FORCE BALANCE IN THE INTERIOR OF THE BLAST FURNACE

FORCE BALANCE IN THE INTERIOR OF THE BLAST FURNACE

By

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Abstract

The goal of this thesis is to advance knowledge about the balance of forces acting on granular materials in the interior of the blast furnace and on the walls. Using the principles of fluid and granular flows, a mathematical model is developed and used to generate new knowledge about the influence of process parameters, under control of the blast furnace operator, on the granular stress at the level of the gas inlet and the walls. The mathematical model developed is validated under ambient conditions by comparing predictions with experimental data obtained from physical scale models of the blast furnace.

Comparison of the wall gas pressure profile from a commercial blast furnace with results from the mathematical model developed, indicate that gas temperature is an important factor in estimating the magnitude of the external force exerted by gas flow on granular materials. Results also show that the vertical stress acting on the upper boundary of the coke bed in the hearth can be altered by changing variables which are under the operator's control. These variables include the gas properties (mass flow rate and pressure) and the properties of the granular column (bulk density of granular materials and cohesive zone location).

Information generated in this thesis can be used by blast furnace operators for guidance in controlling the vertical stress at the upper boundary of the coke bed in the hearth and for defining the force at this boundary for subsequent studies of hearth region.

Acknowledgements

The author wishes to express his gratitude to the supervisory committee, Dr. G. Irons, Dr. S. Pietruszczak and Dr. W-K Lu for their patience and assistance over this long journey.

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Declaration of Academic Achievement

All results reported in this dissertation were generated by the author unless otherwise specified. This includes the results from mathematical modeling, validation exercises and commercial blast furnace simulations. Also, subroutine software development to interface with the commercial software ABAQUS (ABAQUS, 2004) was performed by the author.

Chapter 1 Introduction

Steel is an important engineering material. World crude steel production in 2012 totaled 1.5 billion tonnes, of which, approximately 1.1 billion tonnes was produced in oxygen blown converters (WorldSteel Association, 2013). Hot metal, which is liquid iron with dissolved carbon and other impurities, typically comprises 70 to 90% of the steelmaking charge with the balance being scrap.

The blast furnace is the primary process for hot metal production and has operated commercially, in its present form, for more than 100 years (Ricketts, 1998). Over this time, improvements in raw materials, refractory/cooling protection, equipment and process control have allowed significant increases in the scale of operation of the blast furnace and led to the replacement of multiple smaller units with a single larger unit. As a consequence, integrated plants have come to rely on fewer larger blast furnaces to supply hot metal to their oxygen steelmaking facilities (Luengen et al., 2011). With these developments, continuity and reliability of operation have become more critical.

A few blast furnaces have achieved a campaign life, the time between major repairs, in excess of twenty years (Fujita et al., 2000; Klein et al., 2005; Tsalapatis et al., 2005; Ogata et al., 2003). The limitation is usually hearth life. Hot metal flow is a key factor in determining refractory life of the hearth - higher hot metal velocities increase hearth floor and sidewall temperatures reducing refractory life expectancy.

Hot metal velocity is influenced by the height of the floating coke bed above the hearth floor. A narrow gap between the base of the floating coke bed and the hearth floor will increase hot metal velocities along the hearth floor and sidewalls resulting in increased refractory temperatures and premature wear over time.

To appreciate the forces affecting the position of the floating coke bed in the hearth it is necessary to understand the internal structure of the blast furnace, shown in Figure 1.1. The blast furnace is a gas/granular solid counter current shaft reactor with an internal structure consisting of five zones – granular zone, cohesive zone, active coke zone, raceway and hearth. In the granular zone, a column consisting of alternate layers of ore and coke descends under the force of gravity as iron ore is reduced, heated and melted by ascending gases. The cohesive zone is formed by the start and finish of the melting of iron ore. The active coke zone consists of the residual coke. The raceway refers to the zone in front of the tuyeres, above the hearth, where preheated air is introduced to the furnace to combust coke and injected fuel. Hot reducing gases, generated in the raceway, ascend through the active coke, cohesive and granular zones. The molten iron and gangue from iron ore, coke and coal collects in the hearth and are drained via the taphole. The coke bed submerged in the hot metal can be sitting on, floating or partially floating above the hearth floor.

The height of the floating coke bed above the hearth floor is influenced by the net vertical force acting on it at tuyere level. This force is determined by the interaction of multiple forces – the downward force of gravity acting on the granular materials, the friction between granular materials and between the granular materials and furnace wall, and the drag exerted by upward moving reducing gases from the tuyeres. The floating position of the coke bed in the hearth is determined by a balance of the net vertical force, referred to above, and the buoyancy exerted by the liquid metal and slag on the submerged coke bed.

Identifying the process parameters that affect the multiple forces comprising the net vertical force is key to influencing the position of the floating hearth coke bed and its effect on hearth refractory temperature and wear. In addition, the process parameters that affect the forces exerted by granular materials on the furnace wall can be identified to understand the implications for wall wear. Determining the sensitivity of these forces to changes in process parameters is essential to identifying the major factors that can be changed by operators. Finally, this work can be applied to understand the broader and longer term implications of current standard practices and to suggest changes as required.

In summary, this study is focused on the development of a mathematical model to predict the net vertical force acting on the hearth coke bed, identification of the major process parameters affecting the net vertical force, determination of the sensitivity of the net vertical force to changes in major process parameters and understanding the implications of the results for the blast furnace and future work.

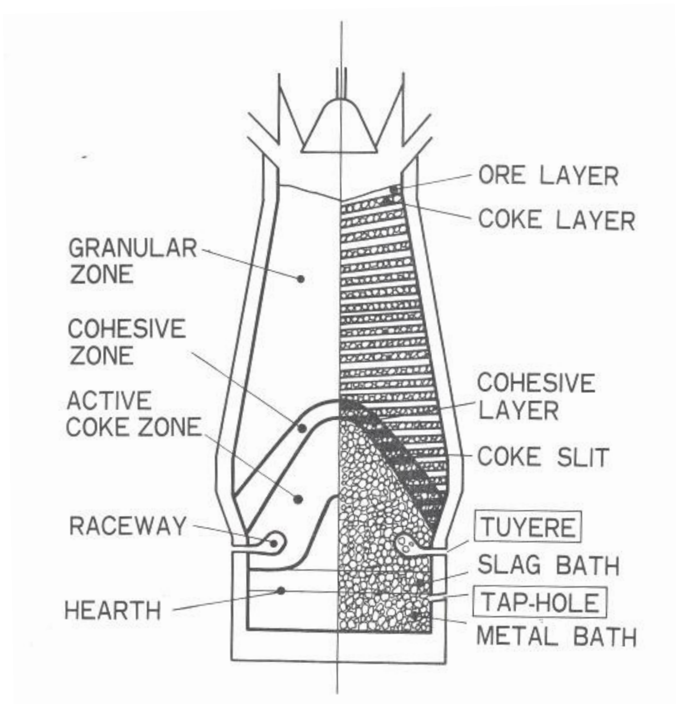


Figure 1.1 Internal Structure of the Blast Furnace (Hasimito et al., 1989)

Chapter 2 Literature Review

The blast furnace is a complicated process involving coupled fluid and granular flow, mass and heat transfer, chemical reaction between gas, liquid and solid phases and a complex internal structure. The balance of forces on the granular material in the interior of the blast furnace has an effect on service life through its influence on the spatial distribution of the coke bed in the hearth and the location and magnitude of the force of the granular materials on the wall. In this review a description of important features of the blast furnace, the influence of the spatial distribution of the hearth coke bed on service life, the factors that influence the force balance on the granular materials and relevant studies on the topic are detailed. The gap in process knowledge on the topic is described.

2.1 The Commercial Blast Furnace

2.1.1 Blast Furnace Shape

The modern blast furnace is a cylindrical refractory lined shaft furnace with an inner volume between 1000 and 6000 m^3. The shape of the blast furnace has evolved over time and features (Figure 2.1), a vertical section at the top called the throat, a conical section called the shaft, a short vertical section called the belly, an inverted conical section called the bosh and at the bottom a vertical section called the hearth. The shape of the blast furnace as determined by the angles between the different sections is an important factor influencing the stress on the flowing granular materials.

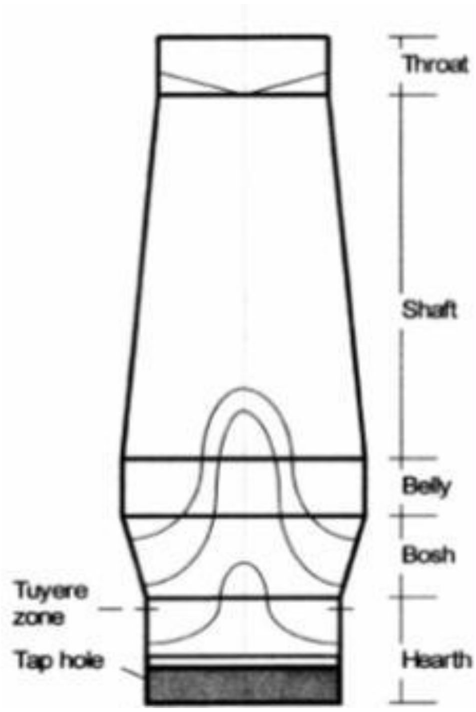


Figure 2.1 Sections of the Blast Furnace (Raipala 2003)

2.1.2 Internal Zones of the Blast Furnace

The dissection of experimental and operational blast furnaces in Japan revealed important features of the blast furnace internal structure (Omori, 1987). The physiochemical processes in these zones (Figure 2.2) are described.

2.1.2.1 Granular Zone

Burden materials are charged in alternating coke and ore (sinter and/or pellet) layers with specialized distribution equipment to control their relative thickness across the furnace radius. This radial distribution of ore/coke determines the gas distribution. In the granular zone the coke and ore maintain the distinct layered structure during their descent. As the granular material descends moisture is driven off, then at about 400 °C reduction of iron oxide begins. By the end of the granular zone the iron ore is reduced to wustite.

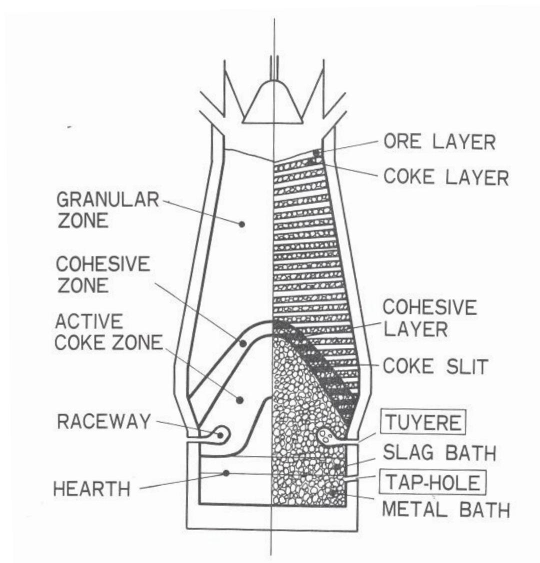


Figure 2.2 Main Zones of the Blast Furnace (Hashimoto et al., 1989)

2.1.2.2 Cohesive Zone

In the cohesive zone the ore begins to soften and melt. This results in a decrease in void fraction and thus an increase in resistance to gas flow. The gas is forced through the lower resistance “coke slits” between the cohesive materials. Liquid metal and primary slag become separate at its base.

The shape of the cohesive zone found in dissected blast furnaces is varied (Figure 2.3). The ‘inverted V’, W and V shapes were found. The shape is the result of the operating conditions and raw materials used at time of shutdown.

In most cases the root is located near the tuyere level while the apex varied from about 3 m to 12 m above the tuyere level. The location and shape of the cohesive zone is important as it influences the thermal efficiency, gas distribution, overall permeability, hot metal quality and wall heat losses. Control of the cohesive zone is affected mainly through control of burden distribution (radial ore/coke layer thickness) and reduction/softening characteristics of the ore.

2.1.2.3 Active Coke Zone

Coke is the only granular material present in the active coke zone. Liquid iron and slag generated in the cohesive zone drip through this coke bed. Reduction of iron oxide and metalloids takes place. Coke flows to the raceway between the cohesive zone and a stagnant conical pile of coke in the center called the deadman.

2.1.2.4 Raceway

Preheated air (or air and oxygen) introduced in the tuyeres is used to partially combust coke entering from above the raceway and injectants such as coal, oil or natural gas introduced through lances. This generates heat and reducing gas required for the process. The consumption of coke in the raceway initiates flow of granular materials in the blast furnace.

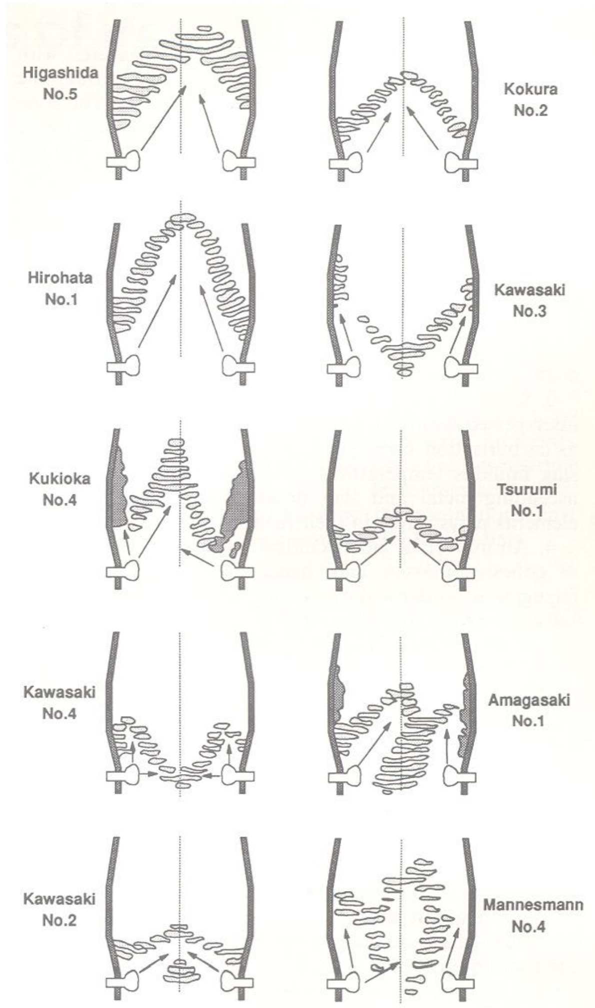
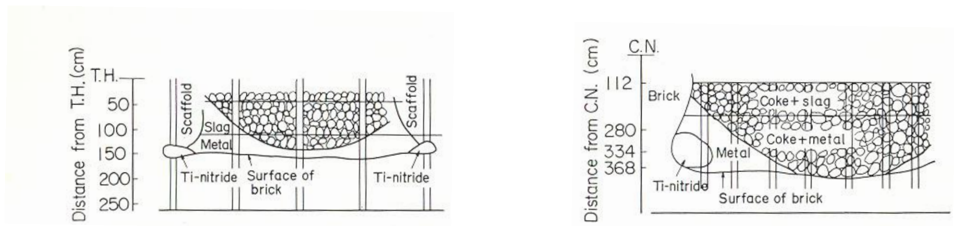


Figure 2.3 Comparative appearance of various cohesive zones, obtained from dissection studies (Busby, 1994)

2.1.2.5 Hearth

Iron and slag accumulate and separate by gravity. Coke is present as a granular material. Dissected furnaces revealed a coke free layer above the hearth bottom (Figure 2.4). The shape of the bottom of the coke bed is the result of the balance of forces acting on the hearth bed at the time of shutdown.



(a) (b)

Figure 2.4 Hearth Coke Bed (a) Higashida No. 5 BF (b) Kukioka No. 4 BF (Nakamura et al., 1978)

2.1.3 Improvement of Blast Furnace Campaign Life

Blast Furnace campaign life has increased significantly over the past decades. Campaign life is usually defined as the time between hearth bottom relinings. Typically relining of the hearth bottom requires substantial time so refurbishing of other components is done concurrently. This increase in campaign life is illustrated by Dofasco No. 4 blast furnace. In the 1970s and early 1980s campaign life was only four to six years and usually limited by failure of the cooling/refractory system in the bosh/lower stack (Harshaw et al., 1985). This limitation was overcome with an upgrade in the cooling and refractory system in this area (Bean et al., 1988). The fourth campaign achieved 12 year duration and was limited by hearth wear (Parker et al., 2000). The current goal is for a 20 year campaign and the hearth is believed to be the limiting factor. Improvements in hearth design and refractory materials will contribute to extending hearth life, however, understanding of the processes within the hearth to enable the development of proper control methods is necessary to meet the challenge of long hearth life.

2.1.3.1 Hearth Design

Liquid iron and slag accumulate in the hearth and separate into layers due to the difference in specific gravity (~7.0 T/m^3 for iron, 2.7 T/m^3 for slag). The hearth is drilled periodically to tap these liquids through a taphole. At the end of drainage the taphole is plugged with refractory clay. These tappings coupled with natural convection currents generate internal liquid flows in the hearth.

The hearth is lined with carbon based refractories. Cooling is by sprays on the shell or by cooling panels (staves) with internal water pipes on the inside of the shell. Refractory wear can be due to the following mechanisms:

- Mechanical erosion by flow of iron and slag
- dissolution of carbon from refractory into iron
- chemical attack by zinc and alkalis
- Water/steam attack
- Stress cracking

The chemical based mechanisms are promoted by high carbon temperatures. Therefore some hearth designs incorporate features that keep the carbon temperatures low such as:

- ceramic cup technology (Bachhofen et al., 1999, Janz et al., 2003) where an inner lining zoned with low thermal conductivity material such as corundum and/or mullite placed in front of the carbon.
- thin wall high thermal conductivity carbon based technology such as at ArcelorMittal Dofasco No. 2 BF (Donaldson B., 2014) where heat transfer

is promoted such that a low conductivity skull of solidified iron is frozen on the carbon walls for protection.

However the design of the hearth alone has not guaranteed long service life. Over the span of a campaign the hearth will be challenged to meet additional productivity requirements and changes in raw materials. The operation of the hearth will have to be adjusted to meet the changing demands.

2.1.3.2 Flow of Liquids in Hearth

The effect of spatial distribution of coke in the hearth on the flow of liquids and their effect on the increase in heat transfer at the wall has been the subject of many investigations. A two dimensional physical model has been used to make a qualitative assessment of the effect of the shape of the coke free zone on hot metal flow patterns in the hearth (Peters et al., 1985). A coke bed with a convex shape sitting in the bottom center results in a coke free zone in the hearth corner that increases the flow in this area compared to a completely sitting coke bed. This increase in flow in the corners was considered to be a factor in the 'mushroom' wear observed in blast furnace hearths. Computational Fluid Dynamics have been used to solve the equations of continuity, motion and heat transfer for different coke free space shapes. It was found (Shibata et al.,1990) that the height of a uniform coke free gap between the coke bed and the hearth bottom determines the magnitude of the velocity along the hearth bottom. As shown in Figure 2.5 if the coke bed floats, to avoid excessive bottom wear it is desirable to avoid a small floating height as liquid velocity will be high. Similar results were obtained (Elsaadawy et al., 2005, 2006) with two and three dimensional modeling of hearth drainage. The maximum shear stress due to flow (indicator of mechanical forces on wall and heat transfer rates) moves away from the taphole as the gap height is increased. Other studies (Panjkovic et al., 2002, Zulli et al., 2002) which also used mathematical modeling to calculate the flow field and included heat transfer in the iron and refractories showed that natural convection currents are important for both the sitting and floating deadman condition.

All studies show that the position of the coke bed, i.e. sitting, partially sitting or completely floating influences the flow pattern of iron in the hearth. Thus it is important to understand the factors that influence the position of the coke bed so that appropriate control actions can be developed.

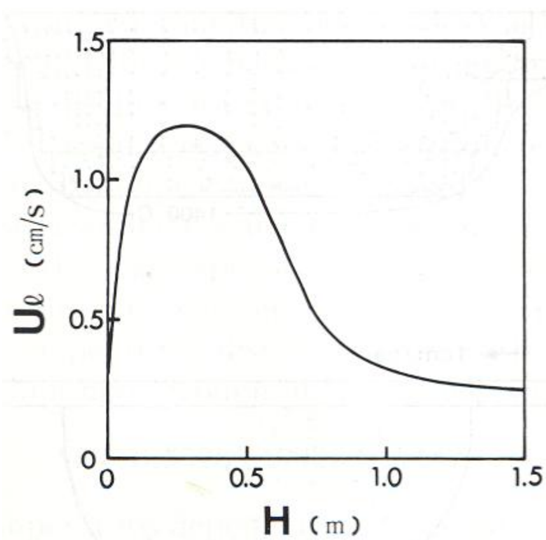


Figure 2.5 Effect of thickness of free space on velocity at the center of the hearth bottom (Shibata et al.,1990)

2.1.3.3 Factors Influencing Hearth Bed Sitting/Floating Status

The balance of the granular solid force from above and the buoyancy force due to the difference in density of the submerged coke particles and iron and slag (Figure 2.6) determines the depth of penetration of the coke bed into the liquid iron and slag. The granular solid force on the coke bed in the hearth is the net result of the force due to gravity, the frictional force between particles in the moving granular bed, frictional force between the wall and the moving granular bed and the drag/frictional force due to gas flow through the moving granular bed. Each component will be reviewed separately.

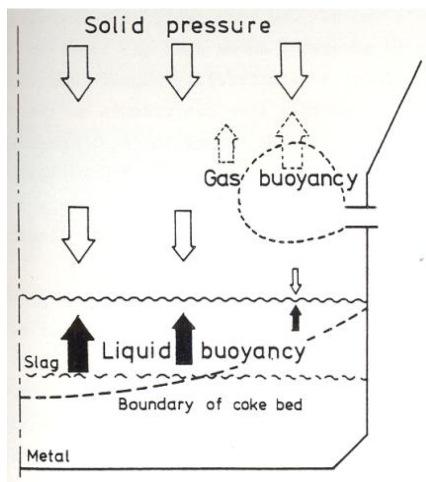


Figure 2.6 Balance of Forces acting on the coke bed in the hearth (Fukutake et al., 1981)

2.2 Granular and Gas Flows

This review will describe key features that should be considered when determining the forces on the granular materials within the blast furnace such as:

- The force on the granular materials due to gas flow

- The stress in granular materials due to granular flow
- relevant studies pertaining to the force on granular materials in the blast furnace

2.2.1 Force on Granular Bed due to Gas Flow

When a fluid passes through a granular bed a force, known as an interphase drag force, acts on the particles in the bed in the direction of the flow. This results in a pressure loss in the fluid. Most studies focus on measurement of the change in fluid pressure as it flows through the granular bed, however, the drag force on the granular bed can be determined if the pressure drop in the fluid per unit length of bed is known.

The pressure drop over a granular bed at low flow rates can be described by Darcy's law (Liu et al., 1994) that relates the pressure drop to granular bed and fluid properties according to the following relationship;

$$-\frac{\Delta P}{L} = \frac{\mu}{k} V \tag{2-1}$$

Here ΔP is the pressure drop across the bed, V is fluid velocity, μ is fluid viscosity, k is bed permeability and L is the length of the bed. Darcy's Equation is valid for low Reynolds number flows and Forchheimer (1901) suggested that departure from predictions at high velocities are due to the inertial effect of the fluid so an inertial term was added to account for this;

$$-\frac{\Delta P}{L} = \frac{\mu}{k} V + a\rho V^2 \tag{2-2}$$

where ρ is the density of the fluid.

Ergun (1952) used a wide range of experimental data to determine the coefficients and developed the following relationship;

$$-\frac{\Delta P}{L} = 150\frac{(1-\varepsilon)^2}{\varepsilon^3(\phi D_p)^2}\mu V + 1.75\frac{(1-\varepsilon)}{\varepsilon^3 \phi D_p}\rho V^2 \tag{2-3}$$

Where ε is the bed void fraction, ϕ is the particle spherocity, and D_p is the particle diameter. Although the relationship was empirically derived, the relationship has been validated by considering three dimensional flow for gas flow through spheres of different sizes and solving the Navier Stokes Equation for gas flow within the pores of granular solid (Fumoto et al., 2012). The Ergun Equation has been generalized to consider two and three dimensional flow through a granular bed in the vectorial form (Cross et al., 1979) as;

$$-\nabla P = (f_1 + f_2|\mathbf{V}|)\mathbf{V} \tag{2-4}$$

Where $f_1 = 150\frac{(1-\varepsilon)^2}{\varepsilon^3(\phi D_p)^2}\mu$ and $f_2 = 1.75\frac{(1-\varepsilon)}{\varepsilon^3 \phi D_p}\rho$

Initially effort (Stanek et al., 1972) was focused on the mathematics of applying the vectorial form of the Ergun Equation to describe the flow through a granular bed with varying permeability. This was expanded to include heat transfer in the packed bed (Stanek et al., 1973). Additionally the vectorial form of the Ergun Equation was solved simultaneously with the continuity equation (Stanek et al., 1974).This initial work was restricted to very simple geometries and spatial distribution of permeability. Extending this modeling approach to more realistic blast furnace arrangement by considering alternate layers of coke and ore in the stack of the blast furnace showed that the radial distribution of ore/coke and the relative difference in permeability between a coke and ore layer have a strong influence the gas flow pattern (Poveromo et al.,1975).

In addition to the vectorial form of the Ergun Equation, gas flow through a porous bed has been modeled by adding a momentum source term (Ansys Inc., 2009), to the standard Navier Stokes Equation for steady state incompressible flow, this has the form;

$$\rho(\mathbf{V} \cdot \nabla \mathbf{V}) = -P + \mu \nabla^2 \mathbf{V} + \mathbf{f}$$

where **f** is defined as the interphase drag force described using the Ergun Equation (Equation 2.3). This methodology has been used in the modeling of gas flow through the blast furnace in several studies (Kitaev et al., 1975, Chen et al., 1992, Dong et al., 2010, Safavi Nick et al., 2013). However, for the blast furnace the interphase drag force dominates so that the macroscopic convective acceleration term $\rho(\boldsymbol{V} \cdot \nabla \boldsymbol{V})$ and viscous effects can be ignored (Bennett et al., 1991). The inclusion of these terms has been shown numerically to have a small effect in the areas with change in gas flow direction such as the change from side entry at the tuyere to vertical flow in the shaft and at the interface between layers of coke and ore (Choudhary et al., 1976).

The validity of using the vectorial form of the Ergun Equation for the internal configuration of the granular materials in the blast furnace has been confirmed experimentally by Ohno et al. (1987) using a 3-D cold model that included blast furnace internal structure features such as ore and coke layers, side entry at the tuyere level and the presence of an impermeable cohesive zone.

For a two dimensional axisymmetric geometry an analytical solution exists for the solution of the Ergun Equation for flow only in the axial or radial directions.

2.2.2 Stress in Granular Bed due to Granular Flow

A granular material can be defined as an assembly of macroscopic, solid and discrete particles that are not bound together by significant attractive forces. Granular flow has two extremes, slow and rapid flows, for which the interaction between particles is different. For slow flows the granular particles interact frictionally through contact with their neighbours. An important feature is that shear stress in slow granular flow is independent of shear rate as represented in Figure 2.7. In rapid flows particles move independently of each other and interact through the transfer of particle kinetic energy and momentum at impact.

The thresholds for the granular flow regimes have been studied using experimental and numerical results for different flow configurations by Groupement de Recherche Milieux Divises (2004). It was found that the thresholds could be linked to the dimensionless rescaled shear rate;

$$I = \frac{\dot{\gamma} d}{\sqrt{P/\rho}}$$

where $\dot{\gamma}$ is the shear rate, P is the pressure, d is the particle diameter and ρ is the flow density. The quasi-static regime is valid for flow with $I < 10^{-2}$. In this regime shear stress is not a function of shear rate. Above this value inertial effects become important and shear stress is dependent on shear rate.

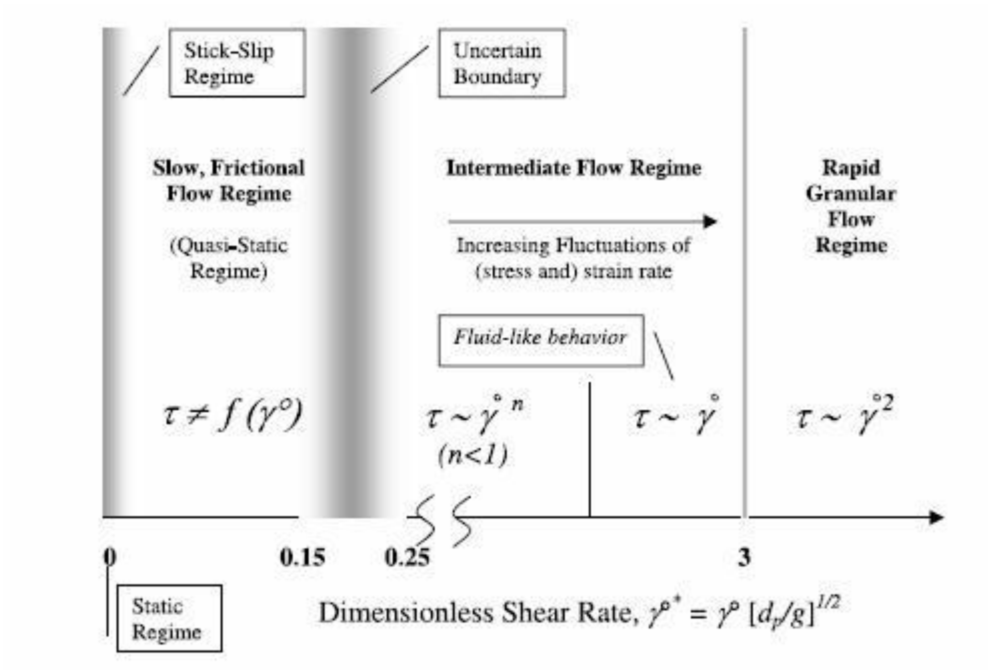


Figure 2.7 Regimes in Powder Flow (Tardos et al., 2003)

In general the stress in the granular bed has been determined using the following methods:

- Statistical collision models for rapid flows
- Discrete element models for slow and rapid flows
- Approximate analytical methods
- Frictional incremental plasticity models for slow flows

Early efforts were directed at calculating the stress exerted by granular materials on walls during storage and drainage of silos. This information was needed to develop appropriate engineering design for silos. Janssen (1895) derived a relationship for the prediction of static silo pressures based the equilibrium of forces on an infinitesimal slice and the following assumptions:

- Vertical stress is uniform across radius (one dimensional analysis)
- Ratio of horizontal to vertical stress is constant
- Granular material is homogenous and isotropic

This simple analysis shows that the vertical stress exerted by granular materials in a cylindrical silo is independent of height beyond a depth of 3-5 diameters depending on the type of granular material. This occurs because some of the weight of the stored materials is transferred to the walls by friction.

The pressures during discharge of a silo may be larger than the static condition. Walker (1966) and Walters (1973) expanded on the Janssen approach and considered the granular material to be on the verge of flowing everywhere, this requires that the state of stress must satisfy a yield criterion. They also considered the effect of silo geometry and identified that during flow the major principal stress direction is mainly vertical in the vertical section of the silo and switches to mainly horizontal in the converging section. This ‘switch’ in principal stress direction leads to high wall pressures which is important for silo design.

The statistical collision model is a continuum approach used to describe rapid granular flows. This method draws on an analogy with the kinetic theory of dense gases with the addition of energy dissipation due to inelastic collisions (Savage, 1984). This type of model is only applicable for rapid flow of granular material with low bulk density, this corresponds to only a very small region of the blast furnace, i.e. coke flow at or near the raceway. Also they are restricted to spherical particles which are not the case for coke.

The discrete element method (DEM) tracks the motion and interactions of each particle in the system. Interactions between particles are described by contact laws that define forces and moments resulting from the relative motion of the particles. Particle motion is determined by integration of Newton's second law taking in consideration the net force and moment on each particle. This enables the determination of the key aspects of granular flow behaviour, including granular stress, velocity and bulk density.

DEM was originally applied to regular shapes such as circular disks and spheres. However techniques have been developed to account for irregular shapes and varying size distributions (Alaa et al., 2003, Nazeri et al., 2000). Granular flow coupled with gas flow has been modeled using CFD to generate the force on the particle due to gas flow using a continuum approach and coupling this with DEM (Zhu et al., 2009).

Particle motion and interaction is calculated over a defined time step. This time step must be small enough that the particle only interacts with its nearest neighbors (Sitharam et al., 2000). This makes DEM computationally expensive for modeling steady state flows. This is also the case for systems with large number of particles.

A plasticity approach has been used to calculate the stress on granular materials for slow granular flow. Flow is represented by the irreversible deformation of a plastically deforming material. The flow is assumed to be quasi-static and the momentum equation in a Lagrangian framework reduces to;

$$\nabla \cdot \boldsymbol{\sigma} + \mathbf{f} = 0 \tag{2-5}$$

where $\boldsymbol{\sigma}$ is the stress tensor and $\mathbf{f}$ is the external body force vector (includes gravity and inter-phase drag forces). Typically the momentum equation is solved using the finite element methodology. A constitutive relationship is used to describe the incremental relationship between stress and strain. In the determination of the stress on granular materials in the blast furnace elastoplastic and hypoplastic constitutive relationships have been used and are described below.

2.2.2.1 Elastoplasticity

The total incremental strain ($d\varepsilon$) is decomposed into a reversible elastic ($d\varepsilon^e$) and an irreversible plastic ($d\varepsilon^p$) component in the elastoplastic approach;

$$d\varepsilon = d\varepsilon^e + d\varepsilon^p \tag{2-6}$$

Three components are required; a yield function, the plastic potential function and a hardening function. The yield function defines the stress state at which irreversible frictional slip between particles occurs and the material begins to deform (flow) plastically. Different yield functions have been proposed for granular materials. The first function proposed was the Mohr-Coulomb yield function which relates the shear stress at yield (τ) to the normal stress (σ) and two material parameter dependent parameters; the angle of internal friction (ϕ) and cohesion (c). This relationship has the form $\tau = c + \sigma \tan(\phi)$. The yield surface has corners when represented in terms of principal stresses in 3D space which can result in numerical problems when determining the direction of plastic flow. Smooth continuous yield functions such as the Druker-Prager (Drucker et al., 1953) overcome this problem however, the observed difference in stress for yield in compression and extension observed in granular materials (dependence of yield on the intermediate principal stress) is not represented in the original Drucker-Prager model. The Extended Drucker-Prager yield function (ABAQUS 2004) used in this thesis includes a dependence on the intermediate principal stress (Appendix 1). The yield function defines whether the material responds elastically or plastically to an increment in stress.

Once the granular material's stress state has satisfied the yield criteria it begins to deform plastically. The plastic portion of the deformation is assumed to be defined by a plastic potential flow rule which determines the relationship between incremental stress and plastic strain under multi-axial loading;

$$d\varepsilon^{p} = d\lambda \frac{\partial G}{\partial \sigma} \tag{2-7}$$

where λ is the plastic multiplier and G is the plastic potential. If the plastic potential is assumed to be equal to the yield function the flow rule is termed as associative, else it is termed as non-associative.

Granular materials exhibit hardening or softening depending on initial bulk density and normal pressure. To account for this it is assumed that the yield function is not only a function of stress state but of stress state and bulk density (Roscoe, 1970). Another approach is kinematic hardening (Voyiadjis et al., 1995) where the yield function is influenced by the direction of plastic strain.

2.2.2.2 Hypoplasticity

Hypoplasticity is an alternative to elastoplasticity that describes the mechanical behaviour of granular materials without additional terms such as a yield surface or a plastic potential and does not distinguish between elastic and plastic deformations. In the initial development (Kolymbas, 1991) the stress $d\sigma$ was described as a function of the strain $d\varepsilon$ and stress σ ;

$$d\sigma = C_1 \frac{1}{2}(\sigma\, d\varepsilon + d\varepsilon\, \sigma) + C_2\, tr(\sigma\, d\varepsilon) + C_3\, \sigma\sqrt{tr(d\varepsilon^2)} + C_4 \frac{\sigma^2}{tr(\sigma)}\sqrt{tr(d\varepsilon^2)} \qquad \text{(2-8)}$$

where C_1, C_2, C_3, C_4 are material constants.

The hypoplastic constitutive equation was expanded to include the influence of void fraction (e) (Gudehus, 1996) and has the general form $d\sigma = f(\sigma, e, d\varepsilon)$. The relationship was further improved to better describe critical state behaviour (Von Wolffersdorff, 1996).

2.3 Relevant studies pertaining to the Blast Furnace

Many studies have been made to determine the stress on granular materials in the blast furnace. Different approaches have been taken including perfect plasticity, DEM and incremental plasticity. A description and review of these studies is given in this section.

2.3.1 Perfect Plasticity

One of the earliest studies was by Polthier (1970) where a force balance was performed on a one-dimensional infinitesimal horizontal slice of the blast furnace. This was then integrated over the height of the furnace. The ratio of vertical to horizontal force was determined based on the assumption of the granular material being in the stress state of active failure everywhere. The effect of gas flow was included by superimposing a gas pressure drop distribution over the height of the furnace. The effect of wall friction was included.

Measurement of vertical and/or horizontal stress during granular flow with cold scale models of the blast furnace (Takahashi et al., 2002, Khodak et al., 1970) indicate that there is an large increase in the horizontal stress at the wall near the transition to the converging section of the bosh (Figure 2.8). This is attributed to the change in principal stress direction from vertical in the shaft to horizontal for the converging (confined by stagnant deadman and bosh wall) granular flow to the raceway. A representation of the change in principal stress direction for the static condition and at steady flow is shown schematically in Figure 2.9.

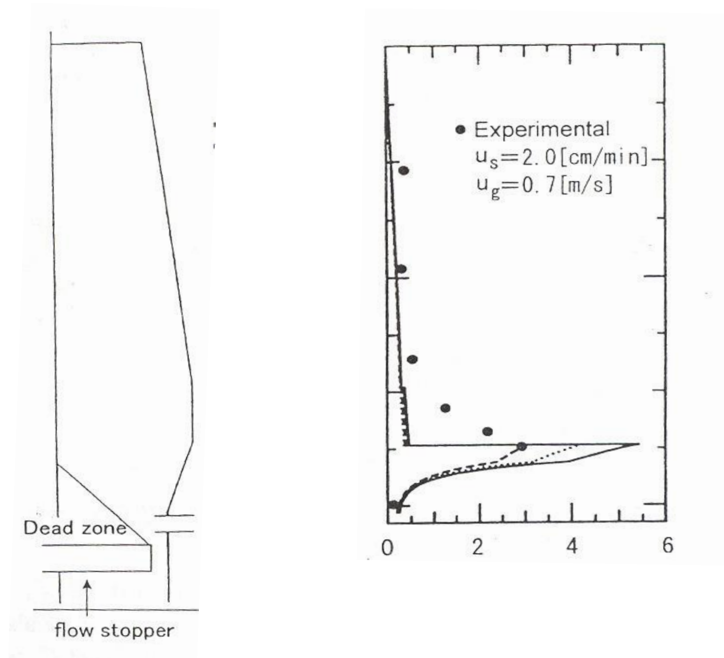


Figure 2.8 Wall Normal Stress in cold blast furnace model (Takahashi et al., 2002)

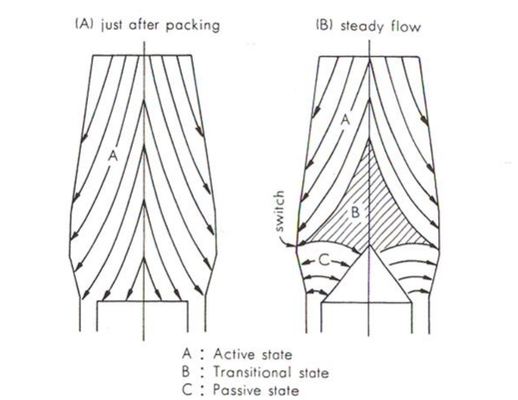


Figure 2.9 Principal stress direction after packing and at steady flow in the blast furnace (Shimizu et al., 1982)

The one-dimensional approach was refined by Ho et al. (1990) and Takahashi et al. (2002) to account for the change in principal stress direction by assuming passive failure in the bosh. Takahashi et al. (2002) included the effect of gas flow using the Ergun's Equation and an assumed deadman (stagnant zone) shape to resolve the shear and normal forces on the deadman surface.

The perfect plasticity approach has the following drawbacks:

- Location of the switch from passive to active failure is assumed and set at one point along height, when there is likely a smooth transition
- One-dimensional analysis, therefore the two-dimensional effect on the interphase drag force due to gas flow due is not included
- only one material property was used, therefore the layered structure of the blast furnace was not considered .

2.3.2 Discrete Element Method (DEM)

The Discrete Element Method has been used to study specific aspects of granular flow in the blast furnace such as the movement of coke in the hearth during the accumulation and discharging of liquids in the hearth (Kawai et al., 2004) the effect of coke consumption point on the movement of coke in the hearth (Nouchi et al., 2002) and gas-solid flow in the raceway (Xu et al., 2002)

DEM has been used to study the effect of gas flow and cohesive zone structure on granular flow in the blast furnace (Zhou et al., 2003). This study will be described in more detail.

The translational and rotational motions of each particle are described using Newton's second law of motion;

$$m_i \frac{dv_i}{dt} = F_{f,i} + \sum_{u=1}^{k_i} (F_{c,ij} + F_{d,ij}) + m_i g$$

$$I_i \frac{d\omega_i}{dt} = \sum_{j=1}^{k_i} (M_{t,ij} + M_{n,ij})$$

where v_i, ω_i are the translational and angular velocities of particle *i*, $F_{f,i}$ is the particle fluid interaction force, $m_i g$ the gravitational force, $F_{c,ij}$ and $F_{d,ij}$ are inter particle forces between particles *i* and *j* accounting for elastic force and a viscous damping force. The torque acting on particle *i* by particle *j* include the torque from tangential force $M_{t,ij}$ and the torque from rolling friction $M_{n,ij}$.

A separate continuum model based on the finite difference method was used to solve the continuity and Navier-Stokes Equations for the gas velocity field. Using this, and an appropriate fluid drag coefficient, the particle-fluid interaction force was determined.

A two-dimensional scale blast furnace model was used to compare the calculated solid flow patterns without gas flow. Numerical simulation results show that increasing the gas flow increased the size of the stagnant coke zone (deadman) as shown in Figure 2.10.

The effect of the cohesive zone was included in the simulations by defining ‘blocks’ that were impermeable to gas flow but do not hinder particle motion. The shape of the cohesive zone (V versus inverse V) had a significant influence on the size of the stagnant coke zone.

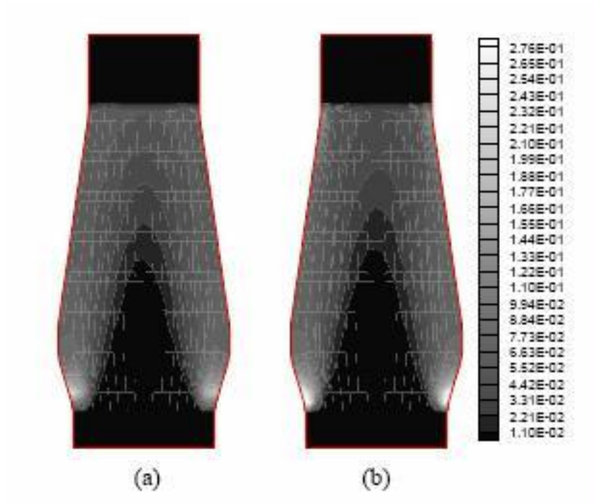


Figure 2.10 Time averaged solid velocity field for different gas velocity (a) 6 m/s (b)15 m/s ((Zhou et al., 2003)

This study was limited to a scale model of the blast furnace and 14000 particles used in the DEM simulations. Despite the limitation in number of particles due to the computational expense this study shows that DEM is useful for qualitatively describing the phenomena in the blast furnace.

Nouchi et al. (2005) divided the blast furnace into two regions, one above the raceway and one below, and output from the upper DEM model is used as a boundary condition for the lower hearth model. The objective of this study was to calculate the effect of hearth depth on the shape of the coke free space in the hearth. Particle size was 0.2 m in the upper and 0.1 m in the lower model. 30000 particles were used in each model. Gas flow and the effect of the cohesive zone were not included. The study showed that hearth depth and load on the hearth were important variables for determining the coke free space distribution.

DEM coupled with a gas flow model (required for calculation of the drag force on granular particles) has the capability to describe the forces on granular materials in the blast furnace. The limitation is that it can only be used in a qualitative manner as it is computationally prohibitive to include the actual size and quantity of particles in the blast furnace.

2.3.3 Incremental Plasticity

Both the Elastoplastic and Hypoplastic approaches have been used to determine the stresses in granular materials in the blast furnace.

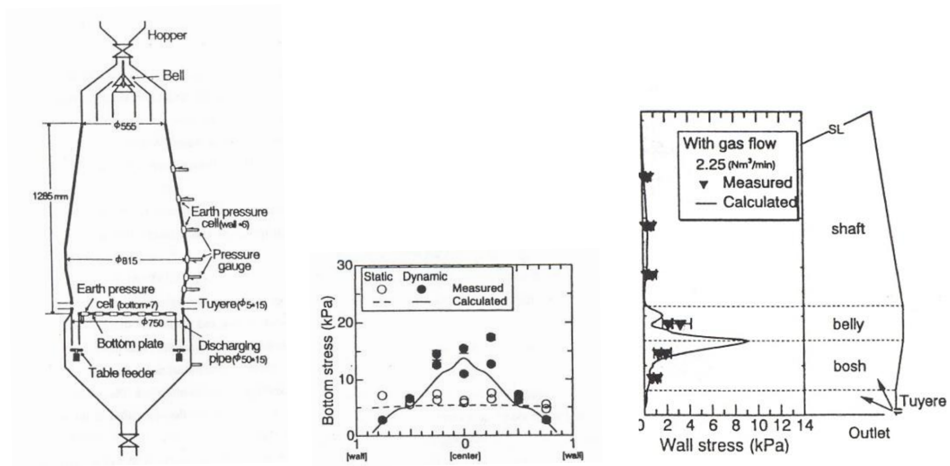
2.3.3.1 Elastoplasticity

Katayama et al. (1998) used an elastoplastic approach to determine the stress on granular materials in the blast furnace. Yield condition is based on the extended Drucker–Prager model using an associative flow rule. Verification of the mathematical model was done using a 1/20th scale three-dimensional model outfitted with pressure gauges in the wall and bottom (at tuyere level). The experimental results highlight several key aspects of the stress in granular materials in the blast furnace such as the increase in stress at the center of the bottom and the increase in wall stress at the transition between the belly and bosh wall compared to the static condition (Figure 2.11). The measured values of the wall stress are in agreement with the numerical results in the shaft. The location of the pressure probes in the belly and bosh do not allow assessment of the pronounced peak in wall stress predicted by the numerical model at the transition from the belly to the bosh. Mohr-Coulomb model parameters such as angle of friction (ϕ) and cohesion (c) were generated experimentally for coke.

Katayama et al. (1998) also estimated the stress field in a large blast furnace (inner volume 5050 m^3) using the elastoplastic approach. Information such as the density of the burden and the gas pressure drop were provided from a separate model (Inada et al., 2003, Takatani et al., 1999), which considers reactions between gas, liquid and solids and the conservation of mass, momentum and energy. The results do include the effect of the cohesive zone and its influence on the inter-phase drag force due to gas flow.

This study does produce an estimation of the stress on granular materials for the operating blast furnace for a single operating condition (not defined). The influence of process variables and raw material properties were not explored.

The elastoplastic model was also used to calculate the effect of furnace profile on the stress on the granular materials in the blast furnace (Inada et al., 2003). The effect of gas flow was not included. For a constant target furnace inner volume the furnace shape influences the stress distribution. Decreasing the bosh angle reduces the vertical stress at the tuyere level center. The effect of gas flow was only determined for the vertical stress at the tuyere level. This was estimated by applying a correction based on the calculated overall pressure drop from tuyere level to furnace top to the ‘no gas flow’ result at the tuyere level. A further study on the effect of furnace size showed that the vertical stress at the tuyere level center increases with increasing furnace inner volume (Inada et al., 2003).



(a) (b) (c)

Figure 2.11 (a) Measurement locations (cold model),(b) Stress Distribution at bottom, and (c) wall (Katayama et al.,1998)

2.3.3.2 Hypoplasticity

Zaimi et al. (1998) used a hypoplastic constitutive equation to describe the relationship between incremental stress and strain rate in this model of granular flow in the blast furnace. The granular flow velocity and stress distributions calculated do not consider the effect of the inter-phase drag force due to gas flow. The stress distribution due to granular flow showed the same general features as Katayama found using the elastoplastic constitutive equation, i.e. a large vertical force at the furnace tuyere level centerline which decreases to zero at the wall, and a switch from mainly vertical to horizontal forces at the wall in the transition from the belly to bosh. A Lagrangian frame of reference was used which required several remeshings until a steady state stress and velocity field was obtained.

Verification of this model (Zaimi et al., 2000) was done by comparing the position of markers after a specified time interval in a three dimensional cold model (Chen et al., 1993) with a numerical prediction. The effect of gas flow was included numerically by inclusion of the Ergun gas-solid drag force to the external body force term in the momentum equation. It was found that the effect of gas flow was to increase the height of the stagnant coke bed (deadman) at the centerline of the furnace.

To include the effect of blast furnace conditions the granular flow model was coupled (Zaimi et al., 2000) with the so called ‘four fluids’ model (Austin et al., 1997) which includes chemical reaction between gas, liquids, powder and granular solids by solving the conservation of mass, momentum and energy equations for each phase. The original granular flow model in the ‘four fluids’ model is based on a viscous flow model where the granular flow is treated as a continuous flow of a viscous fluid. This is replaced by the granular flow model utilizing the hypoplastic constitutive relationship. The models are loosely coupled where each model is run separately with results from the fluid flow model such as the density field and the inter-phase drag force are used as input to the granular flow model. Output from the granular flow model such as the velocity field and the voidage are then used as input to the fluid flow model. This is repeated until a converged solution is obtained.

The resulting stress field for the coupled model is shown in Figure 2.12. The focus of the paper was the methodology for coupling the four fluid model (finite difference methodology) and the granular flow model (finite element methodology). No interpretation of the effect of the inclusion of gas flow (and the redirection of gas flow by the cohesive zone) was presented. A single blast furnace operating condition was considered. The influence of process variables and raw material properties were not explored.

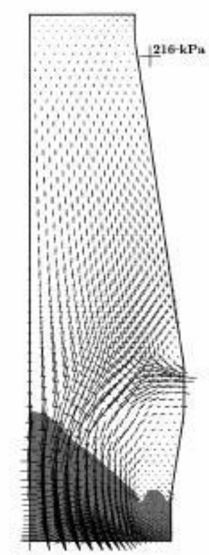


Figure 2.12 Stress field in the blast furnace (Zaimi et al., 2000)

2.4 Literature Review Summary

The ironmaking blast furnace is an important industrial process. The fundamentals of thermal and chemical phenomena within the process are well understood. However, the current understanding of mechanical phenomena especially relating to how process parameters affect the spatial distribution of forces on the coke bed in the hearth is rather limited. A resolution of forces determines the position of the floating coke bed in the hearth which has a significant effect on hearth refractory wear and thus the economics of the blast furnace process.

In order to determine the spatial distributions of forces on the hearth coke bed it is necessary to consider the forces due to mechanical interaction over the entire furnace volume. This includes the interaction between the countercurrent flowing gas and granular solid phases (coke and ore) and the interaction between granular particles due to granular flow. Body forces such as gravity and buoyancy (for particles immersed in the liquid pool in the hearth) must also be included.

The forces on granular materials due to the interaction of gas and granular solids have been determined using the Ergun's Equation (Ergun, 1952). This equation has been used widely and successfully to relate the force on granular materials due to gas flow through a packed bed to the granular bed properties (voidage and particle diameter) and gas properties (density and viscosity) and gas velocity. The vectorial form of the Ergun's Equation has been shown to be appropriate for describing the gas flow through the main internal features of the blast furnace (Stanek et al., 1972, 1973, 1974, Poveromo et al., 1975, Ohno et al., 1987).

The force on granular materials due to the interaction between granular particles during granular flow can be determined using DEM (discrete element method) (Kawai et al., 2004, Nouchi et al., 2002, Xu et al., 2002, Zhou et al., 2003, Nouchi et al., 2005). In this method the interaction between individual particles is considered. Particle motion is determined by integration of Newton's second law of motion while taking into account the forces and moments (due to friction, gravity, etc.) on each particle. This method is attractive as it models granular flow at a basic level using fundamental physical laws. DEM has been used to simulate specific and smaller areas of the blast furnace (raceway, coke movement in the hearth). However, for the present work due to the extremely large number of particles involved and the necessity of obtaining a steady state solution the use of DEM to describe the granular flow and the force on granular materials for the entire blast furnace is computationally not practical.

The alternative to DEM for determining the force on granular materials due to particle interaction during granular flow is to approximate the granular material as a continuous phase and use an incremental plasticity approach (Katayama et al., 1998, Inada et al., 2003, Zaimi et al., 1998, 2000, 2003). With this approach granular flow is represented as a plastically deforming material. The momentum equation is typically solved using finite element techniques and requires a constitutive relationship to describe the relationship between incremental stress and strain rate. Both the elastoplastic and the hypoplastic approach have been used to describe the stress-strain constitutive relationship for granular materials in the blast furnace (Katayama et al., 1998, Inada et al., 2003, Zaimi et al., 1998, 2000, 2003). Both approaches were validated using scale cold models of the blast furnace and have shown that furnace shape and size has a large influence on the stress distribution (considering only granular particle interaction) on the granular materials in the blast furnace.

It has to be made clear that some of the literature reviewed on the application of stress computation in the name of “blast furnace investigation” is in a sense misleading. In these computations the temperature of the system has been considered to be uniform, constant and of ambient value. For their validation it has been done properly by comparing with measurement obtained in cold models of blast furnace. In view of the complexity of a blast furnace, including heat transfer and chemical reactions, the assumption of constant temperature, and without chemical reactions, did allow these authors to obtain interesting results, otherwise, it would not be possible. An alternative approach has been attempted by Zaimi et al. (2000). In the only paper published, they calculated the gas and solid temperature fields, gas composition and velocity fields, using a blast furnace model that solves the equations for conservation of mass, momentum and energy. These results were coupled to a granular flow model. Therefore the effect of temperature was included in the determination of the gas solid inter-phase drag force at each element and the cohesive zone was defined. Despite the sophistication of the models used, this effort has contributed little value on the effect of process parameters on the stress distribution in the blast furnace as only a single case was presented. The cause and effect of variation in process parameters and raw material properties was not explored.

The building blocks for performing a force balance in the blast furnace are in place with methods available to determine the forces due to gas/solid interaction and granular flow. What is lacking is knowledge on the effect of process parameters and raw material properties for blast furnace conditions.

2.5 Knowledge gap

Mathematical models that include mechanical interaction (gas/solid, solid/solid, solid/wall) have been developed to determine the spatial distribution of forces on the granular materials within the blast furnace. These models have been used mainly to establish the influence of furnace shape and size. Process knowledge including the cause and effect of process parameters (including rate of gas flow, system pressure, level of injectant, distribution of granular materials) and raw material properties (softening/melting temperature) has not been developed.

2.6 Goals of the present work

The goal of this thesis work is to advance knowledge on the force balance on granular materials in the interior of blast furnace and on walls. Specifically, a mathematical model based on the principles of fluid and granular flows will be developed to generate new knowledge on the influence of parameters under control of the blast furnace operator on the granular stress at the level of the gas inlet and the walls. Parameters will include the influence of the layered structure of granular materials, granular material properties and mass flow rate of gas.

Information generated in this thesis can be used by blast furnace operators as theoretical guidance and defining the force at the boundary for subsequent studies of hearth region.

Chapter 3 Mathematical Model of System

The objective of the proposed model is to calculate the stress on granular materials in the blast furnace. Above the tuyere level, this stress is the result of the interaction of multiple forces, downward force of gravity acting on the granular materials, the friction between granular materials and between the granular materials and furnace wall and the drag exerted by upward moving reducing gases from the tuyeres. Below the level of the tuyeres, the buoyancy force on the submerged hearth coke bed must be included.

Operator control is exerted at the tuyeres through modulation of the gas and heat input and at the furnace top through changes in the ore to coke ratio and radial distribution of the materials. The blast furnace is divided into two regions with the dividing boundary at the tuyere level. The region between the tuyeres and the furnace top is modeled as a slow moving gravity driven granular flow coupled with gas flow. The effect on the hearth is assessed through the change in the calculated stress at the tuyere level (the upper boundary of the hearth).

To simplify the system, all chemical reactions are ignored and only mechanical interaction is included. The furnace is considered as axisymmetric. The temperature of the system is specified as a function of furnace height and radius. The granular flow model gives the relationship between granular stress and displacement for a granular material subjected to external forces or displacement. A separate sub model determines the external force on granular material due to interphase drag. This is used as input as an external force in the granular flow model. The inclusion of the interphase drag force due to gas flow allows the overall model to be representative of counter current flow of gas and granular material.

3.1 Mathematical Model of Granular flow

The governing equation used to determine the stress on the granular materials in the blast furnace is a force balance where the change in the rate of momentum is equal to the sum of forces acting on the body:

$$\rho \frac{\partial \mathbf{v}}{\partial t} = \nabla \cdot \boldsymbol{\sigma}_{\mathbf{tot}} + \mathbf{f} \tag{3.1}$$

where ρ represents the density, $\frac{\partial \mathbf{v}}{\partial t}$ the rate of change of velocity, $\boldsymbol{\sigma}_{\mathbf{tot}}$ the total stress tensor and **f** the external body force (such as gravity).

For the assumption that granular flow is in the blast furnace is quasi-static (inertial term is insignificant due to the low granular flow rate in the blast furnace), the force balance reduces to;

$$\nabla \cdot \boldsymbol{\sigma}_{\mathbf{tot}} + \mathbf{f} = 0 \tag{3.2}$$

The total stress tensor in a granular media is composed of two parts;

$$\boldsymbol{\sigma}_{\mathrm{tot}} = \boldsymbol{\sigma}_{\mathrm{eff}} + p\,\mathbf{I}$$

where $\boldsymbol{\sigma}_{\mathbf{eff}}$ represents the effective stress tensor, p the fluid pressure, and $\mathbf{I}$ the identity matrix. Effective stress is the stress that produces deformation in the solid skeleton of the porous medium (Bishop, 1959).

Equation 3.2 in terms of effective stress becomes;

$$\nabla \cdot \boldsymbol{\sigma}_{\mathbf{eff}} = \mathbf{f} - \nabla p \tag{3.3}$$

Equation 3.3 is converted from the differential form to an integral form using the principle of virtual work to produce the weak form of the equilibrium equation;

$$\int_V \delta\boldsymbol{\epsilon}^T \boldsymbol{\sigma}_{\mathbf{eff}}\, dV = \int_V \delta\mathbf{u}\, \mathbf{b}\, dV + \int_S \delta\mathbf{u}^T\, \mathbf{t}\, dS \tag{3.4}$$

Where $\delta\boldsymbol{\epsilon}$ and $\delta\mathbf{u}$ are the virtual strain and virtual displacement quantities, $\mathbf{t}$ are the external surface forces and $\mathbf{b}$ the body forces ($\mathbf{b} = \mathbf{f} - \nabla p$). The effective stress and displacement fields for Equation 3.4 are solved using the finite element methodology using commercial software ABAQUS (ABAQUS, 2004) with the assumption that stress increments are a function of strain increments according to;

$$d\boldsymbol{\sigma}_{eff} = D^{ep} d\boldsymbol{\epsilon} \tag{3.5}$$

where D^{ep} is the Jacobian matrix of the constitutive equation for the granular material. The stress and displacement field for a combination of displacement and stress at the boundaries and body forces can be calculated. Only effective stress is reported in this thesis.

3.1.1 Constitutive Equation

The constitutive equation used is the Extended Drucker-Prager relationship as used by ABAQUS (ABAQUS, 2004) due to its simplicity and the fact that it includes the main features describing the response of a granular material under load such as the pressure and intermediate stress dependence of the yield function, inclusion of volume changes, and its use of commonly measured parameters. The granular bed is considered to have an elastic perfectly plastic response under load. It deforms as an elastic material until the yield condition is met, then the bed deforms plastically. A complete description of the Extended Drucker-Prager constitutive relationship is given in Appendix 1. The elastic material parameters required are the elastic modulus and Poisson ratio. The plastic material parameters include internal angle of friction, cohesion and dilatation angle. These parameters are stated for each simulation presented. The materials in the blast furnace, coke and iron ore pellets are considered as cohesionless, however a small value of 100 N/m^2 is used to provide numerical stability (Goodey et al., 2003). The initial packing of the material (dense or loose) can result in a volume change when plastic deformation occurs. However, if the material is flowing the volume can be considered as constant (Karlsson et al., 1998). Therefore, the dilatation angle used is zero. The extended Drucker-Prager model uses the relationship $K = \frac{3 - sin\varphi}{3 + sin\varphi}$ to include the dependence of the yield surface on the value of the intermediate principal stress (ABAQUS, 2004). A value of $K = 0.8$ is used for all simulations to ensure that the yield surface remains convex.

3.1.2 Geometry and Mesh

A two-dimensional axisymmetric geometry is used in this study. The region above the tuyere level is considered in the granular flow model as the flow is gravity driven and majority of granular flow occurs above the tuyeres due to movement driven by the consumption of coke at the tuyeres. The dimensions of the model are dependent on the case being modeled (scale model or full scale blast furnace). In all cases for the wall, the transition between zones was smoothed by assigning a radius of 20% of the belly radius. For simulations of the commercial blast furnace a layered structure was used with the iron ore pellet and coke layer thickness reflecting the ore/coke level specified. The ABAQUS CAX4 four node bilinear axisymmetric quadrilateral element with four integration points per element is used.

3.1.3 Boundary Conditions

The boundary at the tuyere level is fixed for the application of the gravity load. For the granular flow step the raceway nodes are displaced vertically in the direction of gravity.

The interaction between the rigid wall and the granular material is modeled as a contact surface with no separation allowed between the wall and granular material. Friction between the granular material and the wall is based on the principal of Coulomb friction where the critical shear stress between the granular material and the wall is given by;

$$\tau_{critical} = \mu P \tag{3.6}$$

where $\tau_{critical}$ is the shear stress where the granular material will slide relative to the wall, μ is the friction coefficient and P is the normal pressure exerted by the granular material on the wall.

3.1.4 Solution Methodology

Simulation of granular flow in the blast furnace (without gas flow) with Equation 3.3 is accomplished by applying a displacement boundary condition at the raceway location and a friction boundary condition on the walls (Figure 3.1). The external force is gravity. The solution is the stress and displacement field. The commercial finite element software ABAQUS (ABAQUS, 2004) is used to solve Equation 3.3.

The solution methodology is as follows:

1) Application of gravity force with no displacement at the tuyere level. This represents the static condition (no granular flow).
2) Displacement of the nodes in the tuyere region. This represents the movement of granular material due to the consumption of coke in the raceway. This displacement is continued to the point where the stress field becomes independent of displacement.

A mathematical framework based on the momentum balance has been implemented that is capable of calculating the stress on granular material subjected to external forces and displacement. The extended Drucker–Prager constitutive model is used to provide the link between incremental stress and strain. For the representation of flow of a granular material in the blast furnace, the key assumption is that the flow is quasi-static whereby stress is independent of rate of displacement.

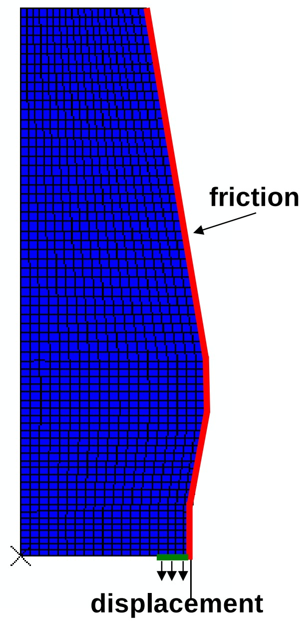


Figure 3.1 Blast Furnace Geometry and Boundary Conditions

3.1.5 Force of Gas on Granular Solids

The external force on the granular bed exerted by the flow of gas through the granular bed is calculated using the Ergun Equation (Ergun, 1952). The Ergun Equation for steady state flow in multidimensional space in the vectorial form (Stanek and Szekely,1972) based on the mass flow vector **G** (kg/m^{2}s) is given as;

$$\nabla P = -(\mathrm{f}_1 + \mathrm{f}_2|\mathbf{G}|)\mathbf{G} \tag{3.7}$$

$$f_1 = 150\frac{\mu(1-\epsilon)^2}{\rho\varepsilon^3(\varphi D_p)^2}$$

$$f_2 = 1.75\frac{(1-\epsilon)}{\rho\varepsilon^3\varphi D_p}$$

where P is the gas pressure, ϵ the bed void fraction, φ the particle spherocity, and D_p is the particle diameter.

Assuming that the change in **G** is negligible in a small region, the Ergun equation can be linearized (Yagi et al., 1980) as;

$$\nabla P = -{}^{\mathbf{G}}/_{a_o}$$

Where

$$a_o = \frac{1}{f_1 + f_2\,|\boldsymbol{G}|}$$

Assuming no sources or sinks of mass, the equation of continuity is

$$\nabla \cdot \mathbf{G} = \mathbf{0} \tag{3.8}$$

Combining the linearized Ergun Equation and the continuity equation the resulting governing equation for gas-solid interaction is;

$$\nabla \cdot (a_o \nabla P) = 0 \tag{3.9}$$

Equation 3.9 has the same form as the steady state heat transfer differential equation. ABAQUS (ABAQUS, 2004) commercial software that is based on solving the steady state heat transfer equation is adapted to solve Equation 3.9. The Galerkin method is used by ABAQUS to rewrite Equation 3.9 in a form suitable for descretization. The user subroutine UMATHT is used to calculate the value of a_o for each iteration. The influence of gas temperature and pressure on the gas density is determined using the ideal gas law to obtain the relationship;

$$\rho_{T,P} = \frac{P\ T_o}{P_o T} \rho_{T_o,P_o}$$

where ρ is the gas density, P is the gas pressure, T is the gas temperature and the subscript o is for standard conditions (1 atmosphere pressure and 25 °C temperature). The interphase drag force in the axial direction $\frac{\partial P}{\partial z}$ and the radial direction $\frac{\partial P}{\partial r}$ (N/m^3) is determined at each integration point.

Boundary conditions are specified as gas mass flow rate at the tuyeres (small opening in wall at base of model), no gas flow through the remainder of wall or through the lower boundary and gas pressure at the top of the furnace. The inter-phase drag flow is dependent on the granular properties ε, Φ, d and the gas properties ρ and μ. The ABAQUS DCAX4 four node linear axisymmetric quadrilateral element with four integration points per element is used. The same mesh dimensions as the granular flow model is used to enable transfer of values to the granular flow model.

The force on granular materials due to gas flow through the granular bed is represented as an external force in the momentum equation. The Ergun Equation in multi dimensional space is solved to determine the magnitude and direction of this force based on gas mass flow rate and gas and granular bed properties.

3.2 Counter-Current Granular and Gas Flow

The external force due to interphase drag (Section 3.1.5) is included in the granular flow model (Section 3.1) as an external body force which makes the model representative of counter current granular and gas flows, this is the essence of blast furnace, except raceways and hearth.

The interphase drag due to gas flow through the granular bed is calculated externally to the granular flow model. The output from the gas flow model is included in the granular flow model as a body force.

Chapter 4 Computational Results at Ambient Temperature

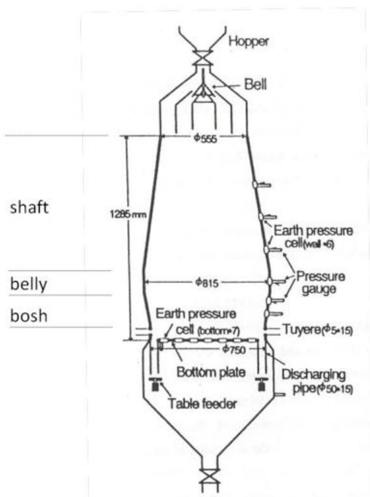
The computed results from the mathematical model (based on Equation 3.3) are compared to data generated on scale models with blast furnace geometry and the granular material and gas at ambient temperature. Conditions considered are granular flow only and combined granular and gas flow. The comparison for the granular flow and combined granular and gas flow is based on the vertical stress at the bottom and the normal stress at the wall. The gas flow model (based on Equation 3.9) is used to calculate the force on granular materials by gas flow. The computed results from this model are compared to the analytical solution for the one dimensional configuration (radial and axial directions). The two dimensional computed results are compared to the measured gas wall pressure distribution on a blast furnace scale model obtained from the literature. Also, the choice of constitutive equation is examined by comparing results with the results found in literature when using an alternative constitutive relationship.

Based on the comparisons between the computed model results and the scale blast furnace physical model data the validity of the present model is assessed.

4.1 Granular Flow Only with Blast Furnace Geometry

The experimental results reported by Katayama et al. (1998) for a 1/20th scale physical model of the blast furnace are compared to the results of the mathematical model (Equation 3.3) for the condition of granular flow at ambient temperature. The experimental arrangement and granular material properties are shown in Figure 4.1. Coke particles between 0.5 and 1.0 mm were used.

The geometry and material parameters stated by Katayama were used in the mathematical model proposed in Chapter 3.

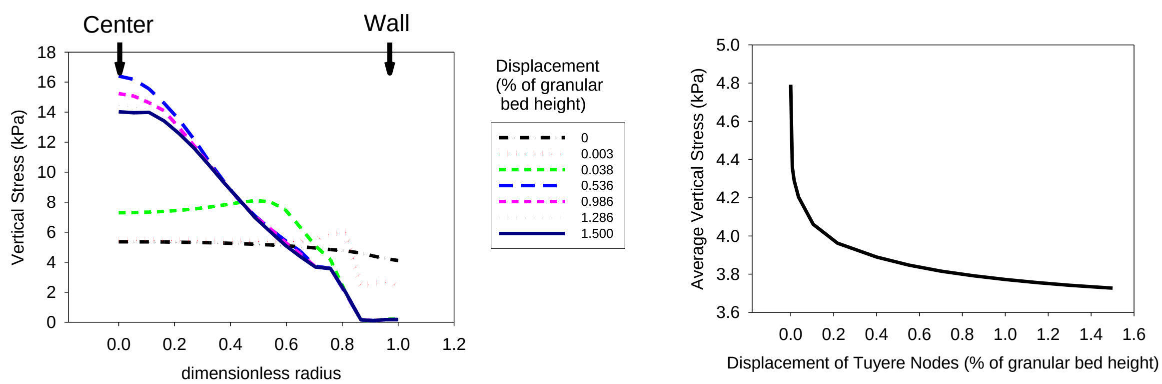


Item/Material	Coke
Bulk density (kg/m^3)	620
Angle of internal friction (deg)	32
Angle of friction between solid and wall (deg)	20
Young’s Modulus (MPa)	5.0
Poisson’s modulus (-)	0.3

Figure 4.1 Blast Furnace Model and Granular Properties used by Katayama et al. (1998)

The experimental results from Katayama include the bottom vertical stress and the wall pressure for the static (no granular flow) and dynamic (with granular flow) conditions. The static condition for the model simulation of Katayama’s experiment is obtained by solving Equation 3.3 for the application of the gravity load with the boundary condition that there is no movement (displacement) of the granular material beyond the boundaries (wall and bottom). The solution for the static condition results in a relatively even radial distribution of the vertical stress at the tuyere level with a slight reduction at the walls (Figure 4.2a). For the dynamic condition, displacement beyond the boundaries (wall and bottom) is not allowed except for a vertical displacement in the tuyere area. This represents the granular flow condition. With the present formulation the terms granular flow and displacement are interchangeable as the assumption is that the flow is quasi-static (Section 3.1). As the displacement increases the vertical stress (compressive vertical stress is reported as positive) in the tuyere area decreases and the peak vertical stress increases and moves closer to the center axis of the furnace (Figure 4.2a). Also, as displacement of the tuyere nodes increases the radial vertical stress distribution at the tuyere level becomes independent of displacement. This is reflected in reduction in the rate of change of the average vertical stress at the tuyere level with displacement (Figure 4.2b). Since further displacement of the tuyere nodes do not change the solution of the stress field significantly beyond one percent of the granular bed height, this is considered to be representative of the solution for the steady state granular flow in this study.

The calculated effective stress at the bottom and wall for the static (gravity only) and dynamic (granular flow) conditions (as shown in figure 4.3) compare well with the experimental data. The increase in the vertical bottom stress near the furnace center and the increase in pressure exerted by the granular material on the wall in the belly region for the dynamic (granular flow) condition indicate that with granular flow a fundamental change in the stress field occurs. The stress field changes from a mainly vertical principal stress over the entire furnace volume for the static condition to an arch of principal stress over the tuyere zone which results in a mainly horizontal principal stress near the belly region as shown in Figure 4.4. This is consistent with the results of Zaimi et al. (2000) and Shimizu et al. (1982).



(a) (b)

Figure 4.2 (a) Radial Vertical Stress at the Tuyere Level with Displacement of the Tuyere Nodes
(b) Evolution of Average Vertical Stress at the Tuyere Level with Increased Displacement of the Tuyere Nodes

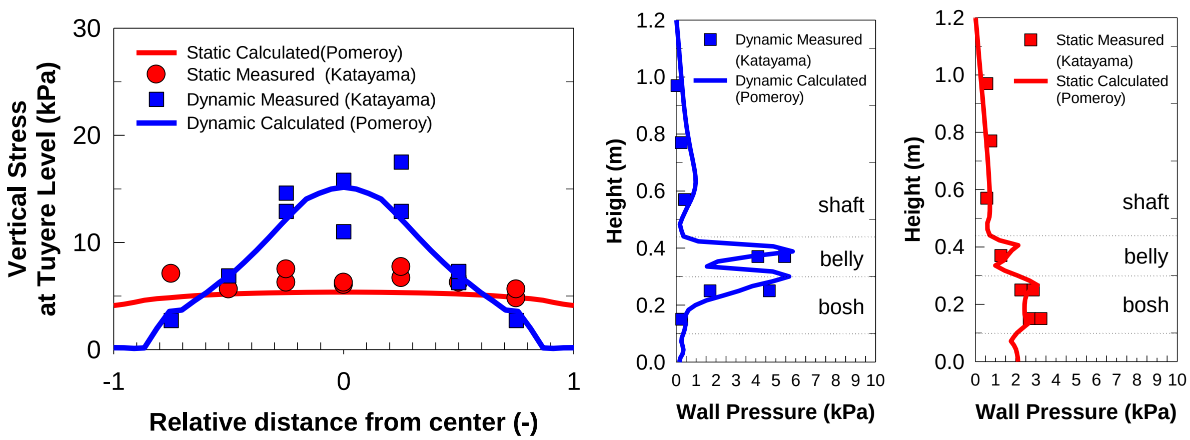


Figure 4.3 Comparison of Vertical Stress(at tuyere level) and Granular Wall Pressure between Mathematical Model (Pomeroy) and Experimental Model Results of Katayama et al. (1998)

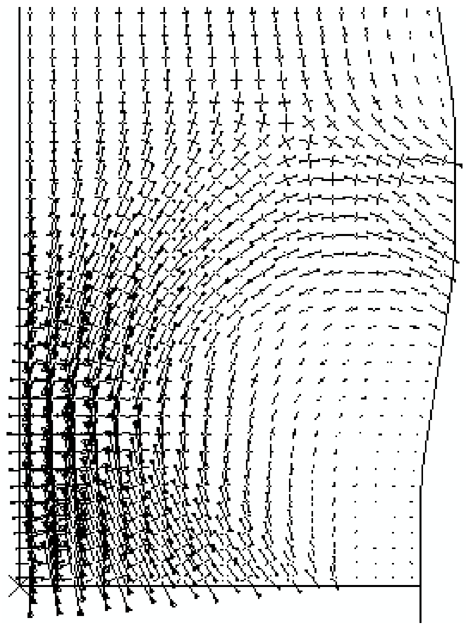


Figure 4.4 Calculated Principal Stress direction for the Experimental Conditions of Katayama et al. (1998) with Granular Flow

The simulations presented in Figure 4.3 each contained 1100 elements. The effect of element size is explored by comparing the computed results for vertical stress at the tuyere level and granular pressure at the wall when using 132, 538, 1188 and 2112 elements. The initial finite element mesh for each case is shown in Figure 4.5. The difference in the calculated results for the vertical stress peaks at the tuyere level in the furnace center and the maxima in wall pressure decrease with increasing mesh density as seen in Figure 4.6. The number of elements greater than 1000 for all subsequent simulations.

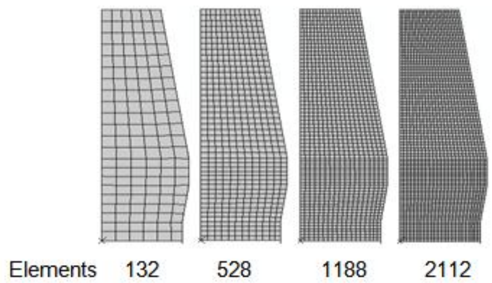


Figure 4.5 Finite Element Mesh considered for evaluation of effect of element size on computed results

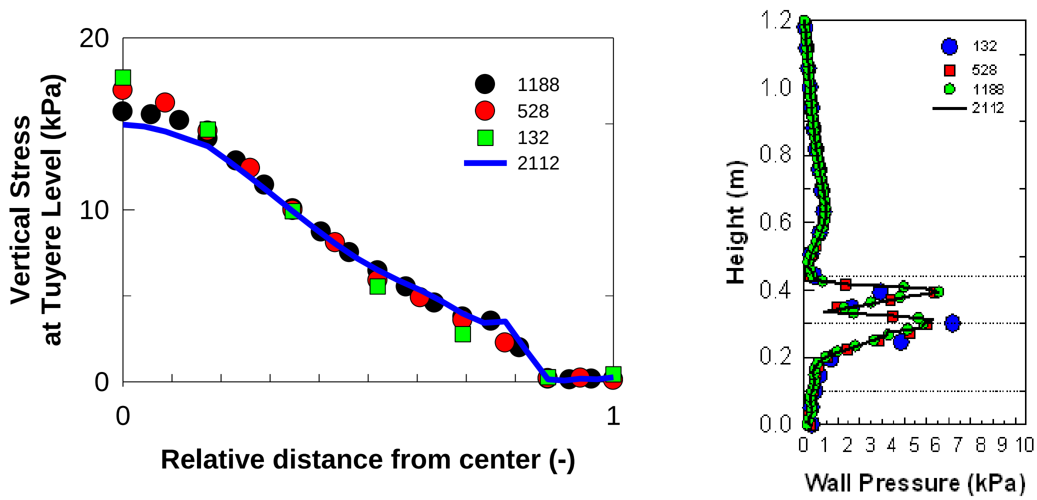


Figure 4.6 Effect of Finite Element Mesh size on the computed Vertical Stress at the Tuyere Level and Granular Wall Pressure

4.2 Force of Flowing Gas on Granular Materials

The Ergun Equation in multidimensional space (Equation 3.9) is used to determine the force of the flowing gas on the granular material. The finite element solution is compared in two ways, comparison to the analytical solution for the one dimensional cases and to experimental data from the literature for flow through a Blast Furnace scale model for the two dimensional case.

4.2.1 Comparison of Computed Force of Flowing Gas on Granular Materials to Analytical Solution for one Dimensional Gas Flow

An analytical solution exists for one dimensional radial and axial flow through a stationary granular bed. The analytical solution for gas pressure compares well with the results of the finite element solution as shown in Figures 4.7 and 4.8.

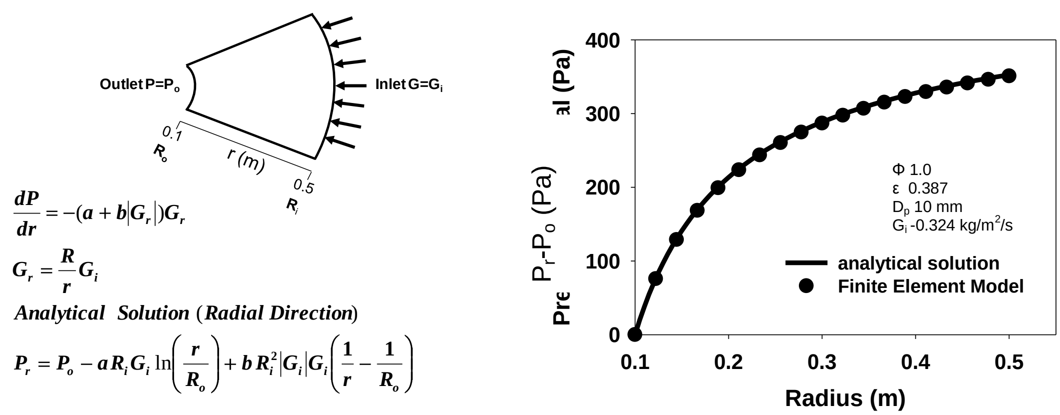


Figure 4.7 Comparison of Finite Element Solution of Ergun Equation (Equation 3.9) with Analytical Solution for One Dimensional Radial Gas Flow Through a Packed Bed

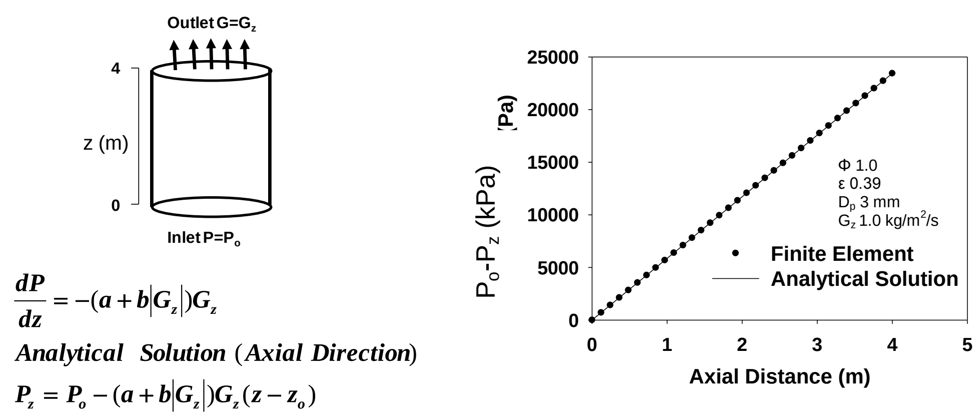


Figure 4.8 Comparison of Finite Element Solution of Ergun Equation (Equation 3.9) with Analytical Solution for One Dimensional Axial Gas Flow Through a Packed Bed

4.2.2 Comparison of Computed Force of Flowing Gas on Granular Materials to Experimental Data for Two Dimensional Gas Flow

Takahashi (2002) measured the gas pressure distribution on the wall for a scale blast furnace physical model having gas flowing through a granular bed filled with sand. The finite element solution of Equation 3.9 using the present model with the physical model geometry, granular and gas properties and boundary conditions stated (Takahashi, 2002) compares well with the measured results as shown in Figure 4.9. The effect of furnace geometry is evident by the increase in rate of change in pressure drop in the shaft as the top of the furnace is approached (Figure 4.9).

The external force on the granular material due to gas flow is determined by solving the Ergun Equation in multi-dimensional space. The mathematical model is validated by comparison of its numerical solution to the 1-D analytical solution. Also, for a scale model relevant to the blast furnace the numerical solution agrees with the measured data.

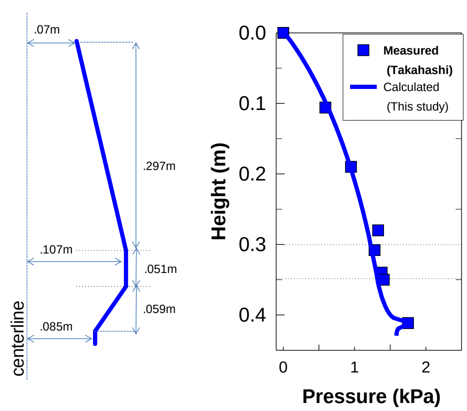


Figure 4.9 Comparison of Finite Element Solution of Ergun Equation for Flow Through a Granular Bed and Experimental Results of Takahashi (2002)

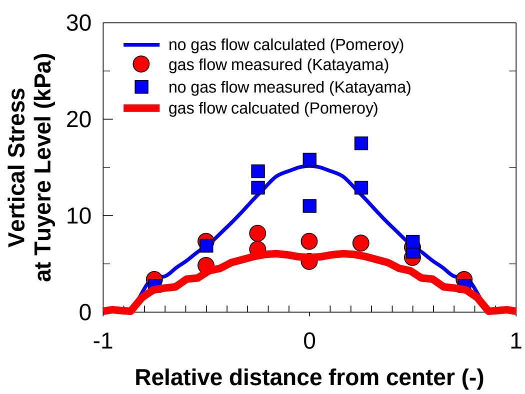
4.3 Counter Current Gas and Solid Flows

The mathematical model (based on Equation 3.3) has been shown to generate the main features of the change in stress field associated with the static condition (no granular flow) and the dynamic condition (with granular flow). The calculation of the force on the granular bed due to gas flow (based on Equation 3.9) was found to be acceptable. The blast furnace includes counter current gas and granular flow. The present model combines the effects of gas and granular flow by including the force due to gas flow as a body force term in Equation 3.2. The appropriateness of this approach is assessed by comparing the experimental data of Katayama (1998) with counter current granular and gas flow with the calculated solution of Equation 3.2. Also, despite the incomplete description of granular material properties, the experimental data of Takahashi (2002) with counter current granular and gas flow is compared to the results from the present model.

The calculated vertical bottom stress and granular wall pressure when including both granular and gas countercurrent flow shows good agreement with the experimental data of Katayama et al. (1998) as shown in Figure 4.10. With gas flow the center vertical bottom stress is reduced from 12.0 (no gas flow) to 5.7 kPa (gas flow) and the peak wall pressure is reduced from 6.4 (no gas flow) to 2.9 kPa (gas flow).

Takahashi et al. (2002) measured the force on the wall and bottom in a scale blast furnace physical model with granular and gas flow, but not the physical properties of granular materials used or wall friction coefficient. In the absence of this data in the present work the angle of internal friction was adjusted to make the computed forces match the measured data of Takahashi's (Figure 4.11). The angle of internal friction used was 36.5°. The calculation of the force on the granular material due to gas flow is considered is be correct as the gas flow model was validated based on the gas wall pressure experimental data generated by Takahashi (section 4.2.2). The resulting calculated vertical stress at the bottom does not exactly match the experimental results (especially the bottom vertical stress at the center) however the general trend and order of magnitude of the stress is similar.

Based on the comparison to experimental data of Katayama (1998) and Takahashi (2002) the present model has been shown to capture the key features associated with combined granular and gas flow, i.e. the decrease in the bottom stress and granular wall pressure relative to granular flow with no gas flow.



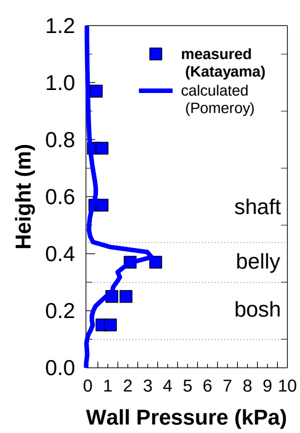


Figure 4.10 Comparison of Vertical Bottom Stress and Wall Pressure between Mathematical Model and Experimental Model Results of Katayama et al. (1998) for Counter Current Granular and Gas Flow

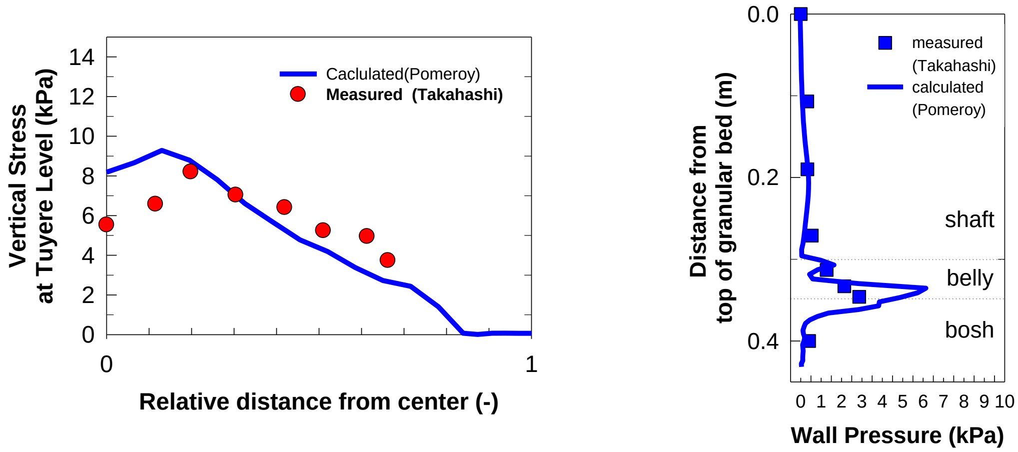


Figure 4.11 Comparison of Bottom Stress and Granular Wall Pressure between Mathematical Model and Experimental Model Results of Takahashi et al. (2002)

4.4 Comparison to Alternative Constitutive Equation

There are many possible constitutive equations that can be used to describe the relationship between incremental stress and strain. In this work an elastoplastic formulation is chosen. A model that calculates the stress field in the blast furnace using the hypoplastic formulation has been reported in the literature (Zaimi, 2003). The results when using the hypoplastic constitutive equation are compared to the present one to show if a difference in calculated results should be expected based on the formulation chosen.

Zaimi (2003) used an alternative constitutive formulation (hypoplastic) and included the sensitivity to furnace geometry, angle of internal friction and wall friction in his results. These results can be used for comparison to the results using the extended Drucker-Prager model (elastoplastic) used in this work. Both models consider the granular bed to be a plastically deforming material, however, have entirely different basis for the constitutive model. In elastoplasticity a yield surface is used to distinguish between elastic and plastic responses. In hypoplasticity, there is no distinction between elastic and plastic regimes and the mechanical behavior is described in a single tensorial equation. Despite the difference in frameworks, both include the angle of internal friction (φ) as a model parameter.

Simulations using the Extended Drucker-Prager Model and the blast furnace geometry described by Zaimi (2003) were performed over a range of angle of internal friction of 30 to 40^{o}. Increasing the angle of internal friction increases the average vertical stress at the tuyere level as shown in Figure 4.12.

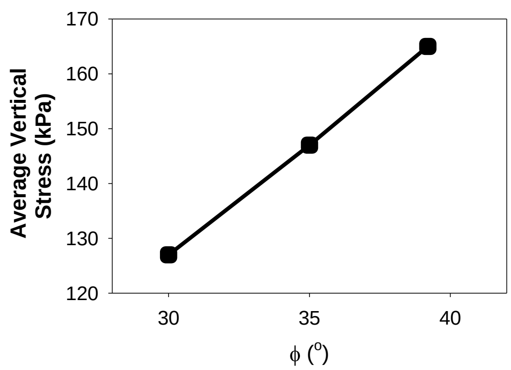


Figure 4.12 Effect of Angle of Internal Friction (φ) on the Average Vertical Stress at the Tuyere Level using the Extended Drucker Prager model (this work) and the Blast Furnace Geometry of Zaimi (2003)

A comparison of the sensitivity to the angle of internal friction (φ) using the Extended Drucker-Prager Model (this work) and the data from Zaimi (2003) for the same furnace geometry is shown in Table 4.1. The sensitivity to angle of friction compares well for both formulations. Perfect plasticity (granular material is at the yield condition) is achieved in most of the blast furnace in Zaimi's work (Zaimi, 2000). This is consistent with this study. Once perfect plasticity is achieved, the stresses do not change with displacement and the proportioning of the major and minor stress at yield will depend on the angle of internal friction. The choice of a hypoplastic or Extended Druker-Prager Constitutive model does influence the results.

Variation in Angle of Internal Friction (φ)	Average Vertical Stress at the Tuyere Level	
	Hypoplastic(Zaimi)	Elastoplastic (This work)
+17%	+15.4%	+13.7%
-17%	-17.1%	-16.5%

Table 4.1 Comparison of Sensitivity of the Average Vertical Stress at the Tuyere Level to the Angle of Internal Friction for Hypoplastic and Elastoplastic Constitutive Equations

4.5 Summary

The mathematical model based on Equation 3.3 is compared with experimental data available in the literature for scale blast furnace geometry for the static condition (no granular flow) and the dynamic condition (granular flow with and without gas flow). The main features of the stress field in these experiments, in particular at the boundaries of the wall and bottom, are satisfactorily explained by the model based on Equation 3.3.

The goal of this work is to study the commercial blast furnace. The mathematical model as presented so far is at ambient temperature. The blast furnace has large temperature gradient in its system. In order to apply this model to the blast furnace condition any attempts to model should include the variation of temperature and pressure through the properties of the system.

Chapter 5 Modification of Model for Application to a Commercial Blast Furnace

The mathematical model is modified to include the relevant conditions of the commercial blast furnace such as temperature and gas pressure profiles, and the packing of granular material. The blast of this ironmaking furnace is pre-heated and compressed air which enters the furnace through tuyeres near the furnace bottom. When the blast contacts pre-heated coke in the raceways, which are regions next to the tuyeres, the carbon in the coke reacts with the oxygen in the air to form carbon monoxide which is used as the reducing agent for the iron ore and generates heat in partial combustion of carbon for the process. The presence of excess amounts of coke in the raceways prevents the formation of carbon dioxide. For the part of the blast furnace which is characterized by counter-current flows, raceways are the source of gases of highest temperature and pressure. From raceways which are at tuyere level, the hot gas is driven upward along the pressure gradient and carries heat to sustain the endothermic chemical process. In order to minimize the resistance to gas flow, the most effective way has been found by charging smaller ore and larger coke separately in different layers. It requires very skillful planning of thickness and shape of these layers and materials handling in charging. Physical properties of coke are most important to provide stable and adequate gas permeability in the blast furnace.

5.1 Packing conditions: ore layers/coke layers/cohesive zone

When solids move downward by gravity, all granular materials are heated by the gas, and iron oxides are reduced to form metallic iron which is partially carburized to form Fe-C alloys. When a certain temperature is reached, slag and metal in partially reduced ore pieces will become soft first and subsequently melt. The ore layer which is going through the process of softening/melting is called the cohesive layer. The cohesive layer is the compressed mixture of liquids and softened solids and is impervious to gas flow. The narrow layer of coke between cohesive layers is called coke slits which provide permeability to gas. The cohesive zone consists of cohesive layers and coke slits.

Coke will neither soften nor melt in the blast furnace. Figure 5.1 shows that above the Cohesive Zone, there are separate ore layers and coke layers; below which the only solids remaining are coke pieces. The presence of liquid phases, which will compete with gases for void space in the granular bed as passages, is ignored in our computation because its volume is negligibly small in comparison with gases.

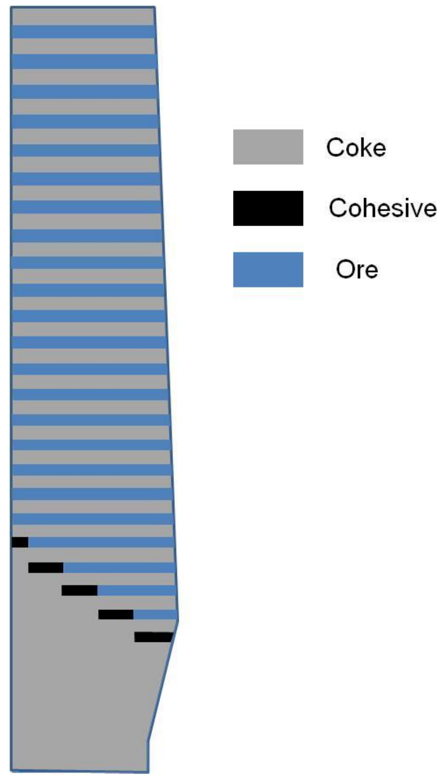


Figure 5.1 Spatial Distribution of Granular Materials for Blast Furnace Simulation

5.2 Temperature and pressure profiles of the system

A blast furnace is a high temperature chemical reactor for reduction of metal oxides to metallic products. At elevated temperatures, the key chemical reactions between metal oxides and carbon are more favoured thermodynamically and kinetically to have a reaction rate of industrial significance. If the materials properties included in the model are made to be temperature-dependent then this counter current system may be used to study high temperature operations. For the relationship between stress and strain used in the granular flow model, the dependence on temperature of the angle of internal friction is required. This information is not available over the temperature range in the blast furnace (200 to 2100 °C). As a starting point, in the absence of any data, the angle of internal friction is assumed to be constant with temperature. The sensitivity to the angle of internal friction is explored separately. The effect of temperature on the properties of gas can be included in the model. In the present formulation based on momentum balance and Ergun's Equation, the model contains physical properties of gas flow such as mass flow rate, density, viscosity, etc. The effects on gas density and viscosity due to variations of temperature and pressure will be assessed.

- Effect of gas density through the ideal gas law
- Effect of gas viscosity through the viscosity vs. temperature relationship based on gas kinetic theory for a gas subjected to intermolecular forces as summarized by Reid et al. (1977).

Gas temperature distribution is developed based on information available in the literature. A simplified distribution is imposed as follows;

- 2000 °C at the tuyere level (Adiabatic Flame Temperature)
- 1200 °C at the cohesive zone
- Linear temperature change between the tuyere and cohesive zone level
- 800 – 1000 °C at the Thermal Reserve Zone (1/3 of area above cohesive zone)
- 150 °C as the gas leaves the granular bed (Ponghis, 2000)

- Linear temperature change between between the tuyere and cohesive zone, cohesive zone and Thermal Reserve zone and Thermal Reserve zone and top of granular bed.

The spatial distribution of the gas temperature used is shown in Figure 5.2.

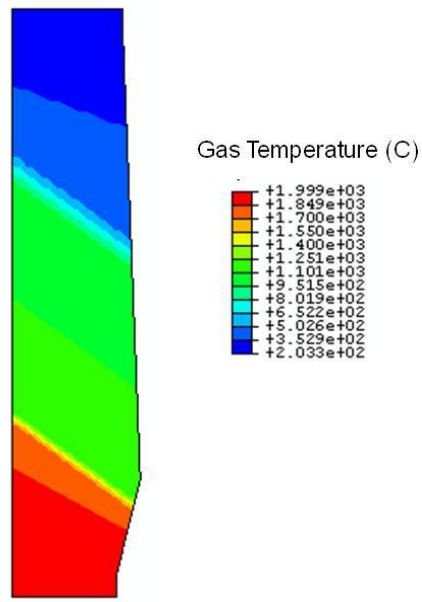


Figure 5.2 Spatial Distribution of Gas Temperature used in Blast Furnace Simulation

5.3 Validation of Gas Flow Model

The computational results of the present model, which includes the stress on granular materials and the gas pressure on the wall and interior, provides few variables to be compared with on the commercial blast furnace. On the wall, some temperature and gas pressure measurement were reported in the literature.

Computed gas pressure on the wall is compared with measurements from a commercial blast furnace (ArcelorMittal Dofasco No. 2 Blast Furnace) for validation of the gas flow model for the commercial blast furnace. The granular material properties, blast furnace geometry and operating parameters used for this validation are shown in Tables 5.1, 5.2 and 5.3 respectively. The particle diameter and void fraction for the cohesive zone (Table 5.1) are reduced to small values to make this material essentially impervious to gas flow. The operating parameters and wall pressure data represent the average of one year of operation with days including downtime removed. The boundary conditions are the bosh gas mass flow rate at the tuyere and the top pressure at the top of the furnace. The simplified gas temperature profile was imposed. The cohesive zone location and shape was modified such that the measured wall pressure matched the calculated wall pressure as shown in Figure 5.3. Also included in Figure 5.3 is the effect of the granular material type, layered structure and temperature. For a blast furnace filled with coke or pellet only or with a layered structure (including cohesive zone) the calculated wall pressure is lower than the measured values. The inclusion of temperature with a layered structure is required to match the calculated and measured wall pressure values.

Material	Coke	Pellet (ore)	Cohesive Layer
Diameter (m)	0.04	0.010	0.00005
Void Fraction (-)	0.4	0.30	0.005

Table 5.1 Granular Material Properties for Gas Flow Model

Geometry	
Throat radius (m)	3.20
Belly radius (m)	4.58
Hearth radius (m)	3.74
Shaft height (m)	17.05
Belly height (m)	0.0
Bosh height (m)	3.38

Table 5.2 Geometry of Commercial Blast Furnace

Operating Parameters	
Wind rate (Nm3/min)	1874
Bosh Gas Volume (Nm3/min)	2493
Top Pressure (kPa)	36
Coke Rate (kg/thm)	367
Ore (Pellet)(kg/thm)	1500

Table 5.3 Operating Parameters of Commercial Blast Furnace

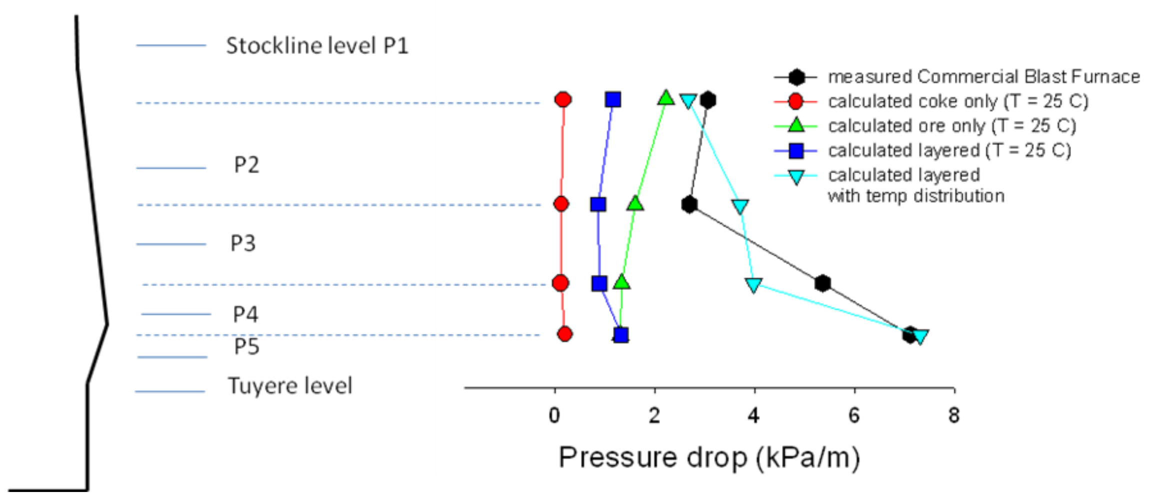


Figure 5.3 Comparison of Model Predicted and Commercial Blast Furnace Wall Gas Pressure

The contribution of temperature to the pressure drop for the commercial Blast Furnace is significant as shown in Figure 5.4. The influence of temperature on gas density to the pressure drop is large relative to gas viscosity.

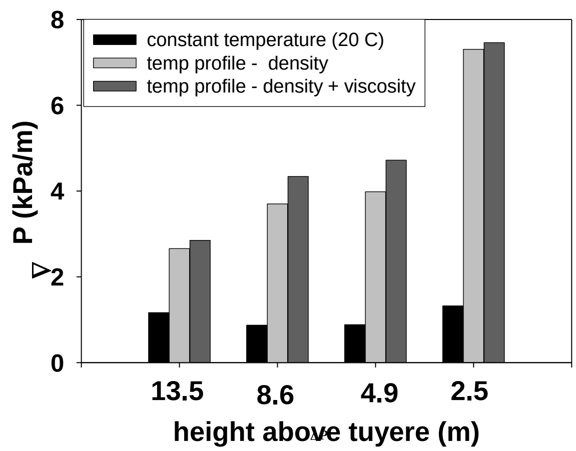


Figure 5.4 Contribution of Gas Temperature (Density and Viscosity) to Calculated Wall Pressure drop for Commercial BF

Comparison of the measured wall pressure in a commercial blast furnace to model results show that to extend the model to represent blast furnace conditions the effect of temperature on the density of gas must be included. The gas temperature effect on gas viscosity is not significant with respect to the gas pressure distribution.

5.4 Effect of Gas Temperature on the vertical stress at the tuyere level

The gas temperature profile in the commercial blast furnace is an important factor for determining the body force on the granular material due to gas flow. The influence of gas temperature on the granular stress distribution is assessed by comparing the case for gas temperature equal to 25 °C with the case for the simplified gas temperature described in Section 5.2. For these simulations the geometry of the blast furnace used has the geometry as described by Zaimi (2003) and the basic operating parameters derived from the reference case of blast furnace performance with coal injection (Ponghis,1998) adjusted to the geometry and a productivity of 2.5 t/d/m^3 working volume. A summary is given in Table 5.4. A single granular mechanical property is used (Table 5.4 (a)). The internal angle of friction for blast furnace granular materials is between 26° for pellets (Gustafsson, 2006, Brown, 2008) and from 32° (Kayayama, 1998) to 40° (Zaimi, 1998) for coke. A value of 30° is used in the commercial blast furnace simulation. The elastic properties for a granular bed can vary between 0.2 and 0.5 for the Poisson's ratio and 2 to 200 MPa for the elastic modulus (Bowles, 1996). A value of 0.3 for Poisson ratio and 135 MPa for elastic modulus is used in the simulations. The packing arrangement used is shown in Figure 5.5. The granular particle dynamics are different from what the current model represents in the raceway area. In the raceway a cavity is formed due to the high momentum of the gas and momentum transfer between particles due to frictional contact is not the dominant mechanism. To avoid convergence issues in the simulation of commercial blast furnace operation the radial component of the interphase drag on the granular material due to gas flow in the raceway area has been excluded.

The effect of gas temperature on the vertical stress at the bottom is significant as shown in Figure 5.6 with a reduction in the peak vertical stress from

600 kPa with a constant gas temperature of 25 °C to 388 kPa with the imposed gas temperature profile. The average vertical stress at the tuyere level decreases by 34 %.

Geometry	
Throat radius (m)	4.4
Belly radius (m)	6.55
Hearth radius (m)	5.9
Shaft height (m)	17.6
Belly height (m)	2.6
Bosh height (m)	3.9
Raceway Depth (m)	1.3

(a)

Operating Parameters	
Coke Rate (kg/thm)	303
Coal Rate (kg/thm)	180
Coke layer thickness at belly (m)	0.25
Bosh Gas Volume (Nm^3/min)	5600
Top Pressure (kPa)	121.7

(b)

Modelling Parameters (Extended Drucker-Prager Model, Appendix 1)

β (equivalent to angle of internal friction φ= 30 °)	50.19°
Young's Modulus (MPa)	135 MPa
Poisson Ratio	0.3
(dilatation)	0
K	0.8
D (cohesion)	100 N
μ (wall friction coefficient)	0.35

(c)

Table 5.4 (a) Blast Furnace Geometry, (b) Operating Parameters and (c) modeling parameters

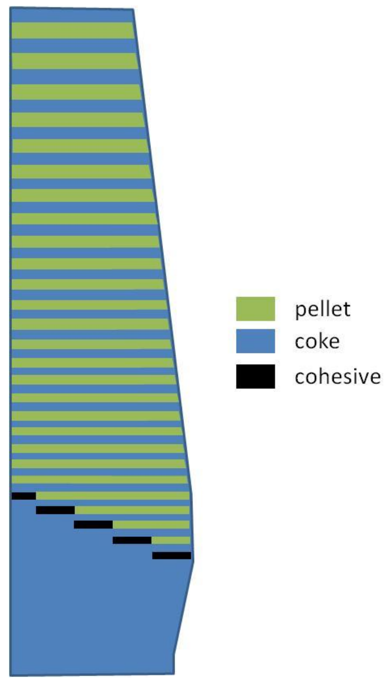


Figure 5.5 Physical Arrangement of Materials used in Simulation

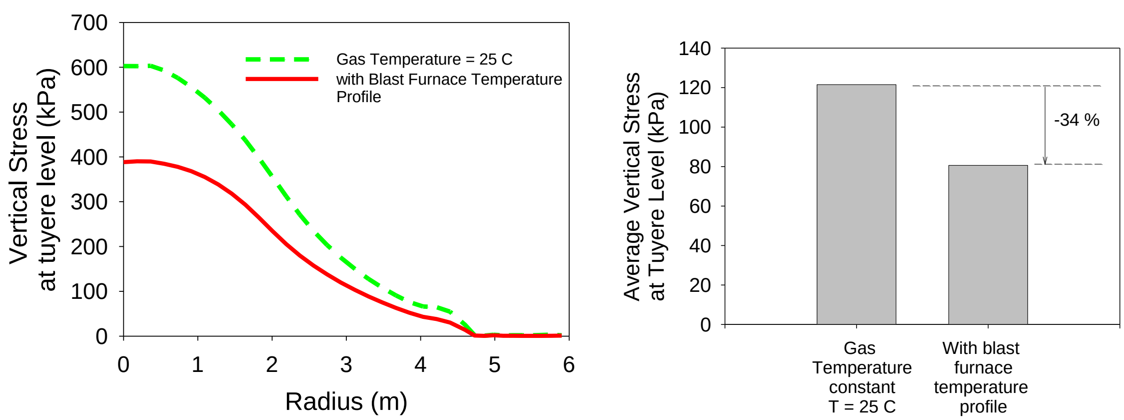


Figure 5.6 Effect of Gas Temperature on the Vertical Stress at the Bottom

5.5 Summary

The mathematical model (based on Equation 3.3) is modified to include the relevant conditions of the commercial blast furnace such as temperature and gas pressure profiles, and the packing of granular material. Comparison to the wall gas pressure measurements from a commercial blast furnace shows that the inclusion of gas temperature and packing arrangement (layered structure and presence of the cohesive zone) are required to obtain a proper estimate of the inter-phase drag force on the granular material due to gas flow (Ergun Equation) for the commercial furnace.

The model is now representative of the commercial blast furnace and can be used to study the parameters that influence the stress field in the interior and at the boundaries.

Chapter 6 Computational Results Relevant to the Commercial Blast Furnace

The model developed in the present work includes calculation of stress on the granular materials at the level of the tuyeres and pressure on the wall. This vertical stress at tuyere level can be used for defining the force at the upper imaginary boundary of the hearth region for subsequent and extensive studies.

For an operating blast furnace where the geometry is fixed the operator can exert influence through manipulation of the inputs to the furnace. Parameters considered in this study are:

- The properties of the gas with respect to mass flow rate and pressure of the system
- The packing arrangement of the granular material determined by the level of fuel injection and the radial distribution of ore/coke ratio at the top of the granular column where solids are charged.
- The properties of the ore. The softening and melting properties of the ore determine the vertical position and shape of the cohesive zone which would influence on gas permeability and distribution throughout the column.

The geometry of the commercial blast furnace and operating parameters detailed in Section 5.4 are used in this section.

6.1 Effect of Gas Properties

The operator can influence the gas flow through modification of the mass flow rate of gas at tuyere level and/or through the pressure of the system by setting the pressure at the top of the blast furnace. The commercial blast furnace geometry, base operating parameters and the modeling parameters are given in Table 5.4.

6.1.1 Mass Flow Rate

The computational results on effect of gas mass flow rate on the vertical stress at the tuyere level are shown in Figure 6.1. The no gas flow (i.e. granular flow only) condition is not relevant for blast furnace operation as blast flow is necessary to combust the coke in front of the tuyeres to create granular flow, however, it is presented here as a limiting case for reference. Increasing the gas flow reduces the resultant average downward vertical stress at tuyere level as the mainly upward vertical force due to interphase drag increases with increasing velocity of gas flow. The resultant peak vertical stress at the center is reduced. The distribution of wall pressure for the commercial blast furnace is similar to the results for the cold scale models described in Chapter 5 with a peak at the belly/shaft and belly/bosh interface as shown in Figure 6.2. The zero value on the scale of furnace height is corresponding to tuyere level. The effect of gas flow is to decrease the wall pressure over the entire furnace height, with a pronounced decrease in the peak value at the shaft/belly interface and in the upper bosh.

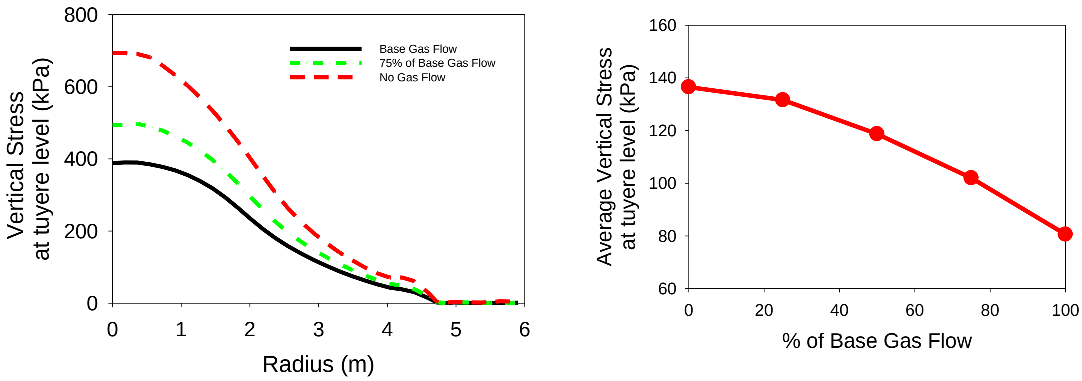


Figure 6.1 Effect of Gas Flow Rate on the Vertical Stress at the Tuyere Level

	Peak Wall Pressure (kPa)	
	Shaft/Belly	Belly/Bosh
Base gas flow	149	215
No gas flow	220	213

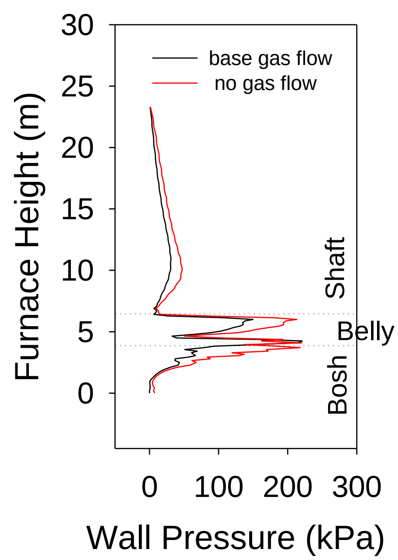


Figure 6.2 Effect of Gas Flow on Wall Pressure

6.1.2 Gas Pressure of the system

Increasing the pressure of the system for the same gas mass flow rate decreases the velocity of the gas flow and thus decreases the inter-phase drag force of the gas on the granular materials. This reduces the resulting average downward vertical stress at the tuyere level and the peak vertical stress at the center as shown in Figure 6.3.

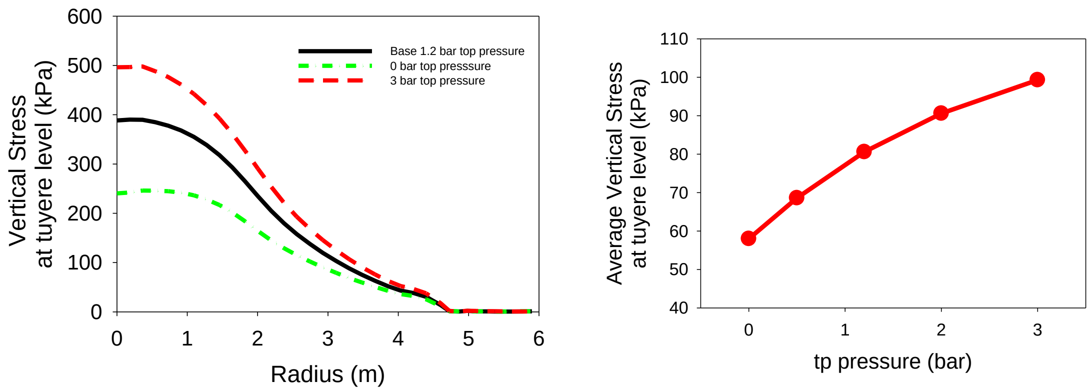


Figure 6.3 Effect of Top Pressure at constant Productivity on the Downward Vertical Stress at the Tuyere Level

6.2 Effect of Granular Packing

The resistance to gas flow by a given set of burden materials can be modified by changing the packing arrangement. This change is typical for different levels of fuel injection, thus, the overall ore to coke ratio which results in a necessary change in the relative thickness of the ore and coke layers to maintain the appropriate energy balance. Also the ratio of the thickness of the ore and coke layers can be adjusted across the radius to influence the gas flow distribution making it more center or wall working depending on the goal of the operation.

6.2.1 Level of Fuel Injection

The influence of the level of fuel injection on the resultant downward vertical stress at the tuyere level is determined by considering the change from an all coke operation (510 kg/thm) to a coke rate of 303 kg/thm (with a corresponding 180 kg/thm coal injection rate). This necessitates a 30% increase in the thickness of the ore layers charged at the furnace top relative to the coke layer thickness. Due to the increase in the proportion of higher bulk density material (ore) in the furnace at low coke rate operation the resultant downward vertical stress at the tuyere level increases at lower coke rate, 303 kg/thm, relative to the high coke rate, 510 kg/thm, case as shown in Figure 6.4. At lower coke rate the higher proportion of ore results in an increase in inter-phase drag force due to its higher resistance to gas flow and a slight increase in wall pressure (Figure 6.5). Both these factors contribute to a reduction in vertical stress at the tuyere level. However, the effect of bulk density is dominant and there is a net increase in the downward vertical stress at the tuyere level.

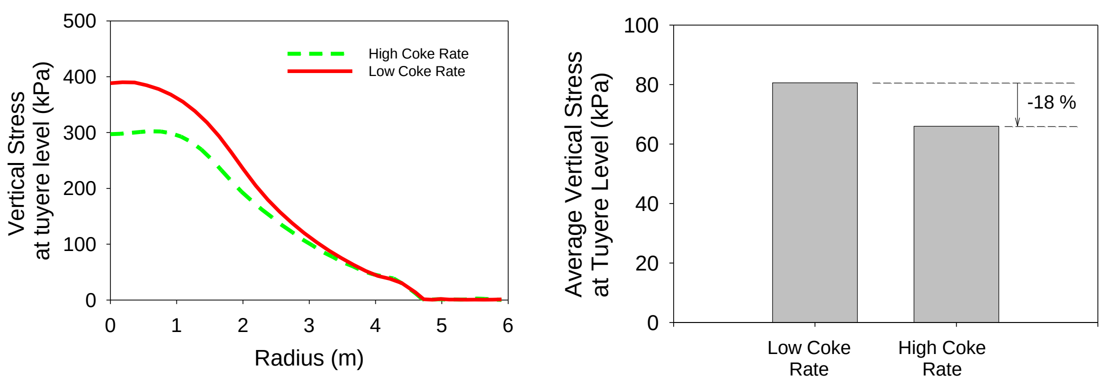


Figure 6.4 Effect of Fuel Injection Rate on the Vertical Stress at the Tuyere Level

Coke Rate	Peak Wall Pressure (kPa)	
	Shaft/Belly	Belly/Bosh
Low	149	215
High	117	216

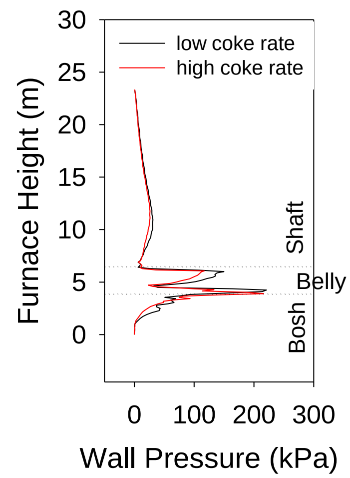
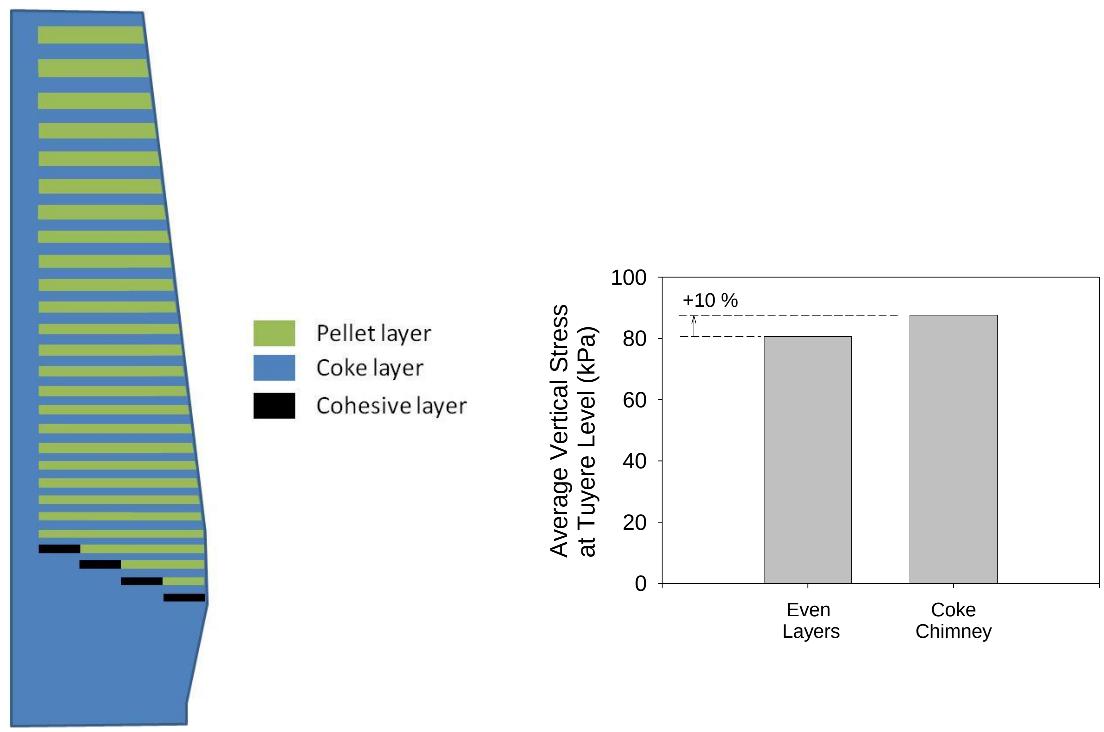


Figure 6.5 Effect of Fuel Injection Rate on the Wall Pressure

6.2.2 Burden Distribution (Coke Chimney at furnace center)

The blast furnace operator is able to adjust the gas flow by adjusting the radial distribution of ore/coke ratio at furnace top. Modification of gas flow can be used to improve thermal and chemical efficiency of blast furnace gas and change distribution of heat flux from gas flow onto furnace walls. Adjusting the gas flow can also affect pressure drop across the packed bed and corresponding inter-phase drag force on granular material. A ‘coke chimney’ type distribution of granular materials column where coke is the only solid present, is used by operators from time to time. The size of the coke-only column may be up to a radius of one meter (Figure 6.6 (a)). This one meter coke-only column results in a 10% increase in the average vertical stress at the tuyere level (Figure 6.6 (b)).

This increase is the result of lower overall resistance to gas flow with the coke chimney which reduces the inter-phase drag force on the granular materials.



(a) (b)

Figure 6.6 (a) Distribution of solid materials with ‘coke chimney’ at furnace center
(b) Effect of ‘coke chimney’ on average vertical stress at tuyere level

6.3 Effect of Ore Properties

The cohesive zone location can be influenced by the high temperature softening and melting properties of the ore for a given operating practice. If the partially reduced ore softens and melts at a lower temperature, the cohesive zone will form at a higher position in the furnace. It will result in a smaller lumpy zone and larger coke zone below the cohesive zone. The change of raising the cohesive zone by 1 meter would result in a decrease in the vertical stress at the tuyere level as shown in Figure 6.7.

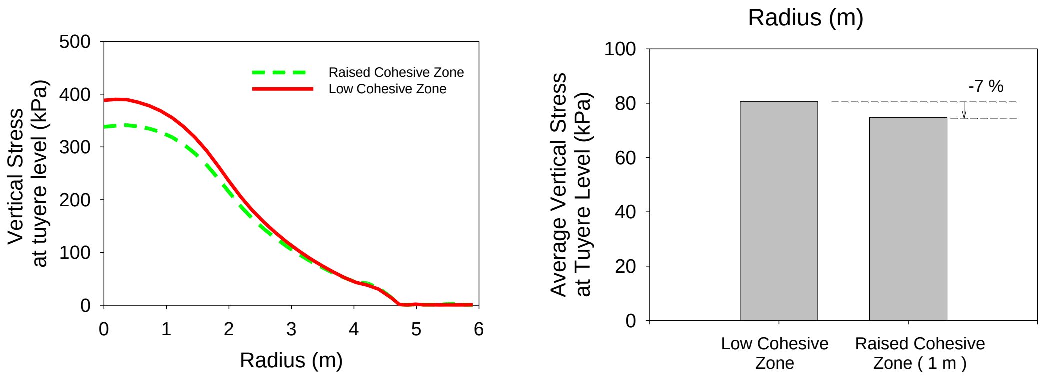


Figure 6.7 Effect of Cohesive Zone (CZ) Height on Vertical Stress at the Tuyere Level

6.4 Sensitivity of computational results to Material Properties and Operating Parameters

The sensitivity of angle of internal friction to the average vertical stress at the tuyere level is shown in Figure 6.8. The angle of internal friction is different for iron ore pellets and coke. Iron ore pellets are commonly used in North America (spherical, uniform sizing) have an angle of internal friction of 26° (Gustafsson, 2006, Brown, 2008). Coke is much more angular and has a higher angle of internal friction ranging from 32° (Katayama, 1998) to 40° (Zaimi, 1998) has been reported. A single value for angle of internal friction (30°) was used when computing the effect of operator parameters on the vertical stress at the tuyere level. Coke is an angular granular material when charged, however, through mechanical and chemically-induced abrasion becomes more rounded and smaller as it descends in the blast furnace (Negro, 1996, Peters, 1991). The generation of fines during this process will impair the gas flow through the bed. The rounding of grains could result in a decrease in angle of internal friction (Shinohara et al., 1999, Cheshomi et al., 2009) and a decrease in the average vertical stress at the tuyere level. In the literature, there is no report on the measurement of angle of internal friction of degraded materials taken out from the lower part of the blast furnace, to the best knowledge of this writer. In light of this absence of data, a constant angle of internal friction assumption is made. We must consider that an excessive generation of fines during the descent of coke could impair the gas flow through the furnace such that the furnace is inoperable. This limits the amount of coke degradation that is acceptable. Also, this condition is outside the scope of study. The range in reported angle of internal friction for coke is acknowledged by including the effect of a 5° increase on the average vertical stress at the tuyere level in Table 6.1

A comparison of the dependency of computational results to the major control variables in the range available to the operator is shown in Table 6.1. The blast furnace operator can make a significant change (up to 25%) to the average vertical stress at the tuyere level, usually for other purposes, using these control variables. The operating variables have different timeframes for control - long and short term. Long term variables are set usually on a yearly basis, while short term variables are changed on a daily basis.

Coke rate is a long term control variable. The target coke rate is set based on the relative cost of coke and injected fuel, the availability of coke and the capacity of the fuel injection system at the site. A large increase in the coke rate, for example, from 303 kg/thm to 510 kg/thm associated with the move from a high coal injection to an all coke practice will decrease the average vertical stress at the tuyere by 18%. Cohesive zone height can be raised through an increase in the softening/melting properties of the iron ore pellet. This is also a long term control variable as pellet choice is usually decided annually. The choice in pellet type can change the position of the cohesive zone, the change from acid to fluxed pellet increases the temperature for the start of pellet softening by 80 °C (Holditch et al., 1985).

Short term control actions available to the operator include the gas flow rate at the tuyeres and the gas pressure at the top of the furnace. The largest effect on the average vertical stress at the tuyere level is a reduction in the gas mass flow rate of 25% from the base level. This reduction in the gas mass flow rate represents the lower level for stable operation of the blast furnace.

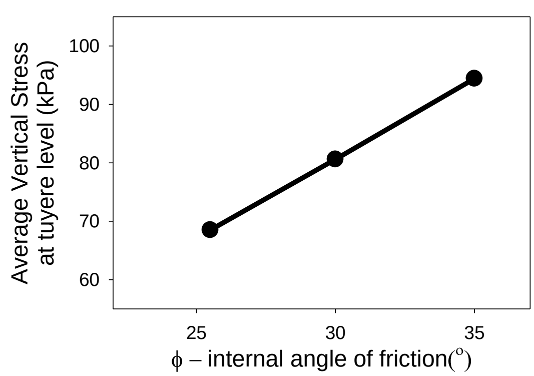


Figure 6.8 Effect of Internal Angle of Friction on the Average Vertical Stress at the Tuyere Level

Variable	Base Case (AVS at Tuyere Level = 98.9 kPa)	Computational Range Developed	Range for changes	Change in AVS at the Tuyere level with change in variable (relative to Base)	Potential Change for BF	change relative to base case
Material Property						
Angle of Internal Friction	30°	25 - 35°	30 – 35 °	2.9 kPa/°	+13.8 kPa	+17%
Long Term Operator Control						
Coke Rate	303	303 - 510 kg/thm	Increase to 510 kg/thm	-0.07 kPa/(kg coke/thm)	-14.6 kPa	-18%
Cohesive zone height	In bosh	Raise 1 m	Raise by 1 m	-5.9 kPa/m	-5.9 kPa	-7%
Short Term Operator Control						
Top pressure	1.2 bar	0.5 - 1.2 atm	Decrease to 0.5 atm	18 kPa/bar	-12.6 kPa	-16%
Bosh Gas mass flow rate	5600 Nm^3/min	4200 - 5600 Nm^3/min	Decrease to 4200 Nm^3/min (-25%)	-0.014 kPa/ (Nm^3/min)	+20 kPa	+25%

Table 6.1 Comparison of Computed Change in the Resultant Average Downward Vertical Stress (AVS) at the Tuyere Level for a change in Operational or Material Parameter

6.4.1 Sensitivity to Void Fraction Changes

The generally accepted assumption used in the calculations for the commercial blast furnace is that the properties of the granular bed (equivalent particle diameter, void fraction) are of the values at their introduction into the blast furnace. This may not be the case for the operating blast furnace as the size of the granular material may be somewhat reduced due to breaking up by mechanical forces or chemical erosion. The void fraction and average size of passages for gas flow may be reduced by fines generated in the raceway or from broken materials.

The effect of a decrease in void fraction which is an important parameter in Ergun's Equation, on the radial distribution of vertical stress at the tuyere level is shown in Figure 6.9. For a constant mass flow rate the downward vertical stress at the tuyere level is reduced with decrease in void fraction due to the increase in inter-phase drag force on the granular material. The average vertical stress at the tuyere level decreases by 2% per 1% decrease in void fraction (Figure 6.10).

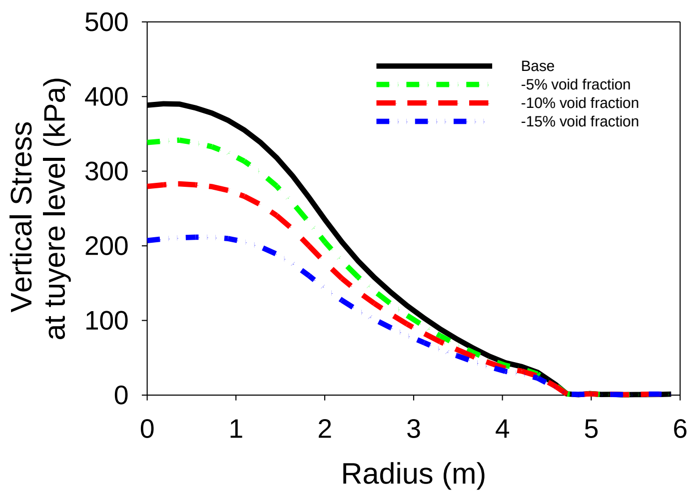


Figure 6.9 Effect of Void Fraction on the Radial Distribution of Downward Vertical Stress at the Tuyere Level

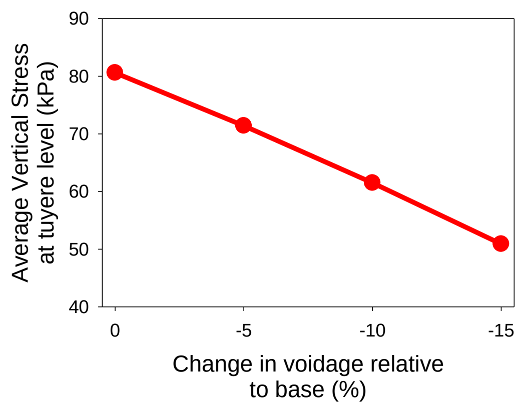
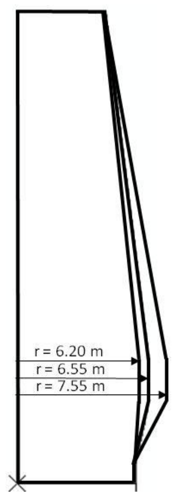
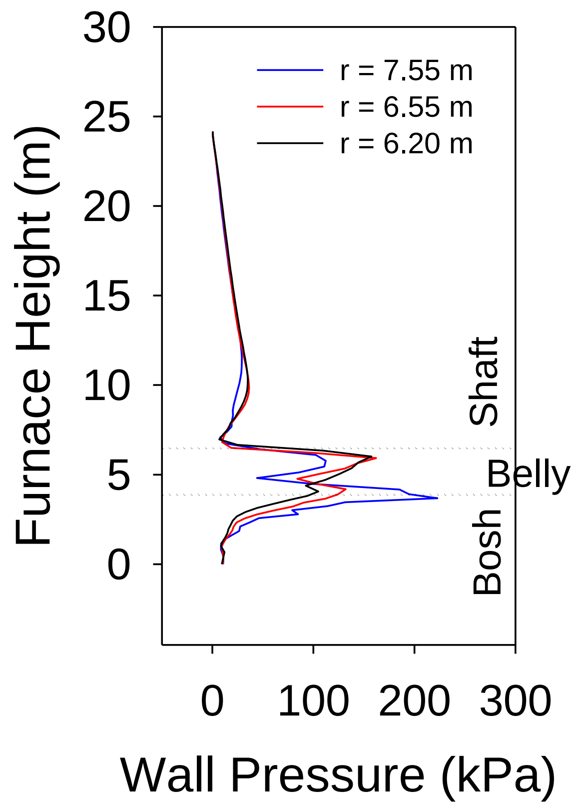


Figure 6.10 Effect of Void Fraction on the Average Vertical Stress at the Tuyere Level

6.5 Influence of Belly Diameter on Wall Pressure

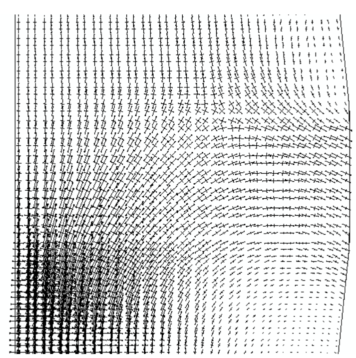
At reline, in order to increase the production capacity, the furnace volume can be increased by increasing the belly diameter. This change increases furnace inner volume without major upgrades to the hearth foundation and furnace top equipment. The influence of furnace shape and size on the vertical stress at the tuyere level has been reported in the literature (Inada et al., 2003). However, the effect on wall pressure for an increase in furnace volume achieved with an increase in belly diameter (with throat and hearth diameter constant) has not been explored. With the present mathematical model, computations are performed with single granular material (density = 1000 kg/m^3) and no gas flow to isolate the effect of changes in belly diameter. As shown in Figure 6.11 and 6.12, changes in the belly diameter influence the wall pressure distribution and the principal stress direction, especially in the belly/shaft and belly/bosh interfaces. Compared to the base belly diameter (r =6.55m), decreasing the belly radius to 6.2 m (5% decrease in furnace volume) decreases the peak wall pressure at the belly/bosh interface. Increasing the belly radius to 7.55 m, results in a shift in the higher peak wall pressure from the belly/shaft interface to the belly/bosh interface and a significant increase in the belly/bosh peak value. This shift and increase in peak value could have consequences in the management of wear in this area especially with the current trend to use copper staves in the lower stack, belly and bosh.



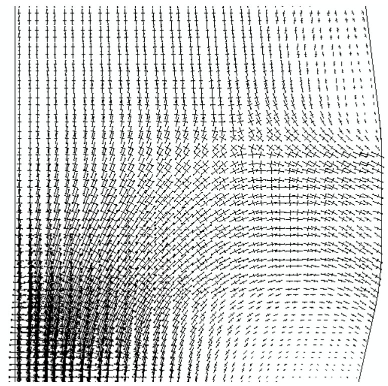


Belly radius (m)	Peak Wall Pressure (kPa)	
	Shaft/Belly	Belly/Bosh
6.2	157	104
6.55	162	131
7.55	112	222

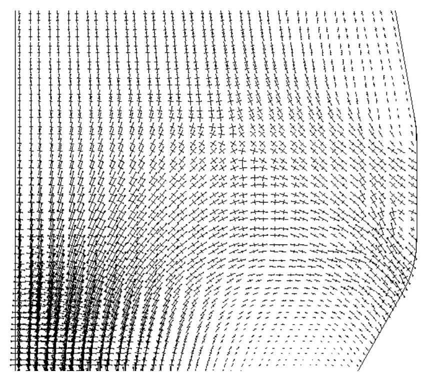
Figure 6.11 Effect of Belly Radius on Wall Pressure (single material with ρ = 1000 kg/m^3 and no gas flow)



(a) r = 6.2 m



(b) r = 6.55 m



(c) r = 7.55 m

Figure 6.12 Calculated Principal Stress direction in Belly for the Commercial Blast Furnace (with no gas flow)

6.6 Quasi-steady state assumption

A key assumption in the model is that granular flow is in the quasi-static regime, where shear stress is independent of shear rate. To test this, an estimate of the dimensionless rescaled shear rate I is derived and compared to the upper limit for the quasi-static flow regime of $I < 10^{-2}$ (Groupement de Recherche Milieux Divises, 2004) . Recall (from section 2.2.2) that;

$$I = \frac{\dot{\gamma} d}{\sqrt{P/\rho}}$$

where $\dot{\gamma}$ is the shear rate, P is the pressure, d is the particle diameter and ρ is the flow density. The model calculates the displacement and stress fields. An estimate of the velocity field is determined by assuming a reasonable axial velocity at the burden surface of 0.001 m/s for the commercial blast furnace, and making the velocity field proportional to the displacement field. The ***maximum*** possible shear rate is if a particle moves at a velocity v over a stationary particle of diameter d;

$$\dot{\gamma} = \frac{v}{d}$$

The maximum value of I is calculated for two regions of the commercial blast furnace as shown in figure 6.13. Path 1 is nearer to the wall, in the lower part of the blast furnace, velocity at .0015m/s is higher and the granular pressure is lower. This combination maximizes I. Despite this I remains below the limit for quasi-static flow (< 10^{-2}). Path 2 is along the furnace centre line, velocity is low in the lower part of the blast furnace and granular pressure is high. Therefore I is at very low values (< 10^{-6}). From this we can conclude for most of the commercial blast furnace that the granular flow is in the quasi-static regime.

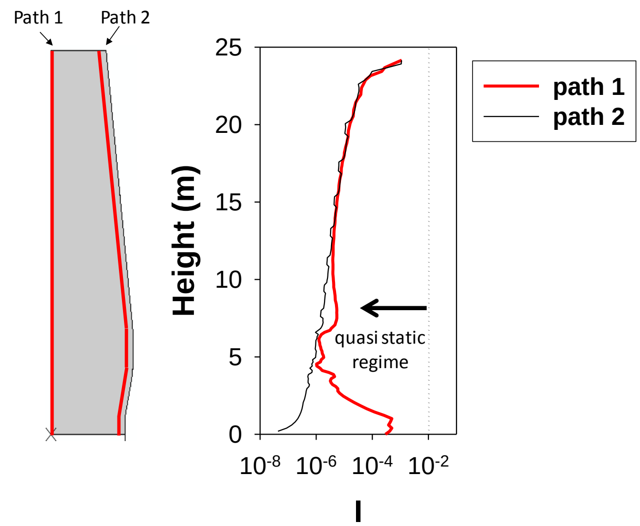


Figure 6.13 Estimate of Dimensionless Shear Rate (I) at the Wall and Centre of the Blast Furnace

6.7 Summary

For a commercial blast furnace with a given geometry, the operator can control the operation through manipulation of properties of coke and iron ore and packing of these solids, mass flow rate of gas, as well as temperature and pressure of the system. For a normal commercial practice, i.e., raw materials of acceptable quality are used and all equipment functions properly, the most effective and convenient means the operator has for controlling the resultant downward vertical stress at the tuyere level are a change in the upward gas linear velocity, through mass flow rate or blast pressure. Results obtained at other boundary of the system of computation are of pressure on the wall, i.e., normal stress perpendicular to the inner surface of the wall. These are sensitive to the configuration around the belly of furnace as well as gas flow. Even though there has been a lack of direct measurements on commercial furnace, the computational results presented in this chapter are certainly consistent with the author’s personal experience of blast furnace operations over many years. Furthermore, through these numerical presentations the mysterious face of blast furnace a little bit clearer. The impact of downward stress at tuyere level on the operations of hearth of blast furnace will be presented in the next chapter.

Chapter 7 Influence on the Coke Bed in the Hearth

The blast furnace has a long history and it has evolved to the current state over hundreds of years. It is a complex reactor with individual regions playing different roles. The generally accepted approach by blast furnace engineers is that phenomena in individual regions are treated separately, for example for studying the force field in the present work, the blast furnace has been divided into two parts. There is gas flow above the tuyere level and below there is a liquid pool of hot metal and slag in the hearth. The mathematical model is based on gas/solid counter-current flows and is valid for regions above tuyere level. The model describes the "force field" of the upper part of blast furnace, i.e., above the tuyere level. It is based on the interplay of gravity, the drag force exerted on solids by gas flow, and the interaction between granular particles. Below the tuyere level and within the pool, the force field is a balance between gravity, the interaction between granular particles and the buoyancy force in the pool.

The Transitional Region may be defined as a portion of the packed column inside the blast furnace, and within this region the lower boundary of the mathematical model of the present work is located. It is an irrigated bed with liquid metal and slag moving downwards by gravity through void space and a generally upward gas flow originating from the raceway. The gas volume generated below this boundary due carbon reduction of metal oxides is negligibly small by comparison. This irrigated bed may be extended up to the cohesive zone for a distance of several meters. The reason for identifying this Transitional Region is to point out the contradictory facts for the space in front of each tuyere where the blast enters the irrigated bed (raceway). The physical state in raceways and the space in between adjacent raceways are not the same, particularly in terms of gas flow and solid movement. However, at some distance above the tuyere level the condition of uniform gas flow would be achieved. Even though the modeling of the hearth region is not within the scope of the present work, results presented in this chapter are intended to be helpful for such a task. The recognition of such non-uniformity is important for the detailed description of the hearth model that should be carried out by another researcher in the future.

For simplicity, the space in the hearth may be considered as the space occupied by liquids only and the space occupied by the coke bed with its lower part submerged in the liquid pool. During casting, liquids from various parts of the hearth flow towards the taphole. If there are alternative paths of flow between two locations, the path through coke-free space is always preferred, because flow through submerged coke bed has to overcome the drag force exerted by the relatively stationary coke. Therefore, the actual path of flow of liquids in a hearth is essentially determined by the geometry of the submerged coke bed in the hearth.

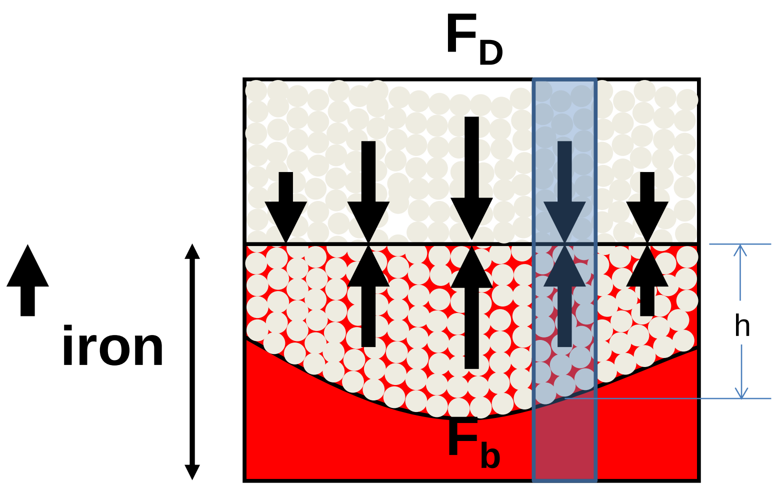
The model developed in the present work calculates the stress on the granular material at the tuyere level. This is the dividing boundary, mathematically. The output of the present model at this boundary may be used as the input for another model for the hearth region. In the present work, the resultant stress varies in radial direction but is independent of angular direction because of the assumption made that gas enters uniformly around the circumference. The effect of non uniformity of gas entry around the circumference can be addressed in future work.

7.1 Force Balance at Lower Boundary in the Current Model

A one-dimensional formulation at this dividing boundary where at each radial position the downward force (F_D) from above is balanced by the upward force from below. For simplicity only buoyancy force originated from submerged coke particles (F_b) is considered here. It is sufficient for the calculation of the depth of penetration (h) of the coke bed as shown in Figure 7.1. This assumption excludes interaction between coke particles and force transmission in the radial direction.

7.2 Penetration of coke bed into liquids

The penetration of the coke bed into the hearth based on the simplified model and that the depth of the liquid iron pool is semi-infinite is shown in Figure 7.2. The peak downward vertical stress from above at the center results in a penetration depth (8 m at base gas flow) which is greater than a typical hearth depth (1.75 to 3 m), this suggests that the hearth coke bed should be touching the hearth bottom in the center. The penetration depth decreases as radius increases, so that at the periphery approaching the side wall the coke bed could be floating (Figure 7.2), i.e., not touching the bottom of the hearth, especially below the raceway.



$$h = \frac{F_D}{(\rho_{iron} - \rho_{coke})g(1-\varepsilon)}$$

ρ_{iron}	7000 kg/m^3
ρ_{coke}	900 kg/m^3
ε	0.3

Figure 7.1 Simple Force Balance of on Hearth Coke Bed

For a 3 meter hearth depth (taphole to hearth bottom), the coke bed will be sitting on the hearth bottom up to a radius of about 3 m (Figure 7.3). It should be emphasized that this is a first order approximation and that a more advanced model is required to generate a more realistic determination of spatial distribution of coke bed penetration into the liquid iron pool.

For the commercial blast furnace the gap where the liquid phase is free of coke, between tip of submerged portion of coke bed and bottom of the hearth, (floating height) will not be uniform. When the model can reflect the non-uniformity due to the presence of raceways, more realistic topography of liquid-only gap may be mapped out.

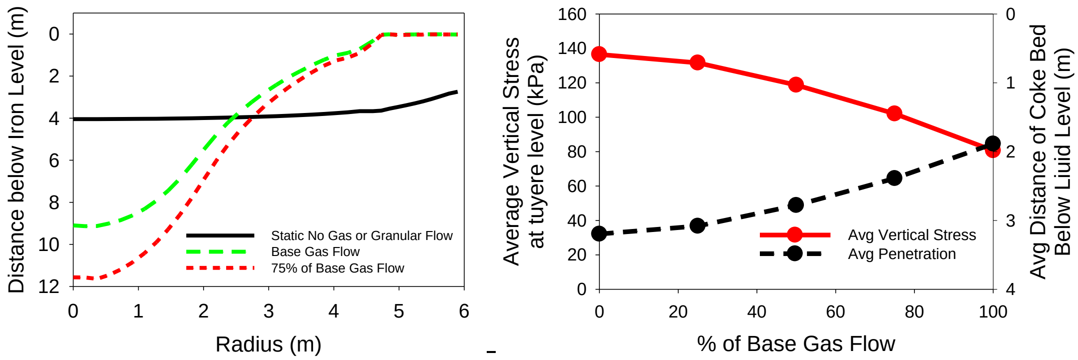


Figure 7.2 Effect of Gas Flow Rate on the Penetration Depth of Hearth Coke Bed

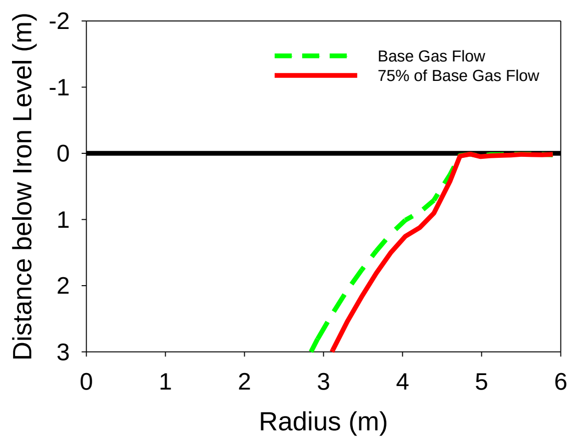


Figure 7.3 Effect of Gas Flow Rate on the Penetration of the Coke Bed into the Hearth Liquid Pool for a hearth with a sump depth of 3 m

An estimate of the potential change in average floating height of the hearth coke bed (above hearth bottom) based on a simplified 1-D force balance on the hearth coke bed was determined for a generic Blast Furnace (2500 m^3 working volume) using the vertical stress from the model as a boundary condition at the top of the hearth coke bed. The sensitivity of variables under control of the operator is shown in Table 7.1. The average penetration depth of the coke bed below the liquid level increases by 0.47 meters for a 25% decrease in the bosh gas mass flow rate due to the increase in average downward stress at the tuyere level based on this simple model. This relationship is for the average condition. In reality, the penetration depth varies in the radial direction and could vary in the angular direction due to the difference in the vertical stress at the tuyere level caused by the difference in physical state in raceways and in the space between adjacent raceways. A comparison of the effect of operator control actions on penetration depth are shown in Figure 7.4.

Variable	Base Case (Average Penetration of Coke bed into liquid pool = 2.2 m)	Range for changes	Estimated Change in Average Penetration Depth of Coke bed below liquid iron level (m)
Material Property			
Angle of Internal Friction	30°	30 – 35 °	+0.32
Long Term Operator Control			
Coke Rate	303	Increase to 510 kg/thm	-0.34
Cohesive zone height	In bosh	Raise by 1.0 m	-0.14
Short Term Operator Control			
Top pressure	1.2 bar	Decrease to 0.5 atm	-0.30
Gas mass flow rate	5600 Nm^3/min	Decrease to 4200 Nm^3/min	+0.47

Table 7.1 Estimated Change in Average Hearth Coke Bed Penetration Depth for a change in Operational or Material Parameter

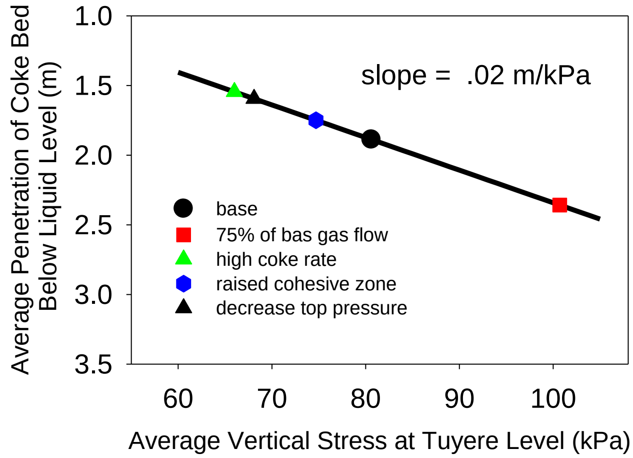


Figure 7.4 Comparison of Operator Control Variables and their Effect on Average Penetration of Coke Bed below Liquid Level

7.3 Example of Operator Control of Spatial Distribution of Coke Bed in the Hearth of a Commercial Blast Furnace

It is extremely difficult to directly measure any properties inside the hearth and the spatial distribution of the coke bed in the hearth is no exception. However, temperature measurements using thermocouples imbedded in the hearth wall and bottom refractory can provide an indirect indication of a change in adjacent flow field of iron from where the heat flux is originated and from this the topography of submerged coke bed in the hearth can be inferred. It was shown in Section 7.2 that the gas mass flow rate influences the penetration depth of the coke bed into the liquids in the hearth. Lower gas mass flow rates increase the penetration depth due to a reduction in the inter-phase upward drag force on the granular materials. This calculated result is examined with respect to the practice of completely blocking or restricting gas flow at a tuyere in a commercial blast furnace. In general, operators keep all tuyeres open to maintain an even circumferential balance of gas flow around the furnace. However, the tuyere blocking practice is used as an emergency response to high temperatures in that part of lining. When an individual tuyere above the wear area is blocked there would be no blast entering this area. This reduces the local upward gas flow and the inter-phase drag force directly above the tuyere. Consequently, penetration of the coke bed into the liquid pool will increase in the vicinity below the blocked tuyere. The increase in coke bed penetration depth will raise resistance to liquid flow due to a decrease in the size of the metal-only gap. The consequence will be a reduction in the rate of heat transfer to the wall resulting in a lower hearth sidewall temperature below the blocked tuyere. The response in hearth sidewall temperature on a commercial Blast Furnace with a blocked tuyere is shown in Figure 7.5. A similar response was reported by Parker et al. (2000) as the result of restricting gas flow on an individual tuyere using a tuyere insert which reduces tuyere diameter from 15 to 5 cm. These are examples of operator control to influence the hearth coke bed spatial distribution as a means of changing the pattern of metal flow to maintain a safe operation.

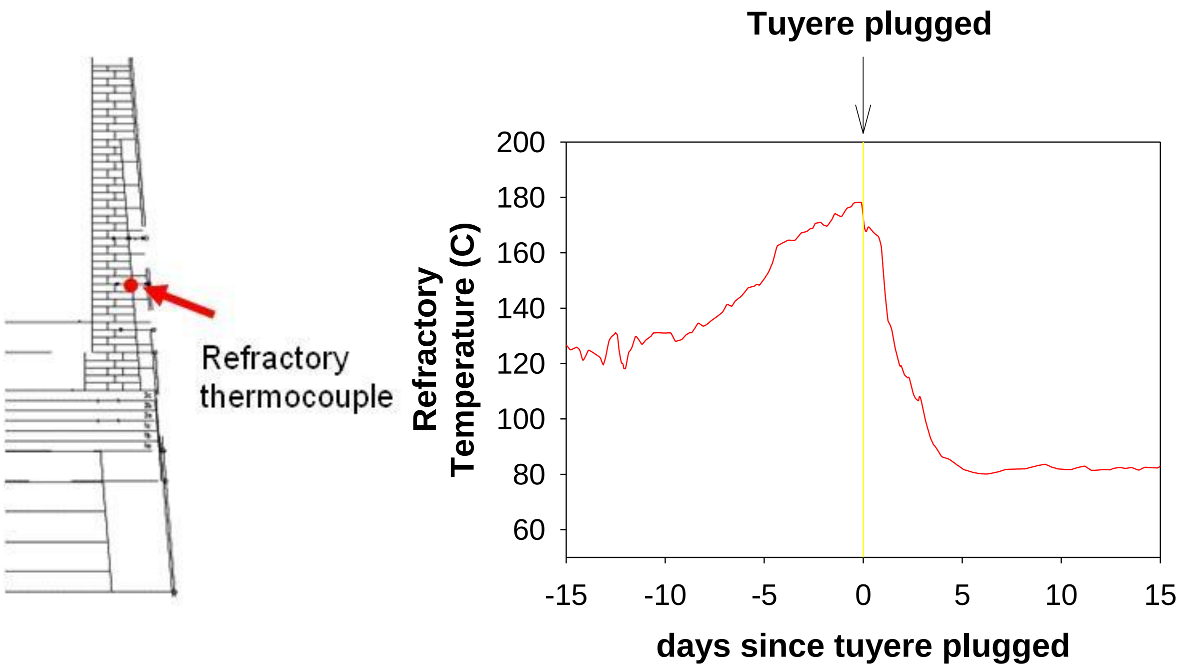


Figure 7.5 Effect of a Plugged Tuyere on the Hearth Refractory Temperature below the Plugged Tuyere on a Commercial Blast Furnace

7.4 Summary

This simplified model of a force balance which estimates the penetration depth of the coke bed into the liquid pool has been applied. This model provides an approximation of the effect of the main operator control variables applied at or above the tuyere level to control the hearth coke bed below the tuyere level. In future work, an improved mathematical model could be developed with some simplifying assumptions removed, and including a non-uniform distribution of gas flow at the tuyere level. A more detailed configuration of the submerged coke bed could be computed and more realistic results would be useful for fine tuning of blast furnace practice.

Chapter 8 Discussions on the Present Work

8.1 Introduction

Advancement of process knowledge of the blast furnace is important to reduce the cost of production, environmental impact of the process and increase the service life of the equipment. The determination of cause-and-effect relationships by experimenting on a commercial scale blast furnace can be risky with respect to maintaining production and safety. Also, the blast furnace is monitored mainly at the boundary, however, important phenomena occur in the interior which are difficult to measure due to high temperature.

The only practical way to develop process knowledge on what is happening inside the blast furnace without incurring the cost and risk of full scale trials is by computation. Mathematical models can be validated through laboratory scale models or boundary measurement for the application in commercial furnace as is the case with the present study.

The least known region of blast furnace is the hearth; particularly the configuration of the partially submerged coke bed in the liquid iron pool. The current model calculates the stress distribution on granular materials above the level of the tuyeres. The results provide the boundary condition for the upper boundary of the hearth which can be used in future modeling work.

8.2 Contributions of present work

The stress on granular materials in the commercial blast furnace has been studied previously. These studies have included the effect of furnace geometry: for size (Inada et al., 2003), for shape (Inada et al., 2003) and for granular material properties (Zaimi, 2003). There has been minimal focus on the effect of operating variables under the control of operators, for example, for raceway depth (Zaimi, 2003). The main contribution of the present study is that the information obtained demonstrates that the effect of chosen operating variables on the force field in the interior and on operations may be calculated for a given furnace. Some of the relationships developed here are consistent with the intuition of experienced operators. The computed results of this study allow for a more quantitative assessment rather than the current qualitative estimation of the effect of variation in practice.

8.2.1 On daily control of blast furnace

The computational results show that the gas flow rate over the control range available in the commercial blast furnace for a stable and efficient operation has a significant effect on the stress distribution in the blast furnace. The average downward vertical stress at the tuyere level is increased by 25%, across the span of stable operations, for a 25% reduction in gas flow rate (Table 6.2). This is the result of the decrease in the interphase drag force exerted by the gas on the granular material predicted by the Ergun Equation at lower gas flow rates.

The temperature of the gas plays is an important role in the determination of the force on the granular bed due to gas flow for the commercial blast furnace. The variation of gas temperature is high in the commercial blast furnace, ranging from 2100 °C at the tuyere level to 100 °C at exit in the top of the furnace. The two variables which have dependence on gas temperature that are included in the Ergun Equation are viscosity and gas density. It was shown (Section 5.3) that the reduction in gas density has the greater influence at higher gas temperatures (through ideal gas law) and increases the interphase drag due to higher linear velocity.

8.2.2 On Practice Planning

The computed results also show that properties of raw materials and arrangement of the packing of the granular column influence~~s~~ the stress distribution in the furnace. The coke rate has a significant effect on the average downward vertical stress at the tuyere level. This is a long term variable that is very critical in practice planning. The switch from a low coke rate operation (303 kg coke/thm) to an all coke operation (510 kg coke/thm) decreases the average vertical stress at the tuyere level by 18%. This is driven by the higher proportion of a lower bulk density material (coke) for the high coke rate operation.

8.2.3 The trend of change or absolute values of computed results

The absolute value of the stress field computed, of course, depends on the degree of simplification and idealization in the formulation of the model and accuracy of the input data. The blast furnace is a complicated process and not all variables are precisely known and included in the model. The simplifying assumptions used would result in a different absolute value. However, the contribution of this work is mainly in the sensitivity of the stress field in a commercial blast furnace to these chosen operating process variables.

The quantitative relationships presented in this work are based on the effect of a single variable around a base condition which is close to the highest production rate yet remaining stable and efficient. In the actual blast furnace, variables are interrelated in complicated fashion. Therefore, a simplification would lead to an error in the result. The trend of changes of blast furnace interior conditions due to variation of certain operating parameter and more importantly their magnitudes as reported in present work, in the opinion of this author, are much more reliable than absolute values calculated. Fortunately, information available in such a form is actually what operators need, the consequences of each action taken in the steering of the blast furnace.

8.2.4 Blast furnace cannot be divided into separate regions

It is generally accepted due to lack of alternatives that the blast furnace has been divided into two separate regions at tuyere level for analysis and control. The present work shows that the influence of any changes of operating control variables at or above the tuyere level on the stress field will be transmitted to the hearth as well. This allows the operator to appreciate that control actions will not only achieve expected results above the tuyere level, but will also have consequences in the hearth, up to present time not knowingly.

8.3 Future work

The mathematical model developed in the present work can be improved by the removal of simplifying assumptions and/or the use of more accurate input data to provide a more reliable value for computed stresses. This includes developing knowledge of the spatial distribution of the granular material properties in the blast furnace that can be applied in the present model. Specifically, an improved understanding of the effect of degradation of materials during descent in the blast furnace on the mechanical and gas resistance properties of the granular materials.

A more accurate value for the average vertical stress at the tuyere level can be generated with a better estimation of gas temperature and volume. This can be achieved by coupling this mechanical model with a comprehensive blast furnace model that takes into account heat and mass transfer and reaction kinetics of the process.

Future work that is doable and would be fruitful, is the development of a mathematical model for the hearth, based on downward vertical stress at tuyere level calculated from current model. This model should include the radial transmission of stress within the hearth coke bed and the angular non uniformity arising from the presence/absence of raceways in cross-sectional area at tuyere level.

Chapter 9 Conclusions

The goal of this thesis is to advance knowledge on the balance of forces acting on granular materials in the interior of the blast furnace and on the walls. Specifically, a mathematical model, based on the principles of fluid and granular flows, is used to generate new knowledge on the influence of parameters that are under control of the blast furnace operator, on the granular stress at the level of the gas inlet and the walls. The mathematical model developed in this thesis is validated under ambient conditions by comparing model predictions with experimental data obtained from physical scale models of the blast furnace. The temperature used in the model is raised to simulate commercial blast furnace operation.

Based on the computational results presented, the following conclusions may be reached:

1. A mathematical model is used to calculate the stress on granular materials with counter current granular and gas flow. The slow moving granular flow is represented as the deformation of a plastically deforming granular column and the external force on granular materials due to gas flow is determined using the Ergun Equation. This model is shown to be suitable for blast furnace geometry and ambient conditions. The model boundaries are the gas inlet and the inner walls above this level.

2. The computed results of stresses at system boundaries are found to be sensitive to mass flow of gas, temperature and pressure of the system. Vertical stress at the tuyere level (gas inlet) strongly depends on the linear velocity of the gas. The normal stress on the inner wall is sensitive to the shape of the inner wall and could be moderated by higher gas flow and/or higher coke rate.
3. The downward vertical stress at the tuyere level and normal stress on the inner wall are examined as functions of major process parameters. Also, an estimate of the effect of operator control actions on the change in the average penetration depth of the hearth coke bed into the liquid pool is made. Computational results are presented in a form directly useful for blast furnace operators.
4. More detailed studies on the configuration of submerged coke bed in hearth which have direct consequences for tapping practice and lining protection may be carried out by modeling. Stress distribution at the tuyere level computed from the present work may be used as the upper boundary condition, which would be the dominant force and input to the system, for the model of blast furnace hearth based on force balance.

Appendix 1 Extended Drucker-Prager Model

A description of the Extended Drucker-Prager Model is given. It is based on the documentation provided by ABAQUS (2004). The Extended Drucker-Prager Model has features that are suitable for describing granular material behavior under load. These include a pressure dependent yield function, hardening, and volume change with inelastic behavior.

1. Stress Invariants

$p = -\frac{1}{3}\mathrm{trace}(\boldsymbol{\sigma})$	Equivalent pressure stress
$q = \sqrt{\frac{3}{2}(\mathbf{S}:\mathbf{S})}$	Mises equivalent stress
$\mathbf{S} = \boldsymbol{\sigma} + p\mathbf{I}$	stress deviator
$\mathrm{r} = \left(\frac{9}{2}\mathbf{S}\cdot\mathbf{S}\cdot\mathbf{S}\right)^{\frac{1}{3}}$	third invariant of deviatoric stress

2. Yield Criterion

The linear Drucker-Prager criteria in terms of the stress invariants is written as Equation 1 and shown graphically in Figure A1.1.;

$$F = t - p\tan\beta - d = 0 \tag{1}$$

where

$$t = \frac{1}{2}q\left[1 + \frac{1}{K} - \left(1 - \frac{1}{K}\right)\left(\frac{r}{q}\right)^3\right]$$

β the slope of the linear yield surface in the *p-t* stress plane (friction angle)

d cohesion.

K ratio of the yield stress in triaxial compression and extension (defines the dependency of the yield surface on the intermediate stress (Figure A1.2)).

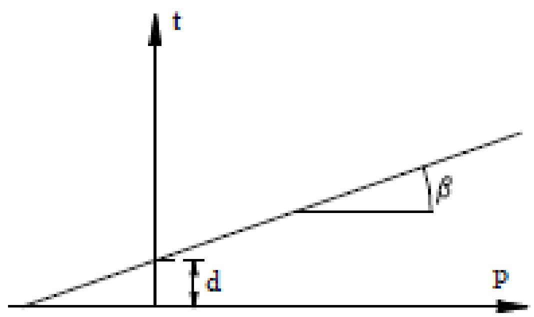


Figure A1.1 Yield Function in the *p-t* stress plane for the Linear Drucker-Prager Model

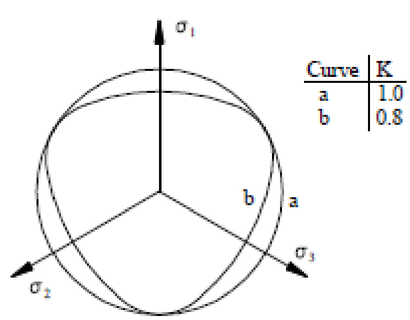


Figure A1.2 Typical Yield Surfaces in the deviatoric plane

3. Plastic Flow

The flow potential G is given by;

$$G = t - p\tan\psi$$

Where ψ is the dilation angle in the *p-t* stress plane. The geometrical interpretation of ψ is shown in Figure A1.3.

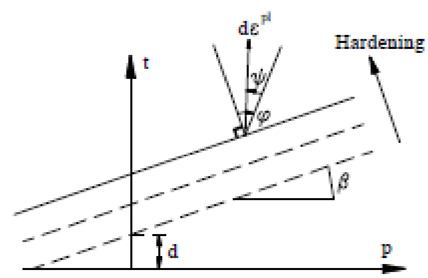


Figure A1.3 Yield Surface and flow direction in the *p-t* stress plane

4. Matching of Mohr-Coulomb parameters

Experimental data often available in terms of the Mohr-Coulomb Model are the internal angle of friction φ and cohesion d. Conversion is accomplished by making the two models provide the same failure definition in triaxial compression and extension. This results in the following relationships;

$$K = \frac{3 - \sin\ \varphi}{3 + \sin\ \varphi}$$

$$\tan\beta = \frac{6\sin\varphi}{3 - \sin\varphi}$$

References

ABAQUS Inc. "version 6.5 Documentation." 2004.

Ansys Inc. "Ansys Fluent 12.0 Documentation." 2009.

Ashmawy, Alaa K., Beena Sukumaran, and Vinh Hoang. "Evaluating the Influence of Particle Shape on Liquefaction Behavior Using Discrete Element Modeling." *Proceedings of the Thirteenth International Offshore and Polar Engineering Conference.* Kyushu, 2003. 542-549.

Austin, P.R., H. Nogami, and J. Yagi. "A mathematical model of four phase motion and heat transfer the blast furnace." *ISIJ International* 37 (1997): 458-467.

Bachhofen, H.J., W. Kowalski, M. Peters, and P. Ruther. "New Experience with an Improved Ceramic Cup Lining in the Blast Furnace Hearths of Thyssen Krupp Stahl AG." *Iron and Steel Maker*, June 1999: 39-45.

Bathe, K.J. *Finite Element Procedures in Engineering Analysis.* Englewood CLiffs, New Jersey: Prentice Hall, Inc., 1982.

Bean, R.M., and R.R. Schat. "Major Rebuild and Upgrading of Dofasco's No. 4 Blast Furnace." In *AISI Year Book*, 395-402. 1988.

Bear, J. *Dynamics of Fluids in Porous Media.* New York: Elsevier, 1988.

Bennet, D., and R. Bradley. "A strategy for an efficient simulation of countercurrent flows in the iron blast furnace." *Appl. Math. Modelling* 15, no. October (1991): 506-515.

Bishop, A.W. "The principle of effective stress." *Techisk Ukeblad* 39 (1959): 859-863.

Bowles, J. *Foundation Analysis and Design.* 5th. McGraw-Hill, 1996.

Busby, N.J., T.A. Fray, and D.C. Goldring. "Nature of cohesive zone in blast furnace." *Ironmaking and Steelmaking* 21 (1994): 229-234.

Chen, J., T. Akiyama, and J. Yagi. "Effect of burden distribution pattern on gas flow in a packed bed." *ISIJ International* 32, no. 12 (1992): 1259-1267.

Chen, J.Z., T. Akiyama, H. Nogami, and J.I. Yagi. "Modeling of solid flow in moving beds." *ISIJ International* 33, no. 6 (1993): 664-671.

Choudhary, M., J. Propster, and J. Szekely. "On the importance of the inertial terms in the modeling of flow maldistribution in packed beds." *AIChE Journal* 22, no. 3 (1976): 600-603.

Cross, M., and R.D. Gibson. "Gas Flow Through Multilayered Regions of Porous Media." *Powder Technology* 24 (1979): 167-178.

Donaldson, B. "Private Communication." *ArcelorMittal Dofasco.* 2014.

Dong, X., A.B. Yu, S. Chew, and P. Zulli. "Modeling of Blast Furnace with Layered Cohesive Zone." *Metallurgical and Materials Transactions B* 41B, no. April (2010): 330-349.

Drucker, D., and W. Prager. "Soil mechanics and plastic analysis or limit design." *Quarterly of Applied Mathematics* 10 (1953): 157-165.

Elsaadawy, E.A., and K.W. Lu. "Mathematical Modeling of Flows in the Coke-Free Layer of a Blast Furnace Hearth." *AISTech Conference .* Charlotte, North Carolina: AIST, 2005. PR-346-027.

Elsaadawy, E.A., and W.K. Lu. "3D Mathematical Modeling of Flows in the Deadman/Hearth Region of a Blast Furnace Hearth." *AISTech Conference.* AIST, 2006. 471-480.

Ergun, S. "Fluid Flow Through Packed Columns." *Chemical Engineering Progress* 48, no. 2 (1952): 89-94.

Forchheimer, P. "Wasserbewegung durch Boden." *Zeitschrift Verein Deutscher Ingenieure* 45 (1901): 1782-1788.

Fujita, M., H. Kojima, H. Marushima, and T. Kawai. "Reduced revamp duration at Chiba No. 6 blast furnace." *ISS Ironmaking Conference.* ISS, 2000. 113.

Fukutake, T., and K. Okabe. "The Hearth Drainage of the Blast Furnace." *International Blast Furnace Hearth and Raceway Symposium.* Australasian Institute of Mining and Metallurgy, 1981.

Fumoto, Y., R. Liu, Y. Sano, and X. Huang. "A Three-Dimensional Numerical Model for Determining the Pressure Drops in Porous Media Consisting of Obstacles of Different Sizes." *The Open Transport Phenomena Journal* 4 (2012): 1-8.

Geiger, G.H., and D.R. Poirier. *Transport Phenomena in Metallurgy.* London: Addison-Wesley, 1973.

Goodey, R.J., C.J. Brown, and J.M. Rotter. "Verification of a 3-dimensional model for filling pressures in square thin-walled silos." *Engineering Structures* 25 (2003): 1773-1783.

Gudehus, G. "A comprehensive constitutive equation for granular materials." *Soils and Foundations* 36, no. 1 (1996): 1-12.

Hashimoto, S., S. Sasaki, and Y. Chikko. "Coke in the Blast Furnace – Property Requirements and How to Realize Them." *McMaster Symposium 17.* Hamilton ON: McMaster University, 1989. 1-19.

—. "Coke in the Blast Furnace – Property Requirements and How to Realize Them." *McMaster Symposium 17.* Hamilton ON: McMaster University, 1989. 1-19.

Herle, I., and G. Gudehus. "Determination of parameters of a hypoplastic constitutive model from properties of grain assemblies." *Mechanics of Cohesive-Frictional Materials* 4 (1999): 461-486.

Hibbitt, Karsson & Sorrensin, Inc. *ABAQUS Theory Manual,.* 2004.

Hill, J.M., and Y.H. Wu. "Plastic flows of granular materials or shear index n – II Yield functions." *J. Mech. Phys. Solids* 41 (1993): 77-93.

Ho, C., Y. Chen, and C. Lin. "On the flow of granular material in a model blast furnace." *Powder Technology* 63 (1990): 13-21.

Inada, T., K. Takata, K. Takatani, and T. Yamamoto. "Effect of blast furnace profile on inner furnace states." *ISIJ International* 43, no. 7 (2003): 1003-1010.

Inada, T., K. Takatani, K. Takata, and T. Yamamoto. "The effect of the change of furnace profile with the increase in furnace volume on operation." *ISIJ Journal* 43, no. 8 (2003): 1143-1050.

Inada, T., K. Takatani, M. Miyahara, and H. Yamaoka. "Mathematical simulation model of blast furnace." *ICSTI/Ironmaking Conference.* ICSTI, 1998. 465-470.

Janssen, A.W. "Tests on Grain Pressure Silos." *Zeits. D. Vereins Deutsch Ing.* 39 (1895): 1045-1049.

Joseph, D., D. Nield, and G. Papanicoloau. "Nonlinear Equation Governing Flow in a Saturated Porous Medium." *Water Resources Research* 18, no. 4 (1982): 1049-1052.

K., Shibata., Y. Kimura, M. Shimizu, and S. Inaba. "Dynamics of Dead-man Coke and Hot Metal Flow in a Blast Furnace Hearth." *ISIJ International* 30, no. 3 (1990): 208-215.

K.H., Peters, H.W. Gudenau, and G. Still. "Hot metal Flow in a Blast Furnace Hearth – Model Test." *Steel Research* 56 , no. 11 (1985): 547-551.

Katayama, K., S. Wakabayashi, T. Inada, K. Takatani, and H. Yamaoka. "Study on the stress field inside blast furnace using elastic plastic theory." *ICSTI/Ironmaking Conference.* ICSTI, 1998. 311-316.

Kawai, H., and H. Takahashi. "Solid Behavior in Shaft and Deadman in a cold model of blast furnace with floating-sinking motion of hearth packed bed studied by experimental and numerical DEM analysis." *ISIJ International* 44, no. 3 (2004): 1140-1149.

Khodak, L., and Y. Borisov. "Velocity and pressure distributions of moving granular materials in a model of a shaft kiln." *Powder Technology* 4 (1970/71): 187-194.

Kitaev, B., et al. "Investigation of the Aerodynamics in Packed Metallurgical Furnaces with Tuyere Wind Entry." *International Conference on Blast Furnace Serodynamics.* Wollongong, Australia, 1975. 68-74.

Klein, C.A., G. Rezende, F.K. Fujihara, and J.I. Gushiken. "Long campaign life of CST No. 1 blast furnace." *Revue de Metallurgie* 102, no. 6 (2005): 413-420.

Kolymbas, D. "An outline of hypoplasticity." *Archive of Applied Mechanics* 61 (1991): 143-151.

Kuwabara, M., and Z Ma. "Further insights into blast furnace phenomena and modeling for researchers and operators." *International Conference on Advances in the Theory of Ironmaking and Steelmaking.* Bangalore, India, 2009. 184-191.

Liu, S., A. Afacan, and J. Masliyah. "Steady Incompressible Laminar Flow in Porous Media." *Chemical Engineering Science* 49, no. 21 (1994): 3565-3585.

Luengen, H.B., M. Peters, and P. Schmole. "Ironmaking in Western Europe." *AISTech.* AIST, 2011. 387-400.

M., Shimizu, A. Yamaguchi, S. Inaba, and N. Narita. "Dynamics of burden materials and gas flow in the blast furnace." *Tetsu to Hagane* 68 (1982): 42-51.

McNally, R., F. Roulet, D. Kuser, J. Schoennahl, and D. Lucke. *Advances and Advantages with Ceramic Cup Technology.* Saint-Gobain, 2000.

Meyerhof, G. "Penetration tests and bearing capacity of cohesionless soils." *Journal of the Soil Mechanics and Foundations Division* 82, no. 1 (1956): 1-19.

Naito, M. "Recent Progress of practical BF Operations in Japan and Innovative Trials for the Future." *5th European Coke and Ironmaking Congress.* Stockholm, 2005.

Nakamura, N., Y. Togino, and M. Tateoka. "Behaviour of coke in large blast furnaces." *Ironmaking and Steelmaking* 5, no. 1 (1978): 1-17.

Nazeri, H., G. Mustoe, and T. Rozgoni. "Computer Simulation of Gravity Flow of ore in Ore Passes by the Discrete Element Method (DEM)." *5th International Conference on Computational Structure Technology.* Leuven Belgium, 2000.

Negro, P., J.M. Steiler, E. Beppler, U. Jahnsen, C. Bennington, and R. Willmers. "Assessment of coke degradation in the blast furnace from tuyere probing investigations." *3rd European Ironmaking Congress.* Gent, Belgium, 1996. 20-27.

Niemunis, A., and I. Herle. "Hypoplastic model for cohesionless soils with elastic strain range." *Mechanics of Cohesive-Frictional Materials* 2 (1997): 279-299.

Nouchi, T., A.B. Yu, and K. Takeda. "A numerical investigation of the coke movement in blast furnace hearth,." *9th APCChe and Chemeca 2002.* Christchurch, New Zealand, 2002.

Nouchi, T., T. Sato, M. Sato, K. Takeda, and T. Ariyama. "Stress field and solid flow analysis of coke packed bed in blast furnace based on DEM." *ISIJ International* 45, no. 10 (2005): 1426-1431.

Ogata, I., and S. Masahiro. "The Latest Trends and Future Aspects in Japanese Ironmaking Technology." *3rd International Conference on the Science and Technology of Ironmaking.* Düsseldorf: VDEh, 2003. 27-33.

Ohno, Y., Kondo, K. "A Mathematical Model of Three-dimensional Gas Flow in Packed Beds." *Tetsu-to-Hagane* 73 (1987): 226-233.

Omori, Y. *blast Furnace Phenomena and Modelling.* Elsevier, 1987.

P., Zulli, F.W.B.U. Tanzil, V. Panjkovic, B.D. Wright, and R. Nightingale. "Hearth Process Design and Control." *International BF Lower Zone Symposium.* Wollongong , 2002.

Panjkovic, V., J.S. Truelove, and P. Zulli. "Numerical modeling of iron flow and heat transfer in blast furnace hearth." *Ironmaking and Steelmaking* 29, no. 5 (2002): 390-400.

Parker, B.J., R.D. Chaykowski, D.H. Pomeroy, and R.J. Donaldson. "Dofasco's No. 4 blast furnace – hearth management to exceed a 12 year campaign." *ISS Ironmaking Conference.* ISS, 2000. 12-24.

Peters, M., H. Gudenau, M. Sceiwe, and R. Sieger. "Stresses Exerted on Coke in the Lower Region of a Blast Furnace,." *European Ironmaking Congress.* Glasgow, UK, 1991. 205-223.

Polthier, K. "Gas-und Stoffbewegung im Hochofen bei hoher Erzeugungsleistung." *Stahl und Eisen* 90 (1970): 240-246.

Poveromo, J.J., J. Szekely, and M. Propster. "Flow Maldistribution in the Iron Blast Furnace." In *Blast Furnace Aerodynamics*, by M. Standish, 1-8. Parkville: Australian Institute of Mining and Metallurgy, 1975.

Qing, G., Ma L., X. Zhang, J. Zhou, and M. Kuwabara. "Numerical investigation of gas Flow through blast furnace shaft with designed layered structure of ore and coke burdens." *Ironmaking and Steelmaking* 37, no. 7 (2010): 546-552.

Raipala, K. *On hearth phenomena and hot metal carbon content in the blast furnace, PhD Thesis.* Helsinki: Helsinki University of Technology, 2003.

Reid, R., J. Prausnitz, and T. Sherwood. *The Properties of Gases and Liquids.* 3rd. McGraw-Hill, 1977.

Ricketts, J.A. "A Short History of Ironmaking." *57th Ironmaking Conference.* Toronto: ISS, 1998. 3-40.

Roscoe, K.H. "The influence of strain in soil mechanics.10th Rankine Lecture." *Geotechnique* 20, no. 2 (1970): 127-170.

Safavi Nick, R, A. Tilliander, T. Jonsson, and P. Jonsson. "Mathematical Model of Solid Flow Behaviour in a Real Dimension Blast Furnace." *ISIJ International* 53, no. 5 (2013): 979-987.

Savage, S.B. "The mechanics of rapid granular flows." *Advances in Applied Mechanics* 24 (1984): 289-367.

Sitharam, T. "Numerical simulation of particulate materials using discrete element modeling." *Current Science* 78, no. 7 (2000): 876-886.

Stanek, V., and J. Szekely. "Flow Maldistribution in Two Dimensional Packed beds Part II: The Behavior of Non-Isothermal Systems." *Canadian Journal of Chemical Engineering* 50 (1973): 22-30.

Stanek, V., and J. Szekely. "The Effect of Non-Uniform Porosity in Causing Flow Maldistributions in Isothermal Paced Beds." *Canadian Journal of Chemical Engineering* 50 (1972): 9-13.

Stanek, V., and J. Szekely. "Three-Dimensional Flow of Fluids Through Nonuniform Packed Beds." *AIChE Journal* 20, no. 5 (1974): 974-980.

Takahashi, H., H. Kawai, and Y. Suzuki. "Analysis of stress and buoyancy for solids flow in the lower part of the blast furnace." *Chemical Engineering Science* 57 (2002): 215-226.

Takatani, K., T. Inada, and Y. Ujisawa. "Three-dimensional dynamic simulator for Blast Furnace." *ISIJ International* 39, no. 1 (1999): 15-22.

Tardos, G.I., S. McNamara, and I. Talu. "Slow and intermediate flow of a frictional bulk powder in the Couette geometry." *Powder Technology* 131 (2003): 23-39.

Tsalapatis, J., and Keil R. "The third campaign of the Whyalla No. 2 blast furnace." *5th European Coke and Ironmaking Congress.* Stockholm, 2005.

Van Laar, J., N. Noort, G.J. Tijhuis, J. Touw, and C.S.M. Stolwijk. "Stress Related Wear Phenomena in Blast Furnace Hearths." *2nd European Ironmaking Congress.* Glasgow UK, 1991. 110-114.

Von Wolffersdorff, P.A. "A hypoplastic relation for granular materials with a predefined limit state surface." *Mechanics of Cohesive-Frictional Materials* 1 (1996): 251-271.

Voyiadjis, G.Z., G. Thiagarajan, and E. Petrakis. "Constitutive modeling for granular media using an anisoptropic distortional yield model." *Acta Mechanica* 110 (1995): 151-171.

Walker, D.M. "An Approximate Theory for Pressures and Arching in Hoppers." *Chemical Engineering Science* 21 (1966): 975-997.

Walters, J. K. "A theoretical analysis of stresses in silos with vertical walls." *Chemical Engineering Science* 28 (1973): 13-21.

WorldSteel Association. *Steel Statistical Yearbook, Tables 1 and 6.* 2013.

Xu, B.H., and A.B. Yu. "Numerical simulation of the gas-solid flow in a fluidized bed by combining discrete particle method with computational fluid dynamics." *Chemical Engineering Science* 52, no. 16 (1997): 2785-2809.

Xu, B.H., Feng Y.Q., D. Pinson, A.B. Yu, S. Chew, and P. Zulli. "Discrete particle simulation applied to the modeling of gas-solid flow in blast furnace raceway." *International BF Lower Zone Symposium.* Wollongong, 2002.

Zaimi, S.A., D. Sert, J.B. Guillot, and H. Biausser. "Recent advances in the modeling of solid flows in the blast furnace." *Steel Research International* 75, no. 5 (2004): 302-307.

Zaimi, S.A., J. Guillot, C. Petit, and Steiler J.M. "Modelling the flow of solids in the blast furnace." *ICSTI/Ironmaking Conference .* 1998 . 343-350.

Zaimi, S.A., J.B. Guillot, and H. Biausser. "A solid flow model for blast furnace based on hypo-plasticity theory." *Ironmaking and Steelmaking* 30, no. 6 (2003): 475-482.

Zaimi, S.A., T. Akiyama, J.B. Guillot, and J.I., Yagi. "Validation of a blast furnace solid flow model using reliable 3-D Experimental results." *ISIJ International* 40, no. 4 (2000): 332-341.

Zhou, Z.Y., D. Pinson, H.P. Zhu, A.B. Yu, B. Wright, and P. Zulli. "Discrete particle simulation of gas-solid flow in the blast furnace." *Third International Conference on CFD in the Minerals and Process Industries.* Melbourne, Australia: CSIRO, 2003.

Zhu, H.P., Z.Y. Zhou, A.B. Yu, and P. Zulli. "Stress fields of solid flow in a model blast furnace." *Granular Matter* 11 (2009): 269-280.

Zulli P., F.W.B.U Tanzil, V. Panjkovic, B.D. Wright and R. Nightingale, "Hearth Process Design and Control", *International BF Lower Zone Symposium*, Wollongong, 2002