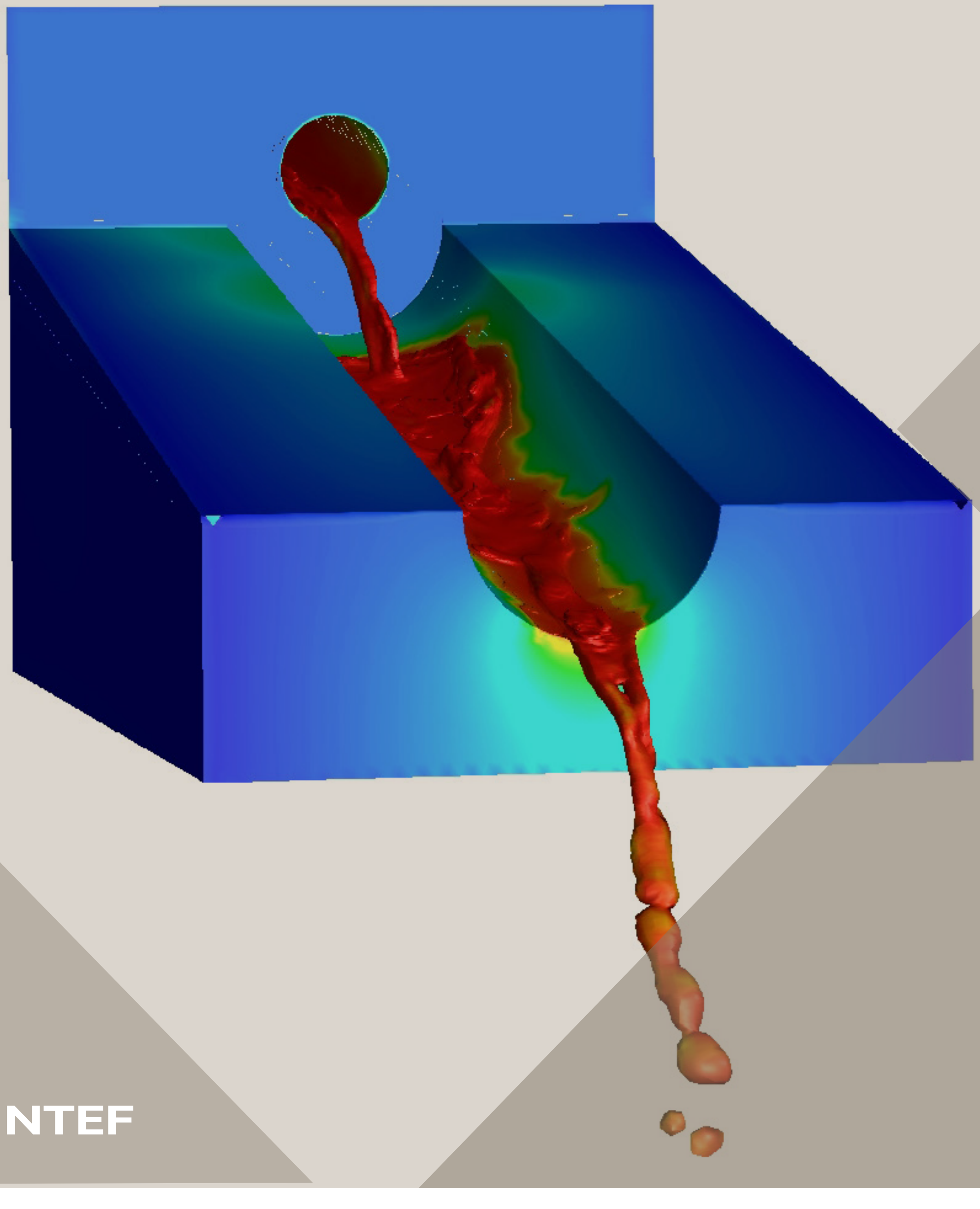
14th International Conference on CFD in
Oil & Gas, Metallurgical and Process Industries
SINTEF, Trondheim, Norway, October 12–14, 2020

SINTEF
PROCEEDINGS
6

Proceedings from the 14th International Conference on CFD in Oil & Gas, Metallurgical and Process Industries



SINTEF

SINTEF Proceedings

Editors:
Jan Erik Olsen, Jan Hendrik Cloete and Stein Tore Johansen

Proceedings from the 14th International Conference on CFD in Oil & Gas, Metallurgical and Process Industries

SINTEF, Trondheim, Norway
October 12–14, 2020

SINTEF Academic Press

SINTEF Proceedings 6
Editors: Jan Erik Olsen, Jan Hendrik Cloete and Stein Tore Johansen

Proceedings from the 14th International Conference on CFD in Oil &
Gas, Metallurgical and Process Industries, SINTEF, Trondheim,
Norway, October 12–14, 2020

Keywords:
CFD, fluid dynamics, modelling

Cover illustration: Tapping of metal by Jan Erik Olsen

ISSN 2387-4295 (online)
ISBN 978-82-536-1684-1 (pdf)

SINTEF Academic Press
Address: Børrestuveien 3
PO Box 124 Blindern
N-0314 OSLO
Tel: +47 40 00 51 00

www.sintef.no/community
www.sintefbok.no

SINTEF Proceedings
SINTEF Proceedings is a serial publication for peer-reviewed conference proceedings on a variety of scientific topics.
The processes of peer-reviewing of papers published in SINTEF Proceedings are administered by the conference organizers and proceedings editors. Detailed procedures will vary according to custom and practice in each scientific community.

COMPREHENSIVE MODEL FOR BLAST FURNACE USING OPENFOAM®

P. B. ABHALE[1]* , S. NAG[1], Y. BAPAT[2+], A. KULKARNI[2‡], N. N. VISWANATHAN[3#]**

[1] Tata Steel Ltd., Jamshedpur, INDIA

[2] Tridiagonal Solutions Pvt. Ltd., Pune, INDIA

[3] Centre of Excellence in Steel Technology, IIT Bombay, Mumbai, INDIA

***** E-mail: prakash.abhale@tatasteel.com
****** E-mail: samiknag@tatasteel.com
+ E-mail: yogesh.bapat@tridiagonal.com
‡ E-mail: ashish.kulkarni@tridiagonal.com
# E-mail: vichu@iitb.ac.in

ABSTRACT

Blast furnace is a complex, multi-phase and high temperature reactor involving multiple reactions between phases, heat transfer and phase change. Limited options are available to know internal state of the furnace through measurements using instruments or sensors. Hence, mathematical and numerical models play an important role in prediction of blast furnace performance.

Considering the complex nature of equations to model flow, heat transfer, phase change, reaction kinetics and coupling between them a robust framework is required. In this context, to take advantage of new computational paradigms in terms of flexibility offered through open source codes, OpenFOAM® is selected as the primary platform. It offers generic field operations and manipulation solvers for partial differential equations in conjunction with excellent scalability across multiple CPUs. A Comprehensive blast furnace model has been developed using OpenFOAM® with axi-symmetric solver.

The model is in implementation stage in the plant and typical simulation results compared with the field data are presented. In addition, the model can be used for scenario analysis, trend prediction, identification of shape and size of cohesive zone over range of process parameters.

Keywords:

Blast furnace, simulation and modelling, process model, OpenFOAM solver, process diagnostics, cohesive zone, CFD application to metallurgical process industry

NOMENCLATURE

Greek Symbols

ρ	Mass density, [kg/m^3].
φ	Velocity potential, [N/m^2].

Latin Symbols

M	Molecular weight, [kg/kmol].
K	Conductance in flow, [m^4/N s].
R	Universal gas constant, [J/kmol K].
$\dot{R}$	Reaction source term, [kg/m^{3}s].
T	Temperature, [K].
$\dot{V}$	Melting source term, [s^{-1}].
$f1$	Viscous resistance, [kg/m^{3}s].
$f2$	Inertial resistance, [kg/m^4].
p	Pressure, [Pa].
$\boldsymbol{v}$	Velocity, [m/s].

Sub/superscripts

g	Gas.
s	Solid.

INTRODUCTION

Blast furnace is a complex, multi-phase and high temperature reactor involving multiple reactions between phases, heat transfer and phase change. Depending on capacity of the furnace it can produce 2000 to 12000 tons of iron per day. In terms of size blast furnace can be as high as 60m and 15m in diameter. Iron ore and coke are charged from the top of the blast furnace to form a desired layered burden. At the periphery of the hearth top, wind and oxygen are blown through number of tuyeres at 1000^{0}C -1200^{0}C. The pulverized coal at ~80^{0}C is injected into tuyeres through lance. Temperature of gases reach to ~2200^{0}C due to partial combustion of coal and coke descending from the top. The resultant mixture of gas contains mainly CO, H_2 and N_2. The gas mixture acts as a reducing agent for ore, resulting in the production of iron ore. The measurements are mainly available at the periphery due to high temperatures inside the blast furnace. These are insufficient to know the internal state of the blast furnace. Hence, mathematical and numerical models play an important role in the prediction of blast furnace performance.

Several models were developed in the past and are reported in the literature (OMORI (1987)). A two dimensional gas flow model to predict gas distribution in the blast furnace was developed by (YAGI (1982)). In further improvements a comprehensive model involving three phases namely gas, solid and liquid was developed (CHEN (1993)). The model demonstrated that gas flow is mainly governed by layered burden and cohesive zone. The model was further refined by (AUSTIN (1997a)) and (AUSTIN (1997b)) by considering the effect of suspended fine particles as fourth phase and was thus named '*Four-Fluid*' model.

Nippon Steel developed '*BRIGHT*' model (MATSUZAKI (2006)), which used three interface model for ore reduction reaction. CRM Belgium in collaboration with then Arcelor and Corus developed another process model '*MOGADOR*' (DANLOY (2008)) to simulate the effect of gas distribution on ore reduction and also to predict the location of the cohesive zone. The model was validated for one of the European blast furnaces using multi-point vertical probing. Existence of another isothermal zone was found in the top region of the blast furnace due to burden moisture evaporation. A detailed review for numerical modelling of blast furnace is available in literature (P. B. ABHALE (2020)).

At IIT Bombay, India researchers have been working on modelling of the blast furnace using first principles with the financial support from NML Jamshedpur, Tata Steel Jamshedpur, and Gov. of India. In their approach, different sub models were developed from scratch using C programming language and were integrated to develop comprehensive mathematical model of blast furnace (P. B. ABHALE (2011)). However, the comprehensive model had bottlenecks in terms of computation time, robustness, and parallel execution. Thus, it was decided to look at the whole modelling exercise afresh and explore the possibilities of using some of the well-established CFD codes to be used for the modelling exercise.

In view of this, Tata Steel Ltd., Jamshedpur in collaboration with the Centre of Excellence in Steel Technology, IIT Bombay and Tridiagonal Solutions, Pune has developed 2-D comprehensive simulation system for the blast furnace. The model has been developed using OpenFOAM® platform. The model consists of multiple sub-models like layer descent, solid flow, gas flow, liquid flow. It also simulates heat transfer, reaction kinetics and species transport in all three phases. The model can predict different zones in blast furnace like lumpy zone, cohesive zone, dripping zone and deadman. The model has been named as '***BlaSim®***' (***Bla****st furnace* ***Sim****ulator*).

OpenFOAM® is an open source CFD framework for '*Field Operations And Manipulations'*. The OpenFOAM® provides generic framework for solution of PDEs in Finite Volume Framework (FVM) with operators for divergence, laplacian and gradient operations. It also provides easy adaptation for parallel computing environment.

MODEL DESCRIPTION

BlaSim® is a mathematical model assuming 2-D axisymmetric behaviour of a blast furnace. The assumption is reasonable as effect of discrete injection points for gas disappears after height of 3-4 m from tuyere the level (YAGI (1982)), (Y. G. SHEN (2015)) and (P. B. ABHALE (2009)) (P. B. ABHALE (2010)). The model limitation is accepted considering significant mesh count reduction leading to less computational time. It has multiple sub-models to describe different physical processes in blast furnace viz. layer descent, solid-gas-liquid flow models, enthalpy balance models of all phases, etc. To consider effects of mass and heat transfer among various phases due to reactions and melting, rate equations governing them are coupled with species balance equations of gas-solid-liquid phases through source terms. The formation of raceway due to blowing of air and its hysteresis was studied by (SARKAR (2007)). Similarly, 3-D raceway shape was obtained by detailed CFD model by (Y. S. SHEN (2011)). For the present model raceway shape is assumed and is used as a boundary for the domain. The is due to more fine grid requirements for combustion modelling, instead, simple mass and heat balance of the raceway is performed separately, and various boundary conditions are obtained for the comprehensive model.

Solution algorithm

The model is run in two steps. During the first step layer profiles in the blast furnace are predicted. The prediction is done using lagrangian tracking of layer profiles using predicted solid velocity field, which is obtained by solving solid flow equations Eq. (1) and Eq. (2) without melting term. The motion of solids is modelled using potential flow theory.

Solid flow equations (OMORI (1987))

$$\nabla.(K_s\nabla\varphi_s) = -\dot{V}_{melting,s} \qquad (1)$$

$$\vec{v}_s = -K_s\nabla\varphi_s \qquad (2)$$

Top repeating profiles of layers of ore and coke are represented by the massless particles (at given co-ordinates) which are then tracked using kinematic cloud solver of the OpenFOAM® till raceway. Further the points representing the final predicted layer profiles are converted into separate STL file for each layer. Generated STL files are then used to patch the layer structure on the mesh, which means that the each cell in the computation domain will either bear a ore, a centre coke, or a surface coke material, having distinct properties. The solution algorithm is as show in Figure 1.

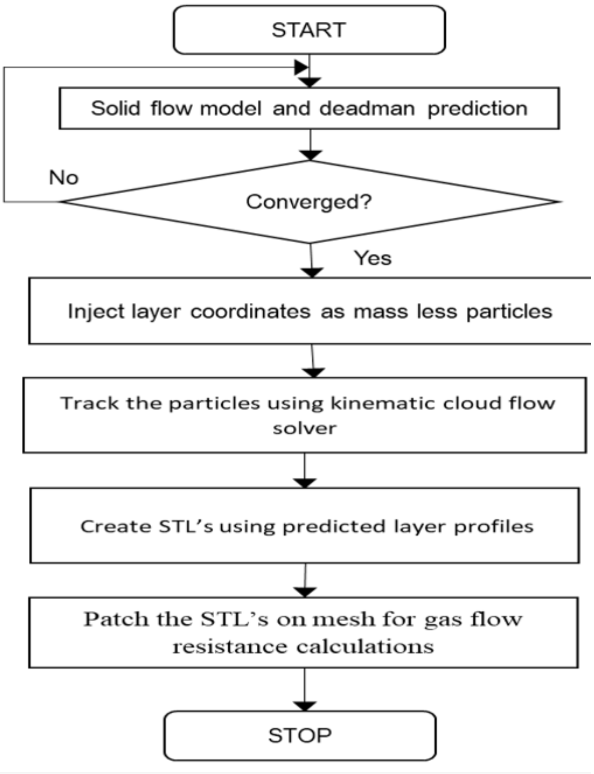


Figure 1: Solution algorithm

In the second step, layer profiles obtained are frozen and the information is mainly used to solve gas velocity fields. For all other models, layers are assumed to be well mixed for the calculation of average properties of the mixed burden. This is required to obtain the steady state results.

The flow of gas through a packed bed is modelled using Ergun equation, continuity and equation of state given by Eq. (3), (4), and (5).

Gas flow equations (OMORI (1987))

$$\left(f1 + f2\,\left|\vec{v}_g\right|\right)\vec{v}_g = -\nabla p \qquad (3)$$

$$\nabla.\left(\rho_g\vec{v}_g\right) = \dot{R_g} \qquad (4)$$

$$\rho_g = \frac{PM_g}{RT_g} \qquad (5)$$

The terms $f1$ and$f2$ in Eq. (3) are standard in chemical engineering to represent viscous, and inertial resistances, respectively to model gas flowing through a packed bed of particles.

As the gas flow is very sensitive to pressure drop within ore and coke layers, which offer widely varying resistances, it is important to get the correct estimates of the resistances in the blast furnace. There are number of ways available in the literature to get the correct estimates for a coarser orthogonal mesh (20x120), (P. B. ABHALE (2009)). However, this involves complex geometrical calculations for knowing layer intersections with the mesh and its inclinations for calculating representative anisotropic resistances.

In the present work much finer non-orthogonal mesh (~10000) is used for its simplicity and take advantage of high-performance CPU's with parallel compute environment provided by OpenFOAM®. The layer profile mapped on the mesh in the first step using STL is used to identify a type of material present in each mesh. Then using the material properties such as mean particle diameter, shape factor and voidage in each zone, resistances $f1$ and$f2$ are estimated. The

Eq. (3), (4), and (5) are solved to obtain gas velocity and pressure distribution.

Three step shrinking core model for ore reduction and homogeneous reaction model for coke gasification reactions are considered in solid phase. Water gas shift reaction, liquid wustite reduction, carbon dissolution and silicon transfer reactions are also considered. Details of all reactions are available in literature (OMORI (1987)). Source terms arising due to reactions and melting are applied to all the continuity equations involving volume, mass, and heat of all three phases. All the equations are solved to obtain steady state results. The complete solution algorithm for second step is given in Figure 2.

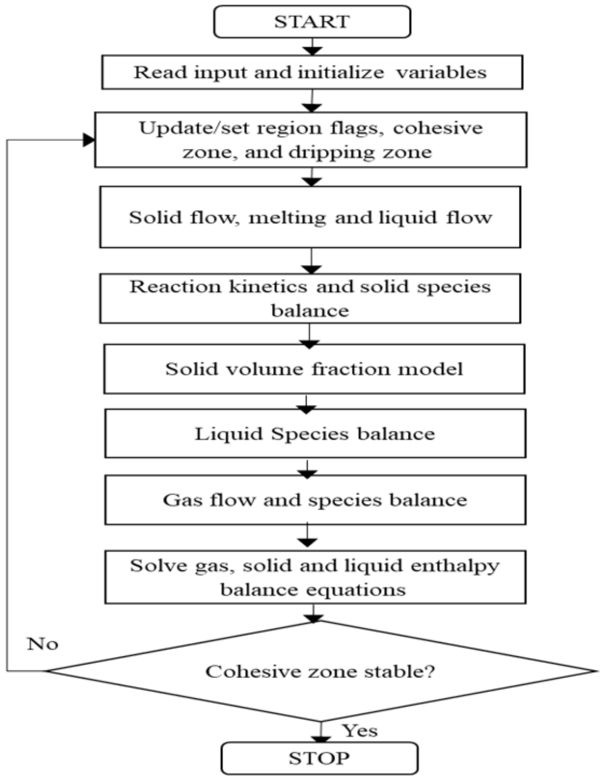


Figure 2: Solution algorithm

Geometry and mesh

The geometry of ‘H’ blast furnace of Tata Steel, Jamshedpur is used for the simulation. Mesh is created in Ansys such that it is one cell thick in the third direction. Cell count for the mesh is 9932. The mesh is converted to ‘polyMesh’ format used by OpenFOAM®. In OpenFOAM® axisymmetric simulation is performed by modifying mesh instead of modifying equations. ‘extrudeMesh’ utility available in OpenFOAM® is used to rotate the ‘polyMesh’ to create an axisymmetric mesh.

Boundary condition

Inputs required for the model are operating parameters, burden profile, burden properties, reaction kinetics parameters, boundary conditions, etc. First all operating and model parameters are provided in excel sheet. A python code is written to perform heat and mass balance of raceway to obtain raceway gas flow rate, temperature, and composition. Then another python utility is used to convert inputs in the format required by the model in OpenFOAM® format. The inputs provided below are from H blast furnace at Tata Steel, Jamshedpur

- Solid velocity at the top boundary = 0.002 m/s
- Solid temperature at the top = 303 K
- Top gas pressure =2.35 bar (abs)
- Gas mass flow rate for 2^{o}=0.8735 kg/s
- Flame temperature at raceway boundary = 2498 K
- Gas species mass fraction specified at raceway boundary
    - CO = 0.4617, H_2 = 0.0057, N_2 = 0.5326
- Softening temperature = 1373 K, Melting temperature = 1673 K

Thermodynamic data required for the model are obtained by fitting a polynomial to a data obtained from FactSage® for the required temperature range.

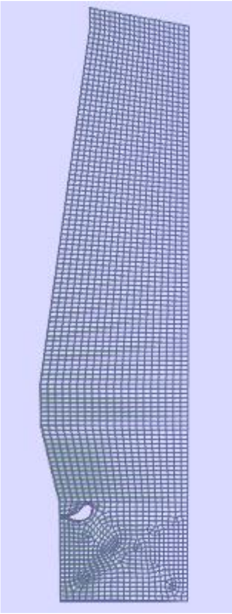


Figure 3: Mesh

Convergence check

As solution is steady state, monitors of important physical variables are used to monitor the convergence. When steady state is achieved, monitors become flat and solution can be stopped. Two such monitors are shown in Figure 4 and Figure 5. Volume weighted value of zone flags is used to plot the monitor. Definition of zone flag is given in Figure 6.

Results

As the model developed is complex and number of assumptions are made during mathematical modelling, to run the model some tuning is required. Tuning is performed by adjusting reaction kinetic parameters and heat transfer coefficients. The tuning is performed by matching results of the model for a particular date with plant measured Key Performance Indicators (KPIs). Once the tuning is done for a particular date the model is used to predict and match results. Results are presented in Table 1.

Simulations can be performed using parallel computations. Typical run time for 9932 cell mesh is about 40 minutes on four processors.

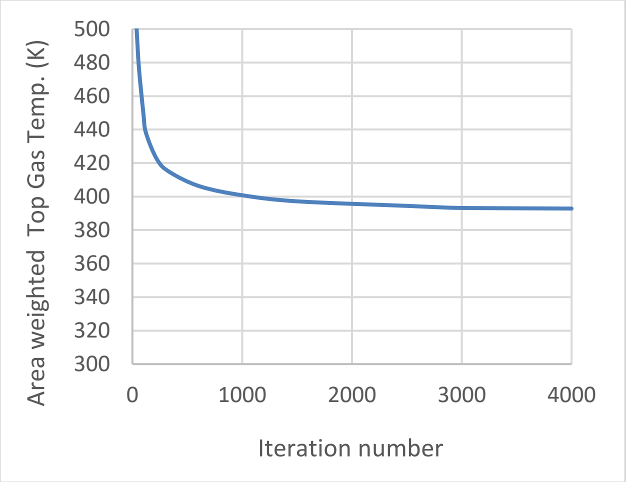


Figure 4: Monitor of top gas temperature

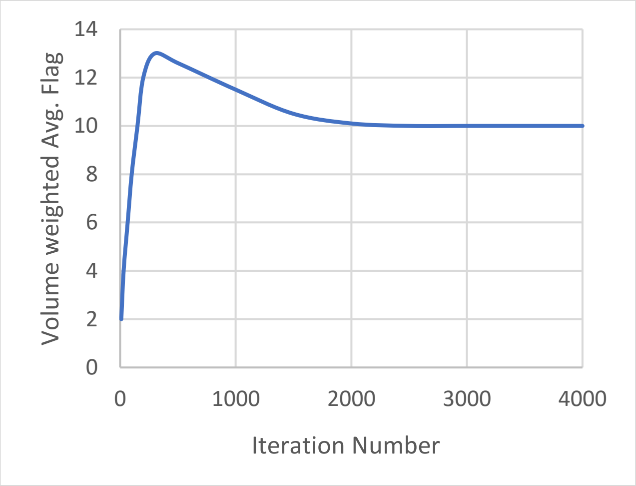


Figure 5: Monitor of flag variable

Following is the list of important output provided by the model

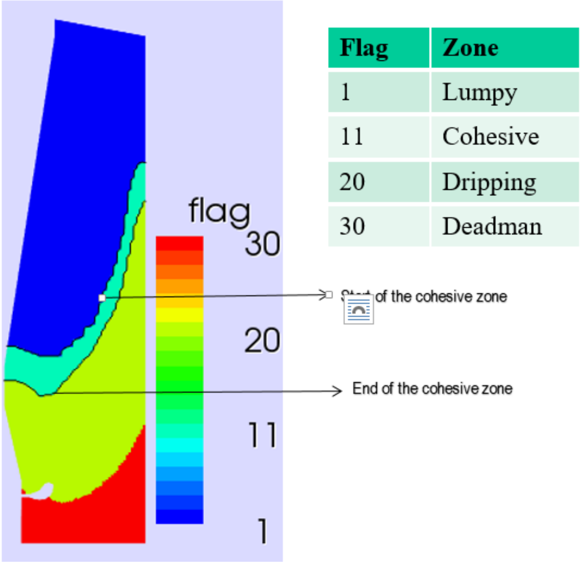
- Velocity, temperature profile for all liquid-gas-solids
- Pressure profile
- Gas-solid-liquid species profiles, ore reduction profiles
- Different zone locations and shapes
- Layer profiles
- Top gas and hot metal composition

Heat and mass balances are also performed to ensure solution satisfies the overall balances. Error in mass balance is 0.003%, whereas, that in heat balance is 0.08%.

Table 1: Comparison between plant and predicted data

Variable	Actual Value	Predicted Value
Dry coke rate (kg/thm)	320	306.6
Delta P (bar)	1.50	1.66
TG Temp (C)	100.0	120.0
Dry TG CO (vol. %)	23.4	23.6
Dry TG CO2 (vol %)	24.0	23.8
Eta CO = CO2/(CO+CO2) (-)	0.5063	0.5016
Dry TG H2 (vol %)	5.0	4.8
Overall heat loss (MJ/thm)	220	200
Hot Metal Cast Temp= Texit -20 (C)	1500	1490

In Figure 6 lumpy, cohesive, dripping and deadman zones can be observed. Location and shape of cohesive zone is a very important output parameter to understand working of blast furnace.



Flag	Zone
1	Lumpy
11	Cohesive
20	Dripping
30	Deadman

Figure 6: Different zones predicted by BlaSim®

In Figure 7 solid velocity streamlines and predicted layer structure are shown. In the layer structure three distinct layers of ore (blue), coke (green) and central coke (red) can be observed.

In the Figure 8, ore volume fraction and gas velocity streamlines are shown. Radial distribution of ore and coke volume fractions is an input to the model and is obtained from burden distribution model (RADHAKRISHNAN (2001)) (NAG (2014)). Ore volume fraction is high at the mid-radius due to practise of charging high amount of ore at the location for better gas distribution and minimizing heat losses. The ore volume fraction is reduced to 0 at the end of cohesive zone due to melting. Gas streamlines show strong impact of cohesive zone on gas flow. Streamlines show that gas flows away from centre through coke layers as mushy ore in the cohesive zone offers very high resistance to gas flow.

Temperature profiles are plotted in Figure 9. Liquid (hot metal + slag) temperature profiles are relevant only below start of cohesive zone as liquid is not present above the cohesive zone. High gas temperature is observed in the centre of the blast furnace indicating strong central flow of gases.

Gas composition and distribution in the blast furnace is shown in Figure 10. Higher CO consumption is clearly visible in the region of maximum ore loading and it is lowest in the central region where ore fraction is very low.

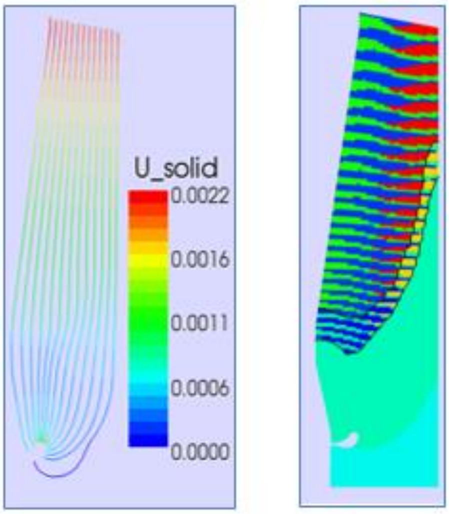


Figure 7: Solid velocity streamlines and predicted layer structure

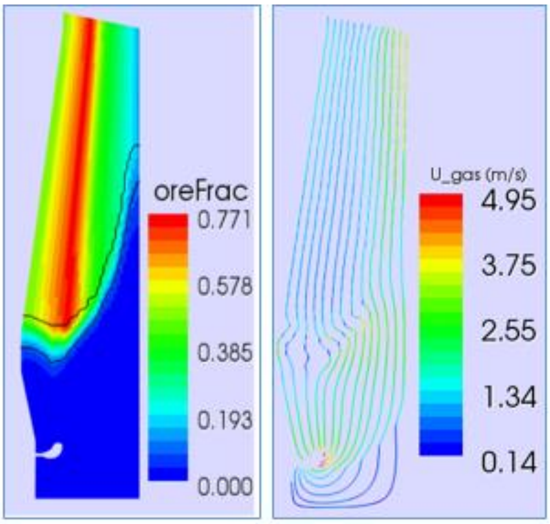


Figure 8: Ore fraction and Gas velocity streamlines

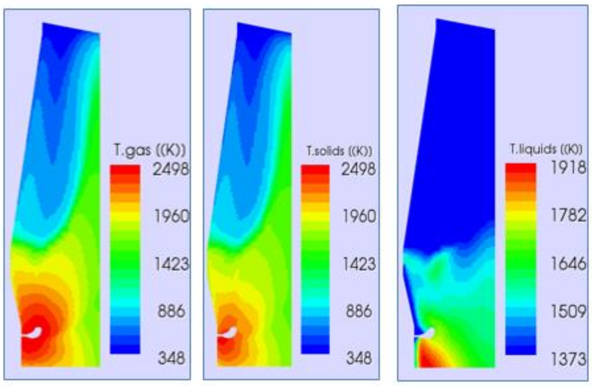


Figure 9: Temperature profiles in gas, solid and liquid

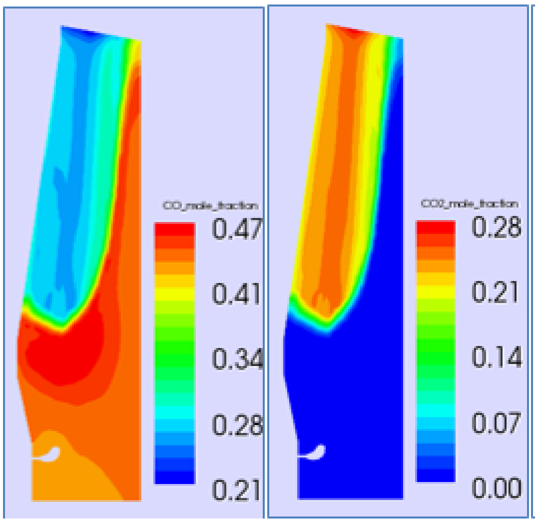


Figure 10: Gas composition, CO and CO2 profiles

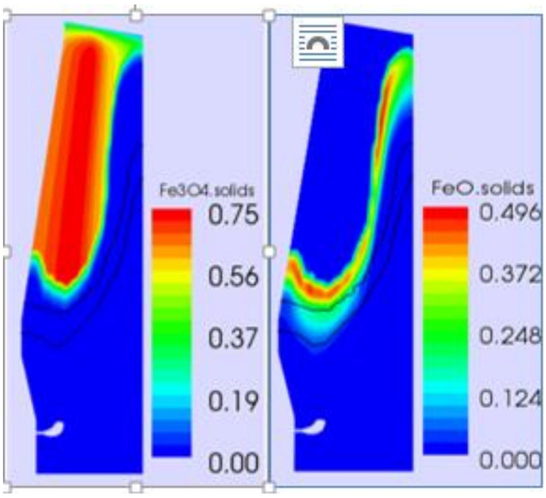


Figure 11: Solid composition magnetite and wustite profiles

Solid composition of magnetite and wustite is shown in Figure 11. Hematite reduction is very fast and occurs in the top region. Magnetite reduction happens deeper into the blast furnace. Thereafter, wustite reduction is quicker and happen in a depth of 1-2 meters at all radius except mid-radius where ore burden is maximum.

Parametric study

Prediction of blast furnace performance with change in operating conditions is an important aspect of the model. Below two such cases are presented in which effect of top gas pressure and effect of central coke burden diameter is predicted. All other inputs are same as that of base case.

Effect of top gas pressure

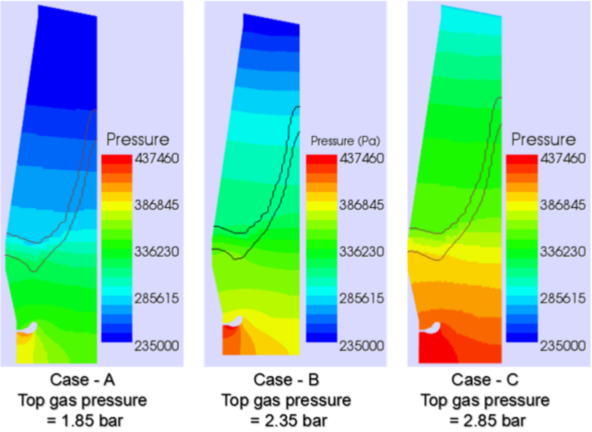
To study the effect of top gas pressure two additional cases are run with top gas pressure of 1.85 bar and 2.85 bar. The base case is with top gas pressure of 2.35bar. Predicted gas pressure drop is 1.84, 1.66 and 1.48 bar for top gas pressure of 1.85, 2.35 and 2.85 bar. Effect on pressure profiles is shown in Figure 12. As top gas pressure is increased from 1.85bar to 2.85 bar overall pressure drop decreases due to lower gas velocities. Decrease in velocity is due to higher gas density at higher pressure. Note that pressure drop, and square of velocities are directly proportional as per gas flow Eq. (3).

Effect of central coke

In general, coke with larger diameter is charged from centre. This produces central chimney where gas flow is higher.

Similar central coke is used in the base case presented above. To check the impact, a new case is run in which central coke is replaced with same coke as used in surface coke layer. Typical surface coke diameter is around 30 mm and for central coke it is around 50 mm. Cohesive zone is shifted down near the centre, whereas it is shifted up near wall. Other effects observed are

- Eta CO is also increased from 49.37 to 50.03 when same diameter central coke is used due to better gas distribution.
- Top gas temperature decreases from 393K to 389K when same diameter central coke is used indicating higher efficiency.

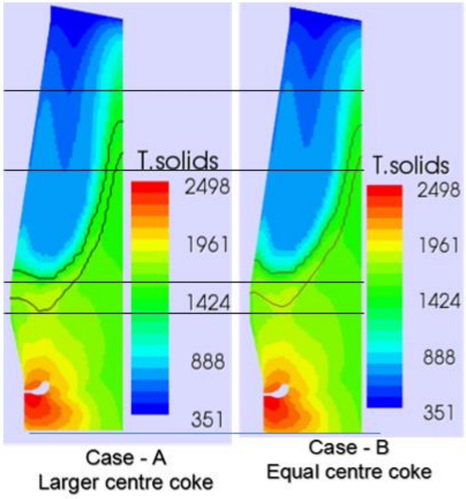


Case - A
Top gas pressure
= 1.85 bar

Case - B
Top gas pressure
= 2.35 bar

Case - C
Top gas pressure
= 2.85 bar

Figure 12: Effect of top gas pressure



Case - A
Larger centre coke

Case - B
Equal centre coke

Figure 13: Effect of central coke size on solid temperature and cohesive zone

Conclusion

A comprehensive, steady state model has been developed for blast furnace process analysis using OpenFOAM®. The tool is tuned to predict the performance of 'H' blast furnace of Tata Steel, Jamshedpur. After tuning the model is ready to be used to predict the performance of the blast furnace with different operating conditions.

Parametric studies are performed by changing process conditions. Results predicted by parametric study agree with expected trends as per working of blast furnace and plant conditions.

The model developed can be used for predictive analysis and efficiency improvement of the BF process. This can result in significant cost saving of blast furnace operation and reduce carbon footprint of the process.

REFERENCES

ABHALE, P. B. (2011). *Mathematical modeling of iron blast furnace.* Ph.D. Thesis, IIT Bombay, INDIA.

ABHALE, P. B., VISWANATHAN, N.N., and SAXEN, H. (2020). "Numerical modelling of blast furnace – Evolution and recent trends,." *Mineral Processing and Extractive Metallurgy* 129 (2): 166-183.

ABHALE, P. B., VISWANATHAN, N.N., BALLAL, N.B. (2009). "Efficient simulation of gas flow in blast furnace." *Computers, Materials & Continua* 10 (2): 195.

ABHALE, P. B., YADAV, V. K., VISWANATHAN, N.N., and BALLAL, N.B (2010). "Investigation of mal-distribution in blast furnace aerodynamics using a three dimensional simulation model." *International Conference on Computational & Experimental Engineering and Sciences (ICCES 2010).* Las Vegas, USA.

AUSTIN, P. R., NOGAMI, H., and YAGI, J. (1997a). "A mathematical model for blast furnace reaction analysis based on the four fluid model." *ISIJ Inter.* 748-755.

AUSTIN, P. R., NOGAMI, H., and YAGI, J. (1997). "A mathematical model of four phase motion and heat transfer in the blast furnace." *ISIJ Inter.* 458-467.

AUSTIN, P. R., NOGAMI, H., and YAGI, J. (1997b). "A mathematical model of four phase motion and heat transfer in the blast furnace." *ISIJ Inter.* 458-467.

CHEN, J., AKIYAMA, T., NOGAMI, H., YAGI, J., and TAKAHASHI, H. (1993). "Modeling of solid flow in moving bed." *ISIJ Int.* 33: 664-671.

CHEW, S., ZULLI, P., and YU, A. B. (2001). "Modelling of liquid flow in the blast furnace application in a comprehensive blast furnace model." *ISIJ Inter.* 1122-1130.

DANLOY, G. (2008). "Modelling of the blast furnace internal state with MOGADOR." *Proceedings of the 4th Ulcos Seminar.*

DONG, X.F., YU, A. B., and BURGRESS, A. B. (2009). "Modelling of multiphase flow in ironmaking blast furnace." *Ind. Eng. Chem. Res.* 214-226.

MATSUZAKI, S., NISHIMURA, T., SHINOTAKE, A., KUNITOMO, K., NAITO, M., and SUGIYAMA, T. (2006). *A development of mathematical model of blast furnace.* Japan: Nippon Steel Technical Report.

NAG, S., GUPTA, A., PAUL, S., GAVEL, D., and AICH, B. (2014). "Prediction of heap shape in blast furnace burden distribution." *ISIJ Int.* 54: 1517-1520.

OMORI, Y. (1987). *Blast furnace phenomena and modelling.* Elsevier Applied Science: London.

RADHAKRISHNAN, V. R., and RAM, K.M. (2001). "Mathematical model for predictive control of the bell-less top charging system of a blast furnace." *J Process Control.* 11: 565-586.

SARKAR, S., GUPTA, G. S., and KITAMURA, S. (2007). "Prediction of Raceway Shape and Size." *ISIJ Inter.* 47 (12): 1738-1744.

SHEN, Y. S., GUO, B. Y., YU, A.B., AUSTIN, P. R., and ZULLI, P. (2011). "Three-dimensional modelling of in-furnace coal/coke combustion in a blast furnace." *Fuel* 90: 728-738.

SHEN, Y.S., GUO, B.Y., CHEW, S., AUSTIN, P. R., and Yu, A.B. (2015). "Threedimensional modelling of flow and thermochemical behaviour in a blast furnace." *Metall Mater Trans B.* 46B: 432-448.

YAGI, J.,TAKEDA, K., and OMORI, Y. (1982). "Two dimensional simulation of gas flow and heat transfer in the blast furnace." *ISIJ International* 22: 884.