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EFFICIENT COMPUTATION OF GAS FLOW IN BLAST FURNACE IN 3-D[1]

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Abstract

Blast furnace continues to occupy prominent place among iron making technologies as it accounts for more than 90% of the hot metal produced in the world. In India, as a part of initiative from Ministry of Steel, efforts are being made to develop offline as well as online models with an aim to improve blast furnace performance. As a part of this effort, offline comprehensive models simulating the internal state of an operating blast furnace are being developed. Such comprehensive models involve systematic integration of various sub-models for gas flow, solid flow, reaction kinetics, enthalpy balance etc. Unlike in many other systems, these sub-processes are highly interlinked in blast furnace and hence call for large number of iteration among the sub-models which ultimately results in significant computation time. Our efforts in integration of these sub-models have indicated that the gas flow is one of the important bottle necks in achieving faster computation. This has led to a development of new and efficient computation scheme to simulate the gas flow in 2-D [1]. This new scheme provided efficient way of handling complex burden profile in a blast furnace. This paper presents the extension of this 2-D gas flow model to 3-D. Further, the 3-D model has been used to investigate the asymmetry in gas flow which can arise from blanking the tuyeres, asymmetric fusion or cohesive zone or formation scabs or scaffolds in the furnace behavior.

Key words: Blast furnace; Non isothermal gas flow; Efficient computation; Layered burden.

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1 INTRODUCTION

Blast furnace continues to occupy prime position among iron making technologies as it accounts for more than 90% of the hot metal produced in the world. With the growing environmental awareness and concerns over carbon emissions, efforts are on to improve its performance both in terms of efficiency and stable operation as well as exploring usage of alternate fuels and other raw materials. In this exercise modeling plays a crucial role in assessing the new efforts especially in narrowing down the window of experiments to be conducted.

A large number of inter-related physico-chemical processes take place inside the blast furnace. Success of any integrated model in predicting blast furnace behavior developed either as an on-line or an off-line tool depends on how well the physics of each of the sub-processes are incorporated into the models. Among these sub-models gas flow plays a crucial role as blast operator uses it in conjunction with burden distribution model to improve its performance both in terms of efficiency and stable operation.

In India, with growing steel production in last one decade, efforts are on to improve blast furnace performance. Modeling has been found to be one of the fruitful approaches towards this aim. As a part of this effort, offline comprehensive models simulating the internal state of an operating blast furnace are developed and being further improved. Such comprehensive models involve systematic integration of various sub-models for gas flow, solid flow, reaction kinetics, enthalpy balance etc.

Unlike in many other systems, these sub-processes are highly interlinked in blast furnace and hence call for large number of iteration among the sub-models which ultimately results in significant computation time. Our efforts in integration of these sub-models have indicated that the gas flow is one of the important bottle necks in achieving faster computation. This has led to a development of new and efficient computation scheme to simulate the gas flow in 2-D. The details of these have been published elsewhere [1], and only a brief description is presented here.

Subsequently, the model is extended to 3-D scenario, with following motivations:

- Study the effect of asymmetric conditions developing in the bed for various reasons like blanked out tuyeres, growth of scabs and scaffolds, asymmetric cohesive zone, etc.
- Effect of asymmetric charging to achieve preferred flows in the burden.

However, the scope of the work presented here is limited only to the first case.

2 2-D MODEL

In order to simulate gas flow through a packed bed, one needs to solve the Navier-Stokes equations with a momentum source term derived from Ergun equation [2] (equation 1) in conjunction with the mass balance equation (equation 2). Bennett and Bradley[2] pointed out that instead of using complete Navier-stokes equations, as used by Fenech, Cross and Voler [3], a simplified vectorial form of Ergun's equation (equation 1) omitting the all the inertial and viscous terms can be used without introducing significant error in predictions.

$$-\nabla P = F_1.\vec{V} + F_2.|\vec{V}|.\vec{V} \qquad (1)$$

Where, $F_1 = \dfrac{150(1-\varepsilon)^2 \mu_g}{(\varphi d_p)^2 \varepsilon^3}$ and $F_2 = \dfrac{1.75(1-\varepsilon)\rho_g}{(\varphi d_p)\varepsilon^3}$.

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$$\nabla.(\rho_g \vec{v}) = \dot{G} \tag{2}$$

Radestock and Jeschar [4,5], predicted flow through a homogeneous packed bed, by solving the above equations directly for the variables *P* and *v*, employing the finite difference formulation and iterative solution using successive over relaxation (SOR). Stanek and Szekely [6-8] and Poveromo, Szekey and Propster [9] used the stream function formulation of these equations to predict the gas flow through a cylindrical layered bed. Stream function formulation results in faster computation than solving for primitive variables, directly. The nonlinear partial differential equation was solved with locally varying gas density and voidage for each layer of the bed. Blast furnace being a packed bed having large number of alternate layers of ore and coke, one needs to solve these equations by taking sufficiently fine grids in each homogeneous layer to capture the furnace aerodynamics. However, this forces the modeler to use large number of grids which leads to obvious increase in computation time. This problem can be handled to some extent by aligning the grids if alternate layers are straight lines [10-15]. However, in the current scenario of advances in modern bell-less top charging technology wherein complex curved patterns of layering can be achieved, the problem becomes more severe.
Cross and Gibson[16] proposed a novel methodology wherein flow through a layered structure is approximated by considering an equivalent anisotropic homogeneous packed bed, in which the resistances in directions parallel and perpendicular to the flow direction are different. In order to take care of the varying slopes of the interface between layers, the modified equations are transformed from the local coordinates aligned with the layers to the global co-ordinate system for each grid point. This anisotropic form of Ergun equation was applied by Cross and Gibson [16] for inclined layers after coordinate transformation as:

$$|v|\begin{Bmatrix} v_r \\ v_z \end{Bmatrix} = \begin{bmatrix} a & b \\ b & c \end{bmatrix}\begin{Bmatrix} -\partial P/\partial r \\ -\partial P/\partial z \end{Bmatrix} \tag{3}$$

Where,

$$a = \frac{cos^2\beta}{F_{\parallel}} + \frac{sin^2\beta}{F_{\perp}},\ b = \left(\frac{1}{F_{\parallel}} - \frac{1}{F_{\perp}}\right) sin\beta.cos\beta$$

$$c = \frac{sin^2\beta}{F_{\parallel}} + \frac{cos^2\beta}{F_{\perp}}$$

And 'β' is the angle between the local normal to the layer and the furnace axial direction.
Cross and Gibson, [16] in their formulation, eliminated the velocity in equation 2 using equation 3 for a gas having uniform density (ρ_g is constant) to obtain a highly nonlinear equation in terms of pressure.
In the blast furnace, pressure and temperature change significantly from bottom to top leading to significant variation in gas density. In order to consider this, one also needs to incorporate the equation of state:

$$PM = \rho_g RT \tag{4}$$

Abhale, Viswanathan and Ballal [1] developed a new computation methodology for simulating gas flow through a layered packed bed having spatial variation of gas

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density due to pressure and temperature along the lines of the anisotropic packed bed formulation of Cross and Gibson [16].
Abhale, Viswanathan and Ballal [1] substituted equation 3 and 4 into equation 2 to obtain,

$$\frac{1}{r}\frac{\partial}{\partial r}\left[r\frac{P_0^2 M}{2RT\,|v|}\left(-a\frac{\partial\phi}{\partial r}-b\frac{\partial\phi}{\partial z}\right)\right]+\frac{\partial}{\partial z}\left[\frac{P_0^2 M}{2RT\,|v|}\left(-b\frac{\partial\phi}{\partial r}-c\frac{\partial\phi}{\partial z}\right)\right]=\dot{G} \quad (5)$$

Where, $\phi = P^2/P_0^2$, 'P_0' being a reference pressure.
It should be noted that the '|*v*|' term in equation 5 is the source of nonlinearity. In other words, if '|*v*|' is 'known', then it is a linear-elliptic equation in 'ϕ'. Therefore, 'ϕ' and '|*v*|' were solved iteratively using equation 3 and 5. In addition, for efficiency of computation, a sparse matrix solver with the bi-conjugate gradient method [17] was used to solve the simultaneous linear equation resulting from the discretization of equation 5.

3 EXTENSION TO 3-D

The governing equation discussed in the earlier section are extended to three directions viz. 'r', 'z' and 'θ', with addition of term related to 'θ' direction. The modified Ergun's equation (equation. 3) can be rewritten for three dimensional flow as,

$$|v|\begin{Bmatrix} v_r \\ v_z \\ v_\theta \end{Bmatrix} = \begin{pmatrix} H_{rr}^{-1} & H_{rz}^{-1} & 0 \\ H_{zr}^{-1} & H_{zz}^{-1} & 0 \\ 0 & 0 & H_{\theta\theta}^{-1} \end{pmatrix} \begin{Bmatrix} -\partial p/\partial r \\ -\partial p/\partial z \\ -\dfrac{1}{r}\dfrac{\partial p}{\partial \theta} \end{Bmatrix} \quad (6)$$

Where, $H_{rr}^{-1} = \frac{cos^2\beta}{f_{\parallel}} + \frac{sin^2\beta}{f_{\perp}}$ $H_{zz}^{-1} = \frac{sin^2\beta}{f_{\parallel}} + \frac{cos^2\beta}{f_{\perp}}$

$$H_{rz}^{-1} = H_{zr}^{-1} = \left(\frac{1}{f_{\parallel}} - \frac{1}{f_{\perp}}\right) sin\beta.cos\beta$$

$$H_{\theta\theta}^{-1} = \frac{1}{f_{\parallel}}$$

Note that only parallel component of anisotropic resistance will appear as layers are symmetric in theta direction i.e. at any 'rz' plane of cross section, a layer angle 'β' (angle made with the horizontal), does not change. The gas flowing in that direction will continue to flow through the same layer, parallel to the interface. The cross resistances in the above equation (H_{rz}^{-1} and H_{zr}^{-1}) appear because of the layer inclination 'β'. The cross resistances, $H_{r\theta}^{-1}, H_{\theta r}^{-1}, H_{\theta z}^{-1}$ and $H_{z\theta}^{-1}$ does not appear due to symmetry in theta direction.

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The final equation can be obtained by substituting equation 4 and equation 6 into equation 2 as,

$$\frac{1}{r}\frac{\partial}{\partial r}\left[r\left(-Q_{rr}\frac{\partial\phi}{\partial r}-Q_{rz}\frac{\partial\phi}{\partial z}\right)\right]+\frac{\partial}{\partial z}\left[-Q_{zr}\frac{\partial\phi}{\partial r}-Q_{zz}\frac{\partial\phi}{\partial z}\right]+\frac{1}{r}\frac{\partial}{\partial\theta}\left[-Q_{\theta\theta}\frac{1}{r}\frac{\partial\phi}{\partial\theta}\right]=0 \quad (7)$$

Where, 'Q' and 'ϕ' carry l meanings described earlier.

4 BOUNDARY CONDITIONS

At the centre, walls and bottom the normal velocity is zero. One has to specify the inlet velocity at tuyere entry and pressure at the top of the first layer surface. Along with this, two more boundary conditions are needed on first and last plane in theta direction. In case of symmetry in theta direction, one can solve for a small sector starting from middle of any tuyere to the middle of the neighboring tuyere and a zero mass flux can be specified on those two planes. Whereas, if there is no symmetry, one has to solve for 360^0 and mass entering into the 0^0 plane has to be made equal to that coming out of the 360^0 plane.

5 RESULTS AND DISCUSSIONS

The parameter such as furnace dimensions and operating conditions like blast rate, production rate, top gas pressure and temperature, ore/coke particle size used for the simulation are given in Table 1.

Table 1. Furnace dimensions and operating conditions

Furnace Dimensions		**Operating Conditions**	
Stack diameter	7.4 m	Blast Rate	1000 Nm^3 per THM
Belly diameter	10.7 m	Production rate	3500 THM per day
Hearth diameter	9.2 m	Top gas temperature	500 K
Throat height	3.0 m	Top gas pressure	1.5 bar
Stack height	15.772 m	No. of tuyeres	24
Belly height	2.4 m	**Material**	**Particle Diameter**
Bosh height	3.215 m	Ore	0.01 m
Hearth height	6.352 m	Coke	0.05 m

In this case, 24 equally spaced tuyeres along the circumference of the furnace at a height of 5.9m from the hearth bottom are considered. The shapes of raceways (1m cube), the deadman (conical) and cohesive zone have also been selected using pre-processor developed for this purpose. The layer structure for this study is taken from our earlier work [18] and is shown in figure 1. Number of grids chosen for the simulation are 37, 192 and 64 in 'r', 'θ' and 'z' directions, respectively. Note that, raceways are assumed to be a cube of size 1 m in front of each tuyere. Hence, tuyere plane and surrounding planes contain raceway region, whereas, the plane which is exactly at center between two tuyeres, does not contain raceway region.

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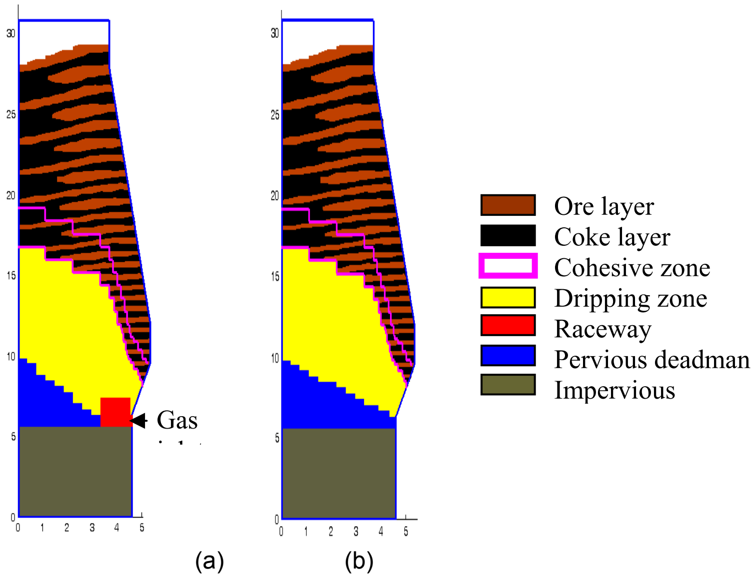

Figure 1. Layer structure along with different zones a) Tuyere plane b) Midway plane between two tuyeres.

Simulation runs have been performed for the following cases:

1. Case I : All tuyeres open
2. Case II: One tuyere closed
3. Case III: Asymmetric cohesive zone
4. Case IV: Scab formation at some location

5.1 Case I

In this case the gas has been allowed to flow through all tuyeres with equal flow rates. The resultant of velocity components in the 'r' and 'θ' direction at a horizontal cross section, 5.9 m from hearth bottom are shown in Figure 2a.
A nice symmetry around each tuyere can be observed. The gas flow in 'θ' direction is mainly due to selective position of gas inlets. At midway between two tuyeres, symmetry in 'θ' direction is seen, as the velocity in that direction is zero. Simiarly, figure 2b shows the surface plot of velocity component along z direction, where one can see that the velocity is very low at tuyere locations and it increases symmetrically on both sides till it becomes maximum at a plane midway between two tuyeres. All the velocities in central region are negligible due to less permeability of the deadman.

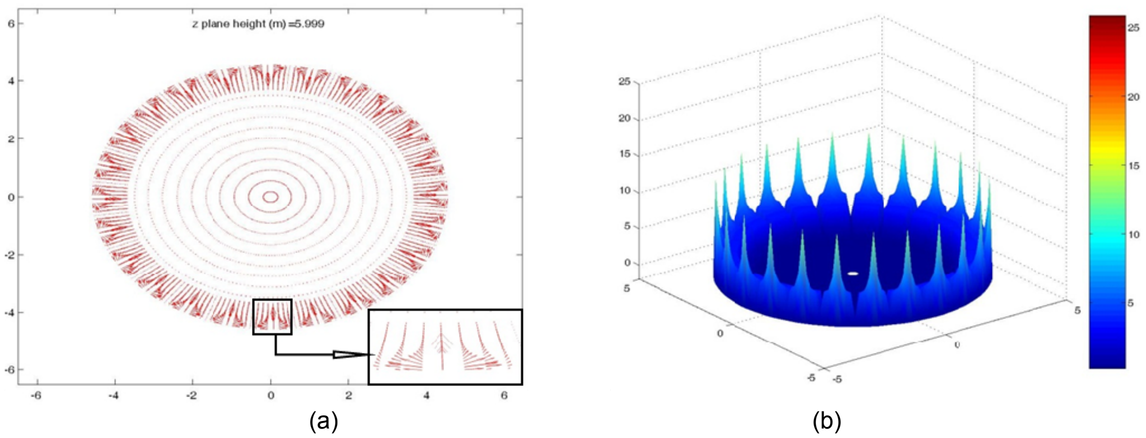

Figure 2. Velocity plots at tuyere level (5.9m) a) vector plot for velocity components r and θ directions and b) corresponding iso-surface plot of component along z direction.

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Figure 3 shows the velocity plots along r and θ direction at a plan 2 m above tuyere level (7.96 m). The first observation one makes is that the velocity in 'θ' direction has become negligible, and the flow is almost two-dimensional within a height of 2 m from the tuyere. Hence beyond this height prediction of a 2-D model should closely correspond to reality. It also shows that the flow direction is in radially opposite directions from a circumference of about 1 m inside from the wall. This is due the fact that wall slope is outwards in the bosh region, so part of gas injected in radially inward direction has to flow outward to occupy all the volume available for flow. Similar change in direction is observed at cohesive zone locations where gas which is flowing towards the center, has to flow outwards through the narrow coke slits.

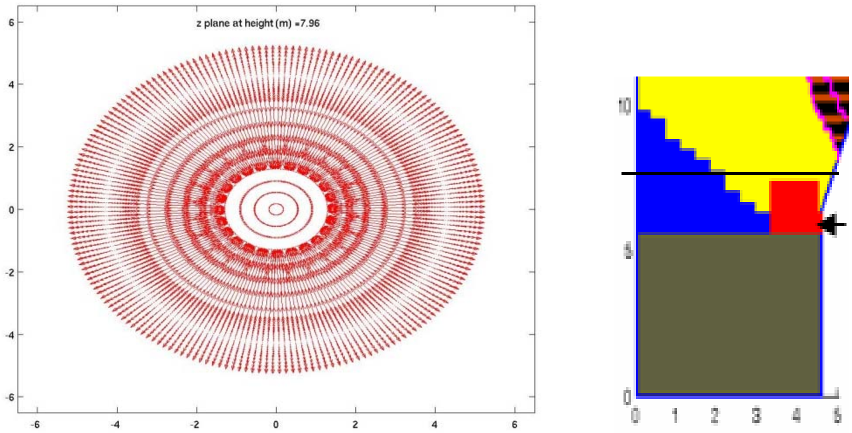

Figure 3. Velocity plots along r and θ direction at a plan 2m above tuyere level (7.96m).

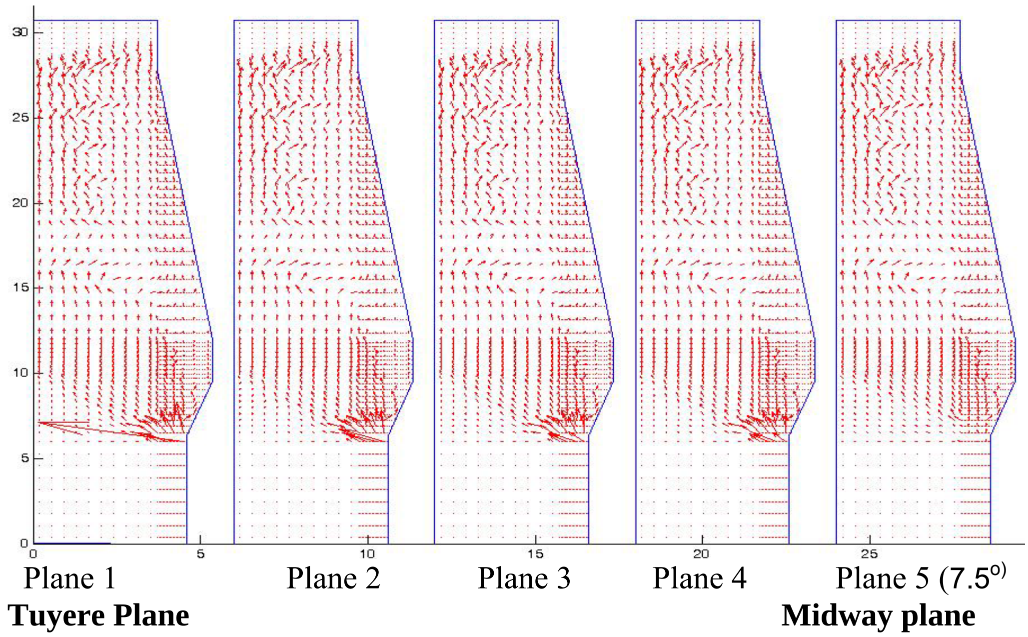

Figure 4. Velocities in r and z direction.

5.2 Case II

Simulations have been performed for a case with one tuyere closed/blanked, keeping the total blast rate same, as in Case I. Figure 5 compares the results obtained for Case I and Case II. One can see from figure 5 that, due to the closed tuyere, gas tries to flow-in from several neighbouring tuyeres in the raceway section itself. As one

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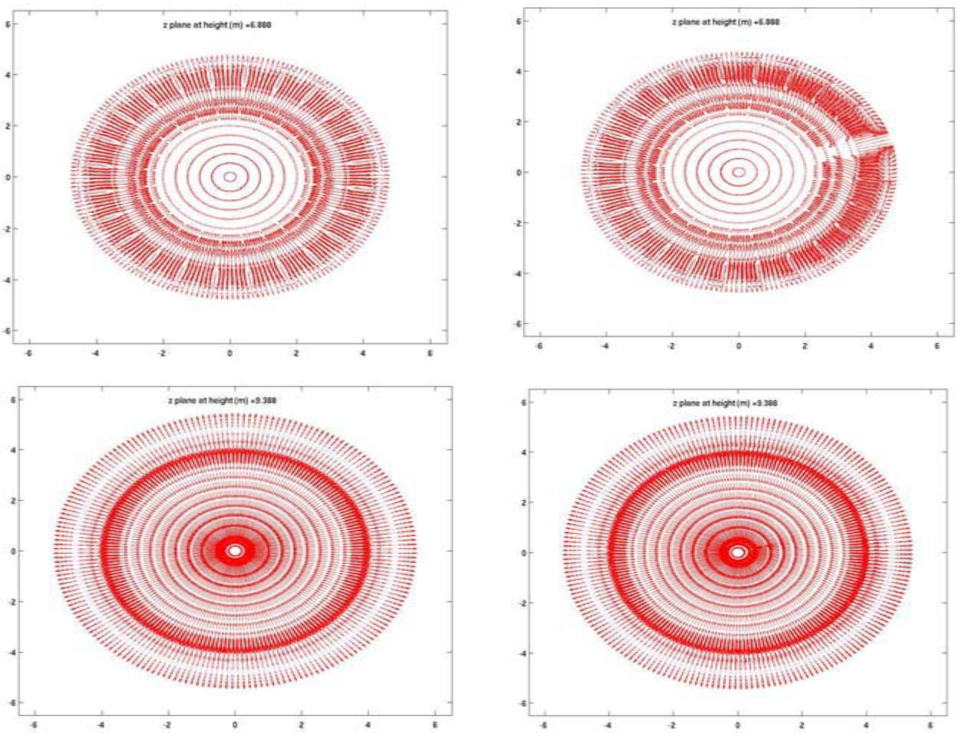
moves up, the asymmetry due to blanked tuyere starts decreasing and within a height of 3.4 m from the tuyere level, the asymmetry almost disappears. This seems to indicate that blanking out one tuyere may have little effect on the working of the furnace, especially on the rates of reactions in the stack. This of course assumes that there are no changes in the burden permeability due to formation of scabs (in the region above blanked tuyere), which may have larger effect on the working of the furnace, especially in the stack.



Case I Case II

Figure 5. Vector plots of velocity components along r and θ direction at different heights.

5.3 Case III

The effect of asymmetric shape of cohesive zone on gas flow pattern is studied. The assumed shapes of cohesive zone are shown in Figure 6. In Case III(a) shape of cohesive zone is moderately changed, where as in Case III(b) large distortion in cohesive zone is considered.

The gas velocities are compared for two cases at different height as shown in Figure 7. It can be seen that the effect of such non-symmetric cohesive zones are large and the simulations capture the disturbunce effectively. It can also be seen that the distubances travel all through the height of the furnace, which may affect the stableworking of the furnace severely.

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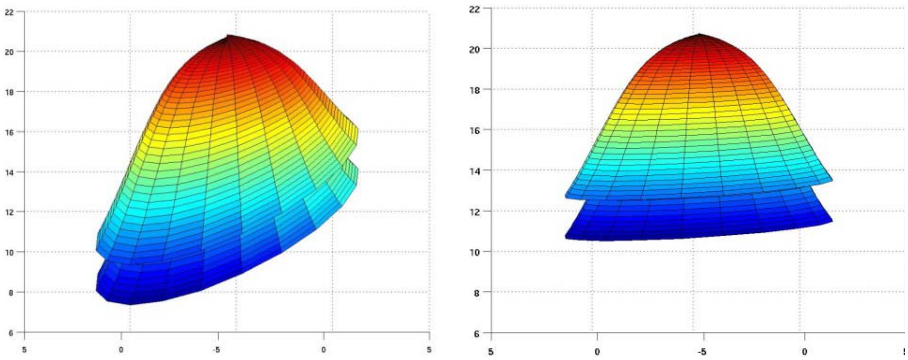
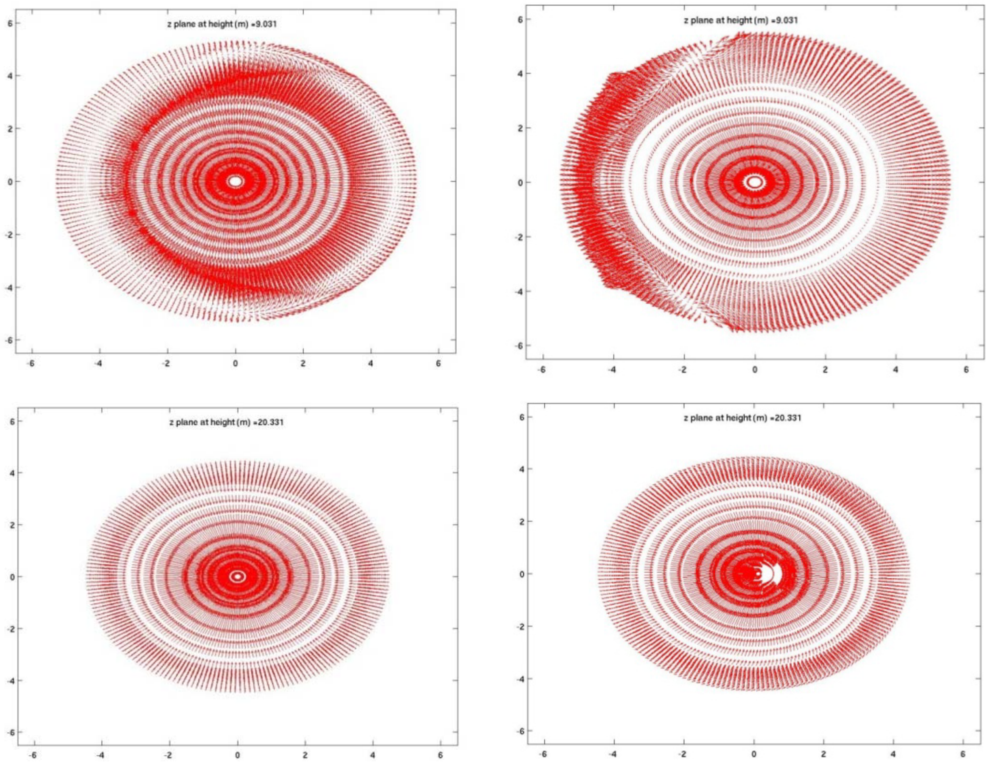


Case III(a) Case III (b)

Figure 6. Shape of asymmetric cohesive zone.



Case III(a) Case III (b)

Figure 7. Velocity vectors in r-θ plane at different heights.

5.4 Case IV

The effect of a scab of 2 m height, 4 m width and 1 m thickness, located at 1.5 m above the tuyere level is given in Figure 8. It can be seen that within a distance of 2 m from the top of the scab the effect becomes very small.

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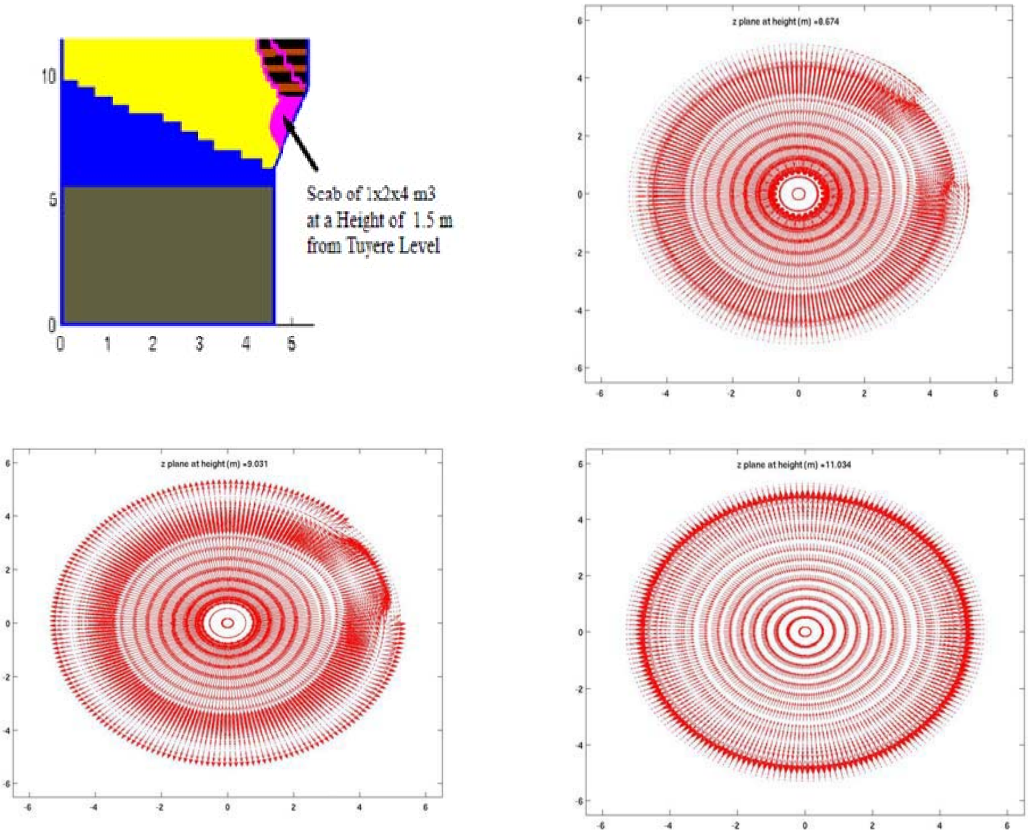

Figure 8. Effect of scab formation on gas flow pattern at different heights.

6 CONCLUSIONS

A 3D gas flow model has been developed for the blast furnace. The model has been shown to be able to capture asymmetry in boundary conditions and bed geometry fairly well. Simulation results predict that the effect of a blanked tuyere is felt only for a distance of about 4m. On the other hand the effect of asymmetric cohesive zone and scaffold is much more extensive.

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