature, slag chemistry and the thermography readings are measured manually. Based on the above data, the oxygen potential of the process and heat loss from the jacket are calculated. The slag coating thickness is determined after the calculation of the temperature profile of the system by thermal model and the determination of the slag solidus by thermodynamic model.

**TECHNICAL ADVANTAGES**

The technical advantages of the present invention includes in

- achieving a stable slag coating thickness within a furnace;
- providing a system for determining the erosion profile of the furnace; and
- improvement of the performance of the furnace.

While considerable emphasis has been placed herein on the components and component parts of the preferred embodiments, it will be appreciated that many embodiments can be made and that many changes can be made in the preferred embodiments without departing from the principles of the invention. These and other changes in the preferred embodiment as well as other embodiments of the invention will be apparent to those skilled in the art from the disclosure herein, whereby it is to be distinctly understood that the foregoing descriptive matter is to be interpreted merely as illustrative of the invention and not as a limitation.
CLAIMS:

1. A system for determining slag coating thickness and depth of refractory erosion of high temperature metallurgical furnace, said system comprising

   - first sensing means adapted to sense and record at least some of the furnace and slag related parameters selected from the group consisting of slag chemistry, bath temperature, shell temperature, and refractory properties;

   - second sensing means adapted to sense the parameters selected from the group consisting of jacket inlet water temperature, jacket outlet water temperature and water mass flow rate in the jacket;

   - processing means coupled with said first sensing means and second sensing means and adapted to define a temperature profile by determining oxygen potential and heat loss of the furnace and further adapted to determine slag solidus of the slag; and

   - determining means adapted to determine the slag coating thickness and refractory erosion based on the sensed parameters, the temperature profile and the slag solidus.

2. The system as claimed in claim 1, wherein said second sensing means is a distributed control system (DCS).

3. The system as claimed in claim 1, wherein said system further comprises a user interface and graphical display means adapted to display the slag
coating thickness and the depth of refractory erosion determined by said determining means.

4. The system as claimed in claim 1, wherein the processing means is adapted to deploy a pre determined thermal model for determining the temperature profile of said furnace.

5. The system as claimed in claim 1, wherein the processing means is adapted to deploy pre determined thermodynamic model for determining slag solidus of said furnace.

6. The system as claimed in claim 1, wherein the system is adapted to operate online and offline to determine the slag coating thickness and depth of refractory erosion.

7. A method for determining slag coating thickness and depth of refractory erosion of high temperature metallurgical furnace, said method comprising the steps of

> sensing at least some of the parameters selected from the group consisting of jacket inlet water temperature, jacket outlet water temperature and water mass flow rate in the jacket, shell temperature, bath temperature, slag chemistry, and refractory properties;

> processing the sensed parameters to define a temperature profile by determining oxygen potential and heat loss of the furnace and determine slag solidus of the slag; and
> determining slag coating thickness based on the sensed parameters, the temperature profile and the slag solidus.

8. The method as claimed in claim 7, wherein the method further comprises the steps of displaying the slag coating thickness and depth of refractory erosion as determined by said determining means.

9. The method as claimed in claim 7, wherein the step of processing the sensed parameters to define a temperature profile of the furnace and determine slag solidus of the slag further comprises the step of
   deploying a pre determined thermal model for defining the temperature profile.

10. The method as claimed in claim 7, wherein the step of processing the sensed parameters to define a temperature profile of the furnace and determine slag solidus of the slag further comprises the step of
   deploying a pre determined thermodynamic model for determining the slag solidus.

11. The method as claimed in claim 7, wherein the step of sensing at least some of the parameters selected from the group consisting of jacket inlet water temperature, jacket outlet water temperature and water mass flow rate in the jacket, shell temperature, bath temperature, slag chemistry, and refractory properties includes the step of
   fetching the jacket outlet water temperature, jacket inlet water temperature and total mass flow rate of water in the jacket from a distributed control system (DCS).
12. The method as claimed in claim 7, wherein the method further comprises the step of stopping the burner close to the affected jacket and stopping the lance close to the affected jacket in case the slag thickness is not appropriate.
FIGURE 1
Figure 6

Q=25 Mcal/hr, Melt temp = 1220 °C, TM=250 °C

(IN min)

(IN °C)
Solidus = 1070 °C, Melt temp = 1220 °C, TM = 250 °C

FIGURE 7
Q=25 Mcal/h, Solidus = 1070 °C, Melt temp = 1220 °C

FIGURE 8
$Q = 25 \text{ Mcal/h}$, Solidus = 1070 $^\circ$C, TM=250 $^\circ$C

**FIGURE 9**
Figure 10 presents a phase diagram with temperature in °C on the y-axis and weight percentage on the x-axis. The phases include Liquid, Liquid + Ca₂Fe₂O₅, and Liquid + Ca₂SiO₄.
FIGURE 11