Numerical investigation of temperature distribution in blast furnace hearth

Divyesh Ubale¹, Prafulla Ubale²
Indian Institute of Technology Bombay, Mumbai, Maharashtra, India¹
GS Science, Arts and Commerce College, Khamgaon, Maharashtra, India²

*Email: ubaledivyesh@gmail.com

Abstract. Erosion of the Blast Furnace hearth affects the life of the Blast Furnace. High temperature across the molten iron and hearth makes it difficult to measure temperature in real life. Temperature prediction inside the hearth is a complex process as it involves conjugate heat transfer. A CFD model is developed for analysing the temperature distribution across slag, molten iron and hearth. It is essential for estimating the life of Blast Furnace and the wear rate of hearth. Three different cases are analysed and the temperature profiles are plotted. The CFD results are validated with the published experimental results in the literature. Only temperature effects are considered and natural convection effect is neglected for the analysis of hearth.

Keywords. Blast Furnace Hearth, Computational Fluid Dynamics (CFD), Conjugate Heat Transfer, Molten Iron

1. Introduction

Blast Furnace is used to produce pig iron. The main parts of blast furnace are Hearth, Stack, Belly, Bosh, Tuyeres. The charge is supplied from the top of blast furnace at room temperature. It consists of fuel, iron ore and flux. The coke moves down to the hearth surface and a hot blast of air is introduced through tuyeres at lower section. Preheated air on coming in contact with coke forms heat and gases. This takes place inside the cavity which is formed around the tuyere exit. These gases and heat are used to produce hot metal and molten slag [1].

The erosion of hearth is mainly a thermal process. CFD models are effective especially when the temperature measurement inside the plant in working conditions is impractical or expensive. Panjkovic et al. [2] established a CFD model which calculates the flow and temperature distributions in molten iron and hearth. The experimental data obtained from plants BHP Steels Port Kembla No. 5 blast furnace and One Steels Whyalla no. 2 blast furnace is compared with the CFD results and the results are found to be in good agreement. Guo et al. [3] developed numerical models. In these models simulation of the flow, heat transfer and mass transfer takes place mainly in the hearth lower part. The numerical model facilitated the mechanisms for erosion of lining and protection of the base wall in hearth. The three aspects dealt were first the Flow of Gas and the liquid surface pressure; second the Flow of molten iron inside the hearth and their temperature distributions in the refractories; and third
aspect involves injection of Titania on the hearth refractory surface. This injection leads to protection of the hearth surface from erosion. It was observed that a stagnant flow zone exists at the bottom. Preuer et al. [4] developed a mathematical model for the dissolution of carbon from the wall of hearth. Numerical Investigation was carried out to predict the rate of erosion with the use of this process. This includes different dissolution conditions in the coke and at the wall and the bottom which were experimentally investigated. Good agreement was observed between the actual wear line profiles and the predicted ones.

Huang et al. [5] investigated the flow behaviour of hot molten metal in the hearth of a blast furnace. Blast Furnace hearth no. 2 at China Steel Corporation (CSC) was selected for obtaining the temperature data. To analyze the flow behaviour and heat transfer at various operating conditions numerical model was developed. 3D Navier–Stokes equations were used considering the effect of conjugate heat transfer and Darcy law. These equations are solved by CFD for hot molten metal which flows through the deadman. It was observed that temperature in the hearth corner increases and temperature gradient is observed. Vernengo et al. [6] investigated the temperature distribution in hearth of the blast furnace using CFD on the basis of simplified structure of deadman. Effect of deadman porosity is considered.

Zhou et al. [7] investigated the combined effect of hot metal flow and the conjugate heat transfer on the blast furnace hearth. Validation of results was done using measurement data from Mittal Steel old, new IH7 blast furnace and U.S. Steel 13 blast furnace. Wear patterns of different furnaces were analysed at different operating conditions. Inner profile of hearth can be predicted based on the study. Shibata et al. [8] used two dimensional model and found the behaviour of formation of coke regions in a blast furnace hearth. Various experiments were performed and it was observed that the carbon solubility changes in molten iron. This change is due to the temperature fluctuations. This then enters into the refractories and thermal expansion is observed in the refractories. This thermal expansion leads to large thermal gradients and erosion of furnace wall takes place.

This paper mainly focuses on temperature distribution inside hearth and its effect on wall surfaces. CFD analysis is carried out for three different cases. Temperature distribution inside the hearth involves conjugate heat transfer. Similar conjugate heat transfer phenomenon is observed in various heat transfer devices [9-12].

2. Geometric Modelling

Model is Prepared in ANSYS 16.2 Design Modeler with base of 16 m as per [5] and height of hearth is choosen as 6 m considering the effect of molten iron and slag. Three Different geometries corresponds to three different cases containing Hearth; Hearth and Molten iron; Hearth, Molten Iron and Slag. Hearth is considered as Symmetric. Geometry of Blast Furnace Hearth is as shown in figure 1.
3. Assumptions

The following assumptions are made for carrying out the simulation:

1. Steady-State process is used.
2. The top surface of refractory wall is adiabatic. Inlet boundary condition is the top surface of liquid molten iron (or slag in case of slag as top surface) and the outer wall of hearth is at constant temperature and is the outlet boundary condition.
3. Coupled Wall boundary condition with negligible thickness is assumed between the conducting linings of slag-hot metal, hot metal-hearth.
4. The presence of refractory fireclay brick is neglected.
5. Chemical reactions between hearth, hot metal and slag are not considered.
6. The free surface of molten iron and slag is flat.
7. Solidification is neglected.
8. 2D Heat transfer takes place and the mode is conduction.
9. The slag, liquid iron and refractory walls have no mass transfer between them.
10. No mixing takes place between liquid metal and slag.

4. Governing Equations

Governing Equations used for carrying out simulations are as per paper [2].

The continuity and momentum equations:

\[ \nabla \cdot (\rho \mathbf{u}) = 0 \]  
\[ \nabla \cdot (\rho \mathbf{u} \times \mathbf{u}) - \nabla \cdot (\mu_{eff} \nabla \mathbf{u}) = -\nabla P + \nabla \cdot (\mu_{eff} (\nabla \mathbf{u})^T) + \beta \rho g (T - T_{ref}) + S_u \]  

Boussinesq approximation is valid in these simulations. The flow resistance occurs in the porous medium and is given by last term in (2).

The resistance force is obtained with the help of Ergun’s equation and is given as:

\[ S_u = -150 \mu_t \frac{(1-\gamma)^2}{\gamma^2 d^2} |u| - 1.75 \rho \frac{1-\gamma}{\gamma d} |u|^2 \]  

Where Bed Voidage (\(\gamma\)) = 0.35

The effective viscosity is the sum of laminar and turbulent viscosities and is given by,

\[ \mu_{eff} = \mu_L + \mu_T \]  

5. Material Properties [2]:

1. Carbon:
   Density (\(\rho\)) : 2267 \(\frac{kg}{m^3}\)
   Specific Heat (\(C_p\)) : 1260 \(\frac{j}{kg - k}\)
   Thermal Conductivity (\(k\)) : 18 \(\frac{w}{m - k}\)
2. Molten Iron:
Density (ρ) : 7000 \( \frac{kg}{m^3} \)
Specific Heat \((C_p)\) : 850 \( \frac{j}{kg\cdot K} \)
Thermal Conductivity \((k)\) : 16.5 \( \frac{w}{m\cdot K} \)
Viscosity \((\nu)\) : 0.00715 \( \frac{kg}{m\cdot s} \)

3. Slag:
Density (ρ) : 15.5 \( \frac{kg}{m^3} \)
Specific Heat \((C_p)\) : 16.5 \( \frac{j}{kg\cdot K} \)
Thermal Conductivity \((k)\) : 5.4 \( \frac{w}{m\cdot K} \)

6. Results and Discussion

6.1 Case I: Temperature Distribution along Hearth.
The Geometry is meshed using ANSYS Mesh and consists of 930 nodes and 824 elements. Inlet Temperature is 1700 K and Outer Wall Temperature is 300 K. SIMPLE algorithm was applied and First order upwind scheme was used to discrete the convective term of equations. ANSYS 16.2 Fluent was used for the simulation results considering the effects of conjugate heat transfer and the results are obtained as shown in figure 2.

![Figure 2. Static Temperature (K) contours along Hearth (Inlet temperature 1700 K)](image)

6.2 Case II: Temperature Distribution along Hearth and Molten Iron.
The Geometry is meshed using ANSYS Mesh and consists of 1512 nodes and 1411 elements. Inlet Temperature is 1800 K and Outer Wall Temperature 300 K is used in this analysis. The results are obtained as shown in figure 3.
Figure 3. Static Temperature (K) Contours along Hearth and Molten Iron (Inlet temperature 1800 K)

6.3 Case III: Temperature Distribution along Hearth, Molten Iron and Slag.
The Geometry is meshed using ANSYS Mesh and consists of 1704 nodes and 1615 elements. Inlet Temperature is 1873 K and Outer Wall Temperature is 300 K.

Figure 4. Static Temperature (K) Contours along Hearth, Molten Iron and Slag (Inlet temperature 1873 K)

From figure 4 it can be seen that temperature at the top surface is 1873 K which is the inlet temperature as defined in Fluent. The top layer is of Slag, middle layer of molten iron and the bottom is hearth. Temperature at the height of 1 m from top surface shows that at the center the temperature is uniform while large temperature gradients are observed near the sidewall. These temperature gradients increase as we move further down. Temperature at the height of 4 m from top surface is around
1240 K. The temperature at some distance from outlet is uniform as the outer wall surface is exposed to cooling water which maintains the temperature to be constant at 300 K. The 1423 K temperature isotherm was used as a base to calculate erosion profile in the hearth lining. Because carbon saturated iron do not exist in liquid form below this temperature. Hence the maximum hot metal temperature that can penetrate inside the hearth lining is based on this isotherm temperature. Though the inlet conditions (in current paper and [14]) are different, Temperature distribution in Current CFD Analysis matches (approximately) with paper by Komiyama et al.

| Table 1. Comparison of results at various heights from top surface of Blast Furnace Hearth |
|---------------------------------|-------------------------------------------------|-------------------------------------------------|
| Temperature at top surface of Hearth (in case III) | Current CFD Analysis | Komiyama et al. [14] |
| Temperature at distance of 2 m from top surface of Hearth | 1560 K | 1518 K |
| Temperature at distance of 4 m from top surface of Hearth | 1240 K | 1061 K |
| Temperature at distance of 5 m from top surface of Hearth | 457 K | 451 K |

Real shape of interior of hearth has significant effect on temperature distribution. CFD results in this paper and the experimental results as mentioned in the above literature [2, 3, 5, 13, 14] matches very well. The result from current CFD analysis is compared with the results from published paper of Komiyama et al. as shown in Table 1. The distances measured approximately from top surface are correlated with the temperatures. The widths of both the hearths are different so there is slight difference in temperatures. The erosion takes place due to the circulation of molten iron at the bottom of the hearth. Also it is observed that the temperature at the bottom of the hearth is almost average of the hot and cold temperature. It is observed that the molten iron enters the hearth and has greater temperature at the center of hearth as compared to edges of walls. The heat is then transferred to refractory brick. The temperature of liquid iron is uniform due to better mixing. The velocity of molten iron due to pouring and buoyancy forces near to the sidewalls induces shear stress to the sidewalls which leads to erosion [14]. Also at the sidewall a larger temperature gradient is observed in all three above cases. This leads to higher thermal buoyancy force. It also leads to vortex like flow giving rise to recirculation and hence erosion at the corner of the hearth. Erosion of refractory wall creates narrow zone causing increase in heat losses and therefore large thermal gradients are observed.

7. Conclusion

Blast furnace hearth is modeled using ANSYS workbench and simulations are carried out at steady state to investigate the temperature distribution using ANSYS Fluent 16.2 for three different cases (Hearth; Hearth and Molten Iron; Hearth, Molten Iron and Slag) with conjugate heat transfer. Temperature contours are plotted for these cases and erosion of hearth due to different factors is studied. Only the effects due to hot metal iron flow and temperature gradients on the surface of hearth are considered for erosion analysis. A good agreement was found between the temperature contours generated using CFD and the experimental results of plants as reported in different literatures. A large temperature gradient is observed at the sidewall in all the three cases which leads to higher thermal buoyancy force and there is also some amount of recirculation due to mixing giving rise to erosion of surface.

References

[1] Du SW, Chen WH and Lucas JA, 2010, Pulverized coal burnout in blast furnace simulated by a drop tube furnace, Energy, 35, pp 576-81.
[2] Panjkovic V, Truelove JS and Zulli P, 2002, Numerical modelling of iron flow and heat transfer in blast furnace hearth, Iron making and Steel making, 29(5), pp 390-400.

[3] Guo BY, Yu AB, Zulli P and Maldonado D, 2011, CFD modeling and analysis of the flow, heat transfer and mass transfer in a blast furnace hearth, steel research international, 82, pp 579-86.

[4] Preuer A, Winter J and Hiebler H, 1992, Computation of the erosion in the hearth of a blast furnace, steel research, 63(4), pp 147-151.

[5] Huang CE, Du SW and Cheng WT, 2008, Numerical Investigation on hot metal flow in blast furnace hearth through CFD, ISIJ International, 48(9), pp 1182-87.

[6] Vernengo S, Milanovic R and Zhou CQ, 2003, Computations of liquid flow and heat transfer in the hearth of a blast furnace, ASME International Mechanical Engineering Congress Washington DC, pp 1-10.

[7] Zhou CQ, Huang D, Zhao Y and Chaubal P, 2010, Computational fluid dynamics analysis of 3D hot metal flow characteristics in a blast furnace hearth, Journal of Thermal Science and Engineering Applications, 2, pp 0110061-10.

[8] Shibata K, Kimura Y, Shimizu M and Inaba S, 1990, Dynamics of dead-man coke and hot metal flow in a blast furnace hearth, ISIJ International, 30(3), pp 208-15.

[9] Ubale D P, Umale S S and Gulhane N P, 2018, Experimental investigation of condensation heat transfer in vertical shell and helical coil heat exchanger, Advanced Science, Engineering and Medicine, 10(3-5), pp 398-402(5).

[10] Ubale D and Dr. Ubale P V, 2017, A critical review on flow, heat transfer characteristics and correlations of helically coiled heat exchanger, International Journal of Advance Engineering and Research Development, 4(9), pp 519-24.

[11] Ubale D P, 2017, Heat transfer enhancement in heat exchanger using twisted tape inserts: A review, International conference on ideas, impact and innovation in mechanical engineering(IJRITCC), 5(6), pp 425-28

[12] Ubale D and Ubale P V, 2018, Heat transfer and numerical analysis in microchannel heat exchanger using nanofluids : A review, International Journal of Scientific Research in Science, Engineering and Technology(IJSRSET), 4(9), pp 198-203.

[13] Cheng WT, Huang CN and Du SW, 2005, Three dimensional iron flow and heat transfer in the hearth of a blast furnace during tapping process, Chemical Engineering Science, 60, pp 4485-92.

[14] Komiyama KM, Guo BY, Zughbi H, Zulli P and Yu AB, 2014, Improved CFD model to predict flow and temperature distributions in a blast furnace hearth, Metallurgical and Materials Transactions B, 45(5), pp 1895-1914.