CFD Simulation for Heat Transfer In Blast Furnace

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ABSTRACT

Iron blast furnace is used in the metallurgical field to extract molten pig iron from its ore through a reduction mechanism. The furnace is a vertical shaft with circular cross section. It has five main parts: stack, belly, bosh, tuyeres and hearth. Amongst these regions, hearth is the most important one for the asset life of a furnace. Erosion of refractory lining of the hearth reduces the furnace's campaign life. So it is necessary to understand the interactions occurring between the slag, molten metal and the refractories. But the severe operating conditions and very high temperature inside the hearth make it impossible to practically observe the processes taking place within it. In order to overcome this problem, the hearth is modeled by using various Computational Fluid Dynamics (CFD) soft-wares such as ANSYS Fluent, ANSYS-CFX, FLUENT for CATIA V5, ANSYS CFD-Flo etc. The numerical model is then supplied with data which are already known from practical situations as boundary conditions. Proper physical properties of the materials are also used as input. The software runs several simulations and provides us with the result that can validate the experimental observations up to the most accurate level. In this study, temperature distribution profile inside a blast furnace hearth has been shown by modeling a simple hearth with the help of ANSYS 15.0 Workbench. The model is simulated by changing some parameters and making several assumptions. The discrepancy in the calculated and the observed temperature opens up new scope for further improvement.

Keywords : Blast furnace hearth, campaign life, Computational Fluid Dynamics (CFD), ANSYS, simulations.

I. INTRODUCTION

Blast Furnace:Blast furnace is a large furnace which is used in metallurgical field to produce metals, especially pig iron. Lead or copper can also be produced in the blast furnace. But our study is confined to the extraction of iron from its ore.

Blast furnace reactions take place in different regions [1]. They are:

➢ The upper region, i.e. Stack or Shaft

➢ The middle region, i.e. Belly and Bosh

➢ The lower region, i.e. Hearth

The major reactions inside a blast furnace can be classified into the following categories [1]:

1. Removal of moisture from the raw materials

$H_2O + C = H_2 + CO$
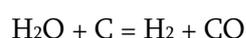
Reduction of iron oxides by CO

$3Fe_2O_3 + CO = 2Fe_3O_4 + CO_2$

$Fe_3O_4 + CO = 3Feo + CO_2$
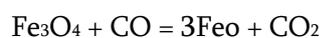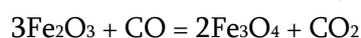
iii) Gasification of carbon by CO_2

$C + CO_2 = 2CO$
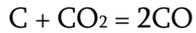
iv) Dissociation of $CaCO_3$

$CaCO_3 = CaO + CO_2$

v) Reduction of FeO by carbon:

$FeO + C = Fe + CO$
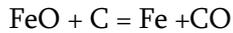
vi) Reduction of some other oxides of ore by carbon

$SiO_2 + 2C = Si + 2CO$

$MnO + C = Mn + CO$ $P_2O_5 + 5C = 2P + 5CO$ $S + (O) + C = (S) + CO$
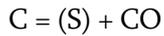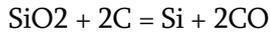
vii) Combustion of coke and coal in front of tuyeres

$2C + O_2 = 2CO$
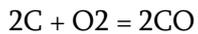
II. SIMULATIONRESULTS &DISCUSSION

Modeling of hearth

Two dimensional models of a simple blast furnace hearth have been developed using the commercial CFD package ANSYS 15.0 Workbench. The following Figure shows the schematic diagram of the hearth

Fig 1: Schematic diagram of the hearth used in the study

a. 2D modelling of only hearth using Fluid Flow (FLUENT):

i. Geometry

1) Select "Fluid Flow (FLUENT)" under "Analysis Systems".
2) Click on "Geometry".
3) Change the "Analysis type" to 2D under "Advanced Geometry" option in the right hand side corner.
4) Double click on "Geometry". Another window will be opened.
5) Select "Meter" for defining geometry dimensions.

6) Click on "Sketching", then on "Settings".
7) Select "Grid". Turn on 2d and Snap option.
8) Select "Poly line" under "Draw".
9) Draw the diagram as per the given dimensions.
10) Click on "Coincide" under "Constraints" command and fix one side of the hearth with the Y-axis.
11) Assign proper dimensions to the Figure under "Dimensions" command.
12) Go to "Concept". Select "Surfaces from Sketches".
13) Click on the base line of the geometry. Then click on "Apply" in left hand side bottom corner.
14) Then "Generate" the diagram.

The diagram will look like this:
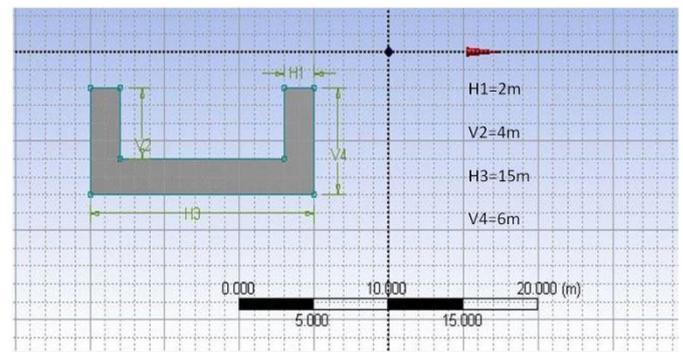
Fig 2 : Hearth model

15) Close the window and "Update Project".

ii. Meshing:

1. Double click on "Mesh". A new window will be opened.
2. Click on "Mesh".
3. Select "Fine" "Relevance Centre" under "Sizing".
4. Then "Generate Mesh".
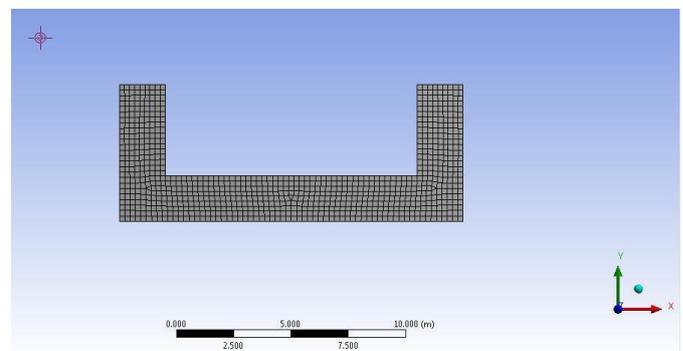
Fig 3: Meshing of the model

5) Select "Edge". Select the upper part of hearth base and right click on that part and select "Create Named Section" under that. Write "Inner Wall". Then follow the same process for outer wall of the hearth.

The "Inner Wall" and "Outer Wall" will look like this:
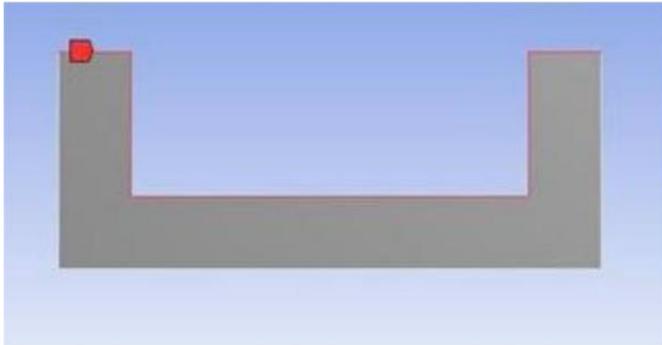
Fig 4 (a): Inner Wall

Fig 4 (b): Outer Wall

6) Close the window and "Update Project".

iii. Setup

1) Double click on "Setup". Select "Double Precision" option. A new window will be opened showing a diagram like this:
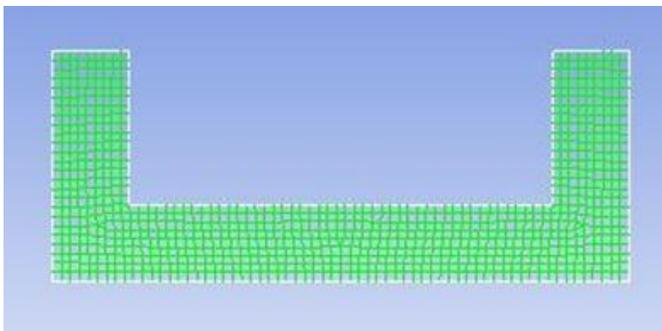
Fig 5: Initial setup diagram

2) Go to "Models" under "Solution Setup". Turn on the "Energy" equation.

3) Go to "Materials", select "Solid". Click on "Create/Edit". Create new carbon material and assign the density, specific heat and thermal conductivity values of carbon.

4) Select the type of the "surface body" under "Cell Zone Conditions" as "Solid". Edit the "Surface body" to "Carbon".

5) Go to "Boundary Condition". Click on "Inner Wall". "Edit" it. Select "Thermal". Set the temperature at 1700 K. The same process is repeated for assigning boundary condition for "Outer wall". Outer wall is at room temperature i.e. 300 K.

6) Then "Edit" the "Residual, Statistics and Force" under "Monitors". Change the energy value to 1e-15.

7) Select "Solution Initialisation" under "Solution" option. Select Initialisation Methods as "Standard Initialisation". Compute from "Inner Wall" and then "Initialise".

8) Select "Run Calculation" under "Solution". Take 50 numbers of iterations. Click on "Calculate".

9) Go to "Graphs and Animation" under "Results". Click on "Contours" under "Graphics". Select contours of "Temperature". Select "Filled" under "Option". Click on "Display".

The result of the temperature distribution profile will be displayed.

b. 2D modelling of hearth containing only hot metal by using Fluid Flow(FLUENT):

i. Geometry:

The hearth geometry was prepared in the same way as in the previous case. This time the geometry of hearth was designed only to model the hot metal part. The following Figure shows the hearth diagram:
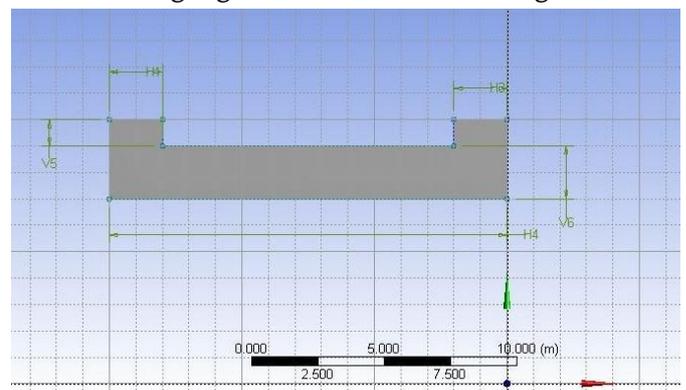
Fig 6: Hearth model

The following steps state how to generate fluid (hot metal) inside the hearth.

1) Click on "New Sketch". Select "Sketch2".

2) Now select "Poly line" under "Draw" and plot a rectangular part. "Coincide" its edges with the inner walls of the hearth under "Constraints" command.

3) Then "Generate" "Surface from Sketches".

4) Change the "Operation" to "Add Frozen" for both the surface sketches.

5) Select both "Surface Body" under "2 Parts, 2 Bodies" and "Form New Part".

6) Change the details of the newly formed part by assigning proper "Solid" and "Fluid" type for hearth and molten metal, respectively.

The 2 parts model is shown below:
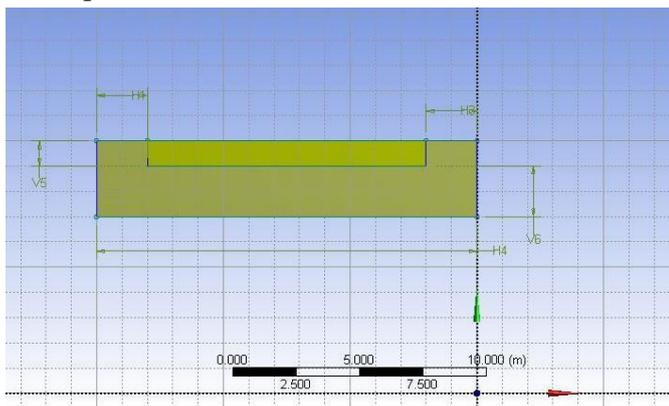
Fig 7: Model of hearth and hot metal

ii. Meshing

Same steps are followed for meshing as in the previous case. Mesh size can be made finer as per requirement by changing the relevance centre. The following picture shows the hearth body after meshing.
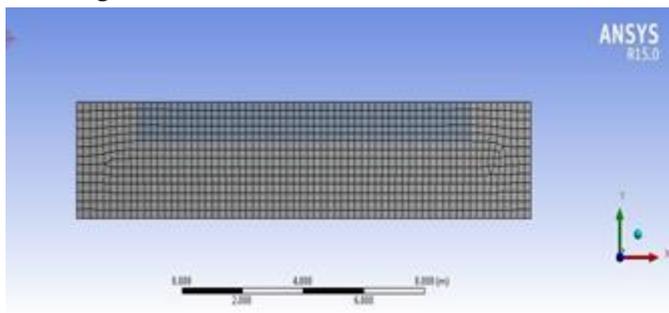
Fig 8: Meshing of two part body

Here the only change is in assigning the "Named Selection". The upper part of the hearth metal is named as "Input". Then follow the same process for naming the outer wall of the hearth.

The "Input" and "Outer Wall" will look like this:
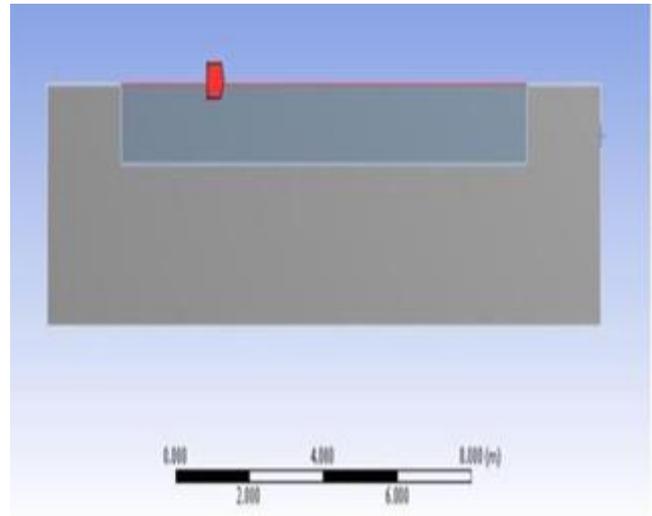
Fig 9 (a): Input
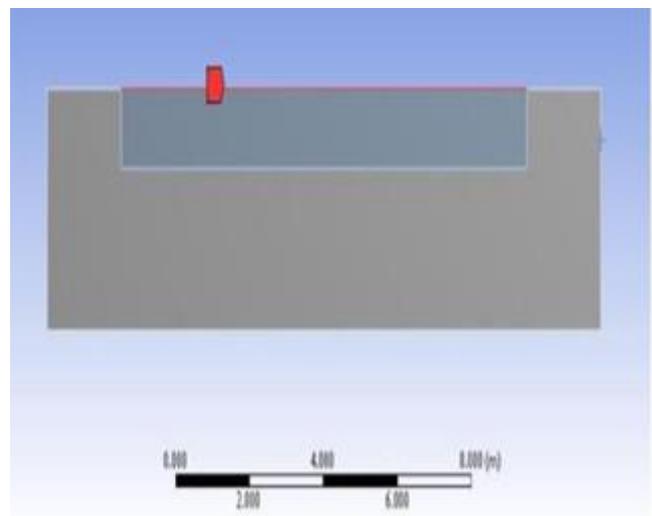
Fig 9 (b): Outer Wall

i. Meshing : Setup

1) Double click on "Setup". Select "Double Precision" option. A new window will be opened showing a diagram like this:
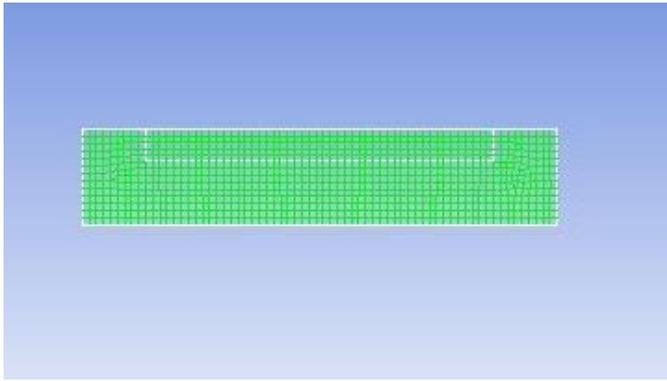
Fig 10 : Initial Setup Diagram

2) Go to "Models" under "Solution Setup". Turn the "Energy" equation on.

3) Go to "Materials", select "Fluid". Create new fluid material ("Molten Iron" in this case) by editing it and assign its physical properties such as density, specific heat and thermal conductivity. Repeat the procedure for "Solid" as done in the previous case.

4) Go to "Cell Zone Conditions". Select "fluid-part-surface body". Set the type as "Fluid". Change the material name to "Molten Iron". Then select "part-surface body". Here type is "Solid". "Edit" it to change the material name to "Carbon".

5) hen go to "Boundary Condition". Click on "Input", then on "Edit". Select "Thermal". Set the temperature at 1800 K. The same process is repeated for assigning boundary condition for "Outer wall". Outer wall is at room temperature i.e. 300 K.

6) Then "Edit" the "Residual, Statistics and Force" under "Monitors". Change the energy value to 1e-15.

7) Select "Solution Initialisation" under "Solution" option. Select Initialisation Methods as "Standard Initialisation". Compute from "Inner Wall" and then "Initialise".

8) "Run Calculation" under "Solution". Take 50 iterations. Click on "Calculate".

9) Go to "Graphs and Animation" under "Results". Click on "Contours" under "Graphics". Select contours of "Temperature". Select "Filled" under "Option". Click on "Display".

The result of the temperature distribution profile will be displayed.

c. 2D modelling of hearth containing both hot metal and molten slag by using Steady-State Thermal:

i. Geometry:

1) Select "Steady-State Thermal" under "Analysis Systems"

2) Draw the 3 body, 3 part diagram by following the steps of second case and "Generate" the diagrams by applying "Surfaces from Sketches".

3) Change the "Operation" to "Add Frozen" for all the surface sketches.

4) Select 3 "Surface body" under "3 Parts, 3 Bodies" and "Form New Part".

5) Change the "Details" of the newly formed part by assigning proper "Solid" and "Fluid" types for hearth, slag and molten metal.

The following Figure shows the 3 part body of hearth
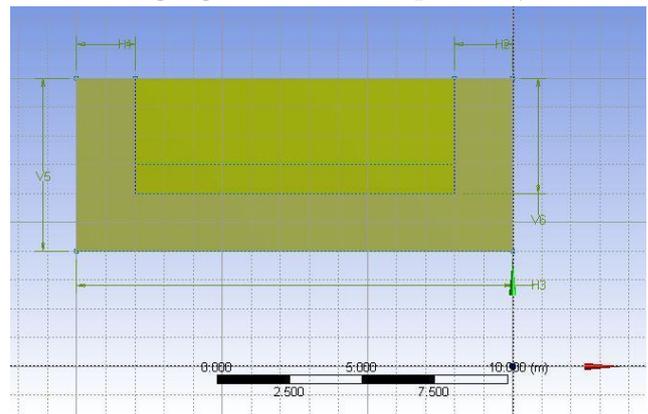
Fig 11: Model of hearth, hot metal and slag

ii. Engineering Data

1) Double click on "Engineering Data".

2) Add new "Carbon" material. Click on "Filter Engineering Data". Select "Density" from "Physical Properties" and assign the density value of carbon. Select "Isotropic Thermal Conductivity" from "Thermal" and assign the corresponding value. Also give the value of "Specific Heat" of carbon.

3) Add new hot metal and slag and follow the same procedure to assign the values of various physical quantities for respective materials.

4) Close the "Engineering Data" and "Update Project".

iii. Modelling

The following Figure shows the model obtained after meshing.
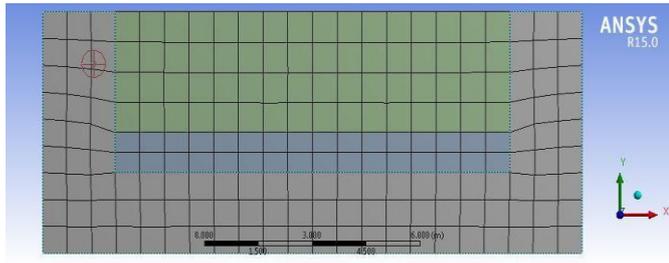
Fig 12: Meshing of three part body

1) Double click on "Model".

2) Select hearth surface body under "Part" of "Geometry". Assign the thickness of hearth and select "Carbon" "Material" as the "Assignment".

3) Then follow the same step to assign the thicknesses of slag and hot metal.

4) Click on "Mesh". Make the "Relevance Centre" "Fine" and "Generate Mesh".

5) Select "Steady-State Thermal" and "Insert" Temperature". Click on "Edge" and then select the upper part of the slag surface. Then "Apply" at the "Geometry". Give the temperature "Magnitude" 1600°C.

6) Follow the same procedure to add one more temperature condition to give the temperature "magnitude" at the "Outer Wall" 270°C.

7) Change "Number of Steps" to 50 at "Analysis Settings" under "Steady-State Thermal".

8) Then "Insert" "Temperature" under "Thermal for "Solution". Then "Solve".

III. MATERIAL PROPERTIES

The following table shows the standard values of model parameters [5].

Table 1: Physical properties of the material used in the simulation

	Density (Kg/m^3)	Specific Heat (J/Kg-K)	Thermal Conductivity (W/m-K)
Carbon	2267	7000	2705
Hot Metal (Iron)	1260	850	-
Slag	15.5	16.5	5.4

a. Governing Equations:

In our simulations, we have used only the conduction equation. Conduction refers to the heat transfer between two bodies through molecules which are, r less, static [14].

Fourier's law of heat conduction states that the rate heat transfer is linearly proportional to the temperature gradient. Mathematically, proportional to the temperature gradient.

It is a property of the material thorugh which heat propagates. This property of the material is called thermal conductivity (W/m-K). The negative sign in the temperature gradient shows that the heat flows from a high temperature to a low temperature. So, the slope dT/dx is negative. Since we consider temperature difference in the temperature gradient term, we can take the temperature either in OC or in Kelvin (10°C = 1 K).
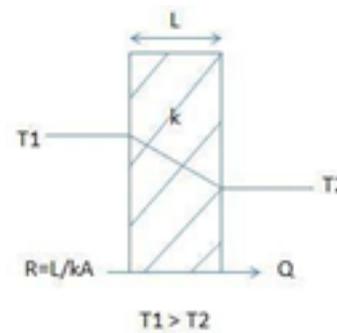

Fig 13: Thermal resistance offered by a wall of thickness L

For the simple case of steady-state one-dimensional heat flow through a plane wall of thickness L, the temperature gradient and the heat flow do not vary with time. So, by integrating the equation (3.1) with its proper limits, we can write:

where, the temperature at the left surface (at x=0) is uniform at T1 and the temperature at the right face (at x=L) is uniform at T2.

Since k is independent of T, after integration, we obtain:

If A is the cross sectional area of the surface normal to the heat flow, then the rate of heat transfer is given by:

If cross sectional area is unity, then the above equation becomes:

Let us consider the case of a composite wall of unit cross sectional area.
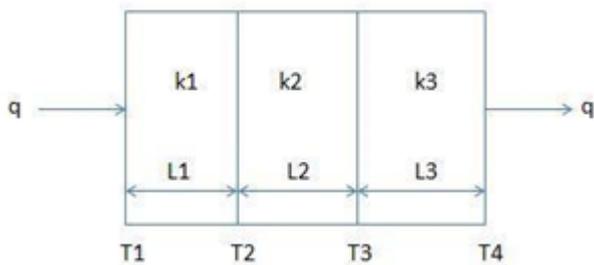

Fig 14: Conduction through three resistances in series

For a composite wall, as shown in Fig 16, there are three resistances in series. The rate of heat conduction is the same through all sections. The total thermal resistance is given by:

R = R1 + R2 + R3 = (L1 / k1) + (L2 / k2) + (L3 / k3)

The rate of heat conduction is given by:

Q = (T1 - T2) * (k1 / L1) = (T2 - T3) * (k2 / L2) = (T3 – T4) * (k3 / L3) (3.5)

Simulation of only hearth:

Assumptions:

The following assumptions were made during the simulation:

The process is a steady-state process.

The presence of hot metal and slag is neglected.

The presence of refractory fireclay brick is not taken into account.

Chemical reactions due to slag and hot metal are neglected.

Boundary conditions:

The following boundary conditions are imposed.

The temperature of the inner side of the hearth is taken to be 1450°C (1700 K).

The temperature of the outer walls of the hearth is taken to be 270°C (300 K).

The top surface of the refractory wall is adiabatic.

The process is a two dimensional heat transfer process.

Cross sectional area is taken to be unity.
Temperature profile:

The following Figure shows the number of iterations taken to complete the simulation process.
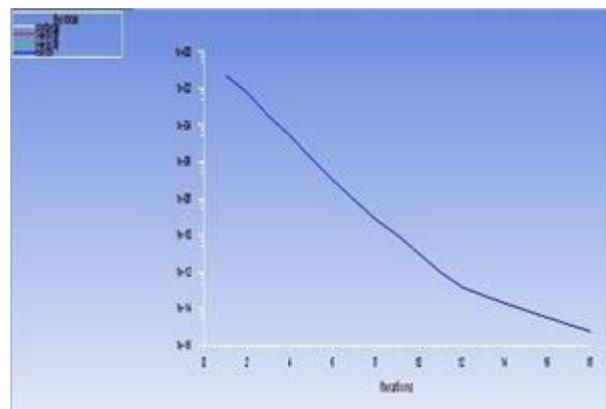

Fig 15: Convergence of the simulation

The temperature profile obtained after the simulation process is shown below.
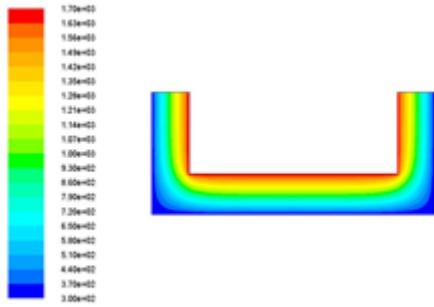
Fig 16: Temperature distribution profile across the section of the hearth

Simulation of hearth containing hot metal:

Assumptions:

The following assumptions were made during the simulation:

The process is a steady-state process.

The presence of slag is neglected.

The presence of refractory fireclay brick is not taken into account.

Chemical reactions between hearth and hot metal are neglected.

The free surface of liquid iron is flat and horizontal.

Solidification is neglected.

Heat transfer takes place by conduction.

There is no mass transfer between the liquid iron and refractory walls.

Boundary conditions:

The following boundary conditions are imposed.

The liquid iron level is constant.

The top surface of the refractory wall is adiabatic.

The temperature of the outer surface of the molten hot metal is taken to be 1550°C (1800 K).

The outer walls of the hearth are at room temperatures i.e. at 270°C(300 K).

The process is a two dimensional heat transfer process.

Cross sectional area is taken to be unity.

Temperature profile:

The following Figure shows the number of iterations taken to complete the simulation process.
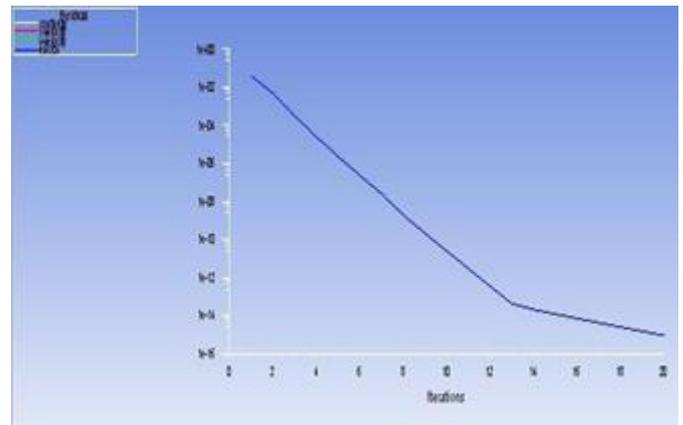

Fig 17: Convergence of the simulation

The temperature profile obtained after the simulation process is shown below.
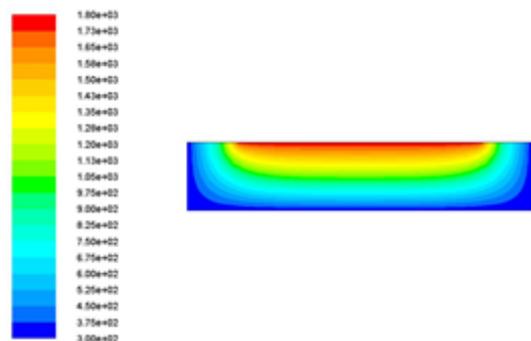
Fig 18: Temperature distribution profile across the section of the hearth

From the temperature distribution contour, it is observed that the temperature at horizontal interface of the hearth and hot metal is around 1300 K. By solving the governing equation (3.5), we obtain the temperature value to be 371 K. This large discrepancy between the observed and calculated temperature value may be due to too much of assumptions.

Simulation of hearth containing both hot metal and molten slag:

Assumptions:

The following assumptions were made during the simulation:

The process is a steady-state process.

The presence of refractory fireclay brick is neglected.

Chemical reactions between hearth, hot metal and slag are not considered.

The free surface of molten slag is flat and horizontal.

Solidification is neglected.

Heat transfer takes place by conduction.

There is no mass transfer between the slag, liquid iron and refractory walls.
There is no mixing of liquid metal and slag.

 Boundary conditions:

· The following boundary conditions are imposed.

· The temperature of the outer surface of the molten slag is taken to be 1600℃ (1900 K).

· The outer walls of the hearth are at room temperatures i.e. at 270℃ (300 K).

· The liquid iron level is constant.

The top surface of the refractory wall is adiabatic.

The process is a two dimensional heat transfer process.

Cross sectional area is taken to be unity.

Density of slag is taken for 16.3% FeO, 2.06% Fe2O3, 33.4% CaO, 10% MnO and 38.2% Si contents.

. Modeling by using Steady-State Thermal:

In case of more than two solid-solid, solid-liquid or liquid-liquid systems, it is impossible to differentiate between materials those are in same phase using Fluid Flow (FLUENT) which creates problem at the time of giving boundary conditions. Moreover, since we are using only conduction method for heat transfer, it is advantageous to use Steady-State

Thermal instead of Fluid Flow (FLUENT). We don't need to assign density, viscosity or any other fluid material properties for simple heat transfer problem. We can add as many parts as we want to a given system without facing any difficulty while assigning boundary conditions.

Temperature profile:

The following Figure shows the temperature profile obtained after the simulation process.
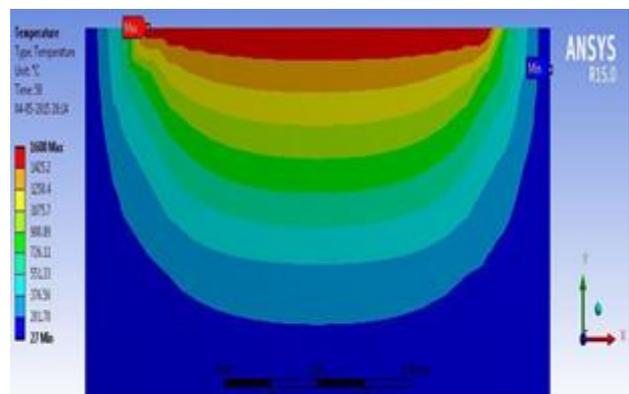
Fig 19: Temperature distribution profile across the section of the hearth

From the temperature distribution contour, it is observed that the temperature at horizontal interface of the hearth and hot metal is around 640°C. By solving the governing equation (3.4) and (3.5), we obtain the temperature value to be around 500°C. Again, the temperature at the horizontal interface of hot metal and molten slag is observed to be 900°C. From calculation, the temperature is found out to be around 1500°C. This large discrepancy between the observed and calculated temperature value may be due to too much of assumptions which lead to imprecision in simulation conditions.

IV. CONCLUSION

A simple blast furnace hearth is modelled by using ANSYS 15.0 Workbench. Several simulations are run with the help of Fluid Flow (FLUENT) and Steady-State Thermal. Only hearth, hearth with hot metal and hearth with hot metal and molten slag are the three cases which are considered for simulation program. Their temperature distribution profiles are displayed and studied. The discrepancy between the observed and the calculated data may arise from the use of too many assumptions in implementing the boundary conditions. We need to work on a few areas to overcome this problem.

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Cite this article as :